Translating the scientific concepts of resilience into a diagnostic tool for urban climate resilience building

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Abstract

More frequent and severe flooding events due to extreme weather conditions are a number one risk for developing and developed countries posed by a changing climate. Dense urban centers are argued to be especially vulnerable since they host a range of human, economic and natural capital and are subject to unpredictable, indirect knock-on effects. Thus, climate adaptation solutions which reduce the vulnerability of natural and human systems against actual and expected climate change effects are urgently needed.

Albeit resilience has gained momentum in the latter approach over the last decades, the understanding of what it entails, or which mechanisms to introduce in order to create resilience in a city system is limited among policy-makers and practitioners. To address this problem, this research aimed at developing a diagnostic tool by which policy-makers can assess the resilience of the current urban system and check their adaptation plans for their resilience benefits according to their fulfillment of resilience principles.

The researcher reviewed the relevant scientific literature across different disciplines (i.e. urban and spatial planning, adaptive governance, disaster resilience, ecological resilience, economic resilience, flood resilience) and identified therein stated characteristics to strengthen resilience (termed principles) to create an integrated assessment framework. This consisted of the following principles: Anticipation & foresight, Preparedness & planning ahead, Homeostasis, Diversity, Redundancy, Buffering, Flatness, High flux, Learning and Flexibility. To account for differing disciplinary notions of these principles and improve its diagnostic value for practitioners, principles were further broken down into intermediate principles.

Assuming that not all of the theoretically based principles are fit to work in practice, the researcher explored their utility for policy-makers and practitioners in two illustrative case studies and their respective flood risk management approaches: Rotterdam and London. The goal was to find out which principles pose problems, why and improve their practicality. By means of policy analysis and semi-structured interviews with key stakeholders, the current adoption of resilience principles in strategies, measures and institutional contexts was investigated in the two cases. Based on the findings, the framework and its indicators were refined to finally present a diagnostic tool for urban climate resilience-building.

List of Abbreviations

ARP: Adaptation Reporting Power
CIRIA: Construction Industry Research and Information Association
DEFRA: Department for Environment, Food and Rural Affairs
DP: Delta Program
EA: Environment Agency
FCERM: Flood and Coastal Erosion Risk Management appraisal guidance -
GLA: Greater London Authority
IAWM: Integrated, adaptive water management
IenM: Ministry of Infrastructure and the Environment
LCCAS: London Climate Change Adaptation Strategy
LCCP: London Climate Change Partnership
LRPS: London Resilience Partnership Strategy
LSFRF: London Strategic Flood Response Framework
NFRR: National Flood Resilience Review
NRR: National Risk Register of Civil Emergencies
NPPF: National Planning Policy Framework
NWP: National Water Plan
RAS: Rotterdam Climate Adaptation Strategy
RCP: Rotterdam Climate Proof
RFRA: Regional Flood Risk Appraisal
RRP: Room for the River Program
RRS: Rotterdam Resilience Strategy
RWP: Rotterdam Waterplan
RWS: Rijkswaterstaat
SES: Social-ecological systems
SNFCR: Strategic National Framework on Community Resilience
SUSD: Sustainable drainage
TCFMP: Thames Catchment Flood Management Plan
TE2100: Thames Estuary 2100
WB: Water Board

1 Introduction

1.1 Climate change impacts in cities

According to the latest IPCC report published in 2014 the surface temperature of the Earth in the last three decades has been warmer than ever before. In addition, changes in extreme weather and climate events were observed to occur since 1950 by increases in warm temperature extremes, high sea level extremes and the number of heavy precipitation events (IPCC 2014).
Impacts of a changing climate, already being felt across all continents, are projected to intensify in the future. Besides the annual mean temperature, sea levels are anticipated to rise at an accelerated rate, affecting river levels. Precipitation in general, and cloudbursts in particular (i.e. extreme precipitation over short periods) will increase and become more intense, causing sewer overflows in urban areas and greater river discharges and thereby amplifying flood risk in river and low-lying coastal areas. More frequent and severe flooding events due to extreme weather conditions are one out of three major risks for developing and developed countries, next to heat stress, drought and freshwater scarcity (European Environment Agency 2012; Royal Netherlands Meteorological Institute 2015). This includes flooding from the rivers (riverine or fluvial flooding), the sea (coastal and tidal flooding) and from rainwater (pluvial flooding or cloudbursts, surface water flooding) which are the priority themes of this paper.

Since impacts are locally aggravated in urban areas, cities are particularly at risk from a changing climate (IPCC 2014). First, densely built-up areas constitute micro-climates which affect temperature, wind direction and precipitation (European Environment Agency 2012). Second, they accommodate a large share of human, economic and natural capital, which makes them especially vulnerable to disruption. The potential damage incurred by an earthquake, landslide or flooding event is considerable. In addition to the loss of infrastructure, property and service provision, many livelihoods are at risk since cities host about 90 percent of the world's population with an ongoing upward trend (IPCC 2014; Dickson et al. 2012). Third, urban centers are also subject to major indirect impacts from disturbances since high levels of connectivity trigger a multitude of complex, mutually influencing feedback mechanisms and potential knock-on effects (European Environment Agency 2012).

1.2 The role of climate adaptation in cushioning expected impacts

The management of risks and impacts associated with climate change has been evolving as a domain of municipalities and regional governments over the past decades. Many channeled financial investments to identify city-wide vulnerabilities and develop climate adaptation plans, recognizing the need to cope with existing impacts (Bulkeley 2010; Bulkeley & Betsill 2013; IPCC 2014; Fünfgeld 2015).
As opposed to climate mitigation which aims at stabilizing and reducing greenhouse gas emissions, climate adaptation consists in initiatives and measures that reduce the vulnerability of natural and human systems against actual and expected climate change effects (Smit et al. 2000). Its basis is the assessment of climate-related vulnerabilities of a city's population and its assets, which results from a combination of its exposure to hazards, and its sensitivity towards perturbations (IPCC 2014; Nelson et al. 2007). Rooted in the concept of adaptation as "*a process of deliberate change in anticipation of or in reaction to external stimuli and stress*" (Nelson et al. 2007, p.395), climate adaptation focuses on response strategies and mechanisms that moderate impacts of actual or expected climatic stimuli by performing "*adjustments in ecological-socio-economic systems"* (Smit et al. 2000, p.225).

Measures can be discerned into three distinct categories: grey, green and soft measures. Grey measures imply structural, built interventions. For flooding, examples are dams, flood defenses, the flood-proofing of buildings and infrastructure by design or water storage capacity (e.g. water squares, drainage system). Green measures pertain to the maintenance and enhancement of green spaces inside and outside of cities that serve as water retention areas and require appropriate spatial and land-use planning. Examples are gardens, green roofs, parks, urban wetlands or the "re-naturalization" of rivers. Finally, soft measures refer to the non-structural strategic planning and planning codes, guiding policies, but it also includes awareness raising and capacity-building of the public to better cope with flood risk (Ligtvoet et al. 2013; Ligtvoet et al. 2011; IPCC 2014; European Environment Agency 2012).

1.3 Contextualizing resilience in climate adaptation

Over the past decade, resilience has gained momentum in policy-making and become an integral part of scientific discussions about climate adaptation and strategic planning (Davoudi et al. 2013). In the practitioners' discourse, resilience is often falsely used as a synonym to climate adaptation. This is partly rooted in the diversity of its interpretation and incongruity of its use (Leichenko 2011; Tasan-Kok et al. 2013). Despite several intersections between the two concepts, their theoretical underpinnings and practical implications vary (see chapter 2.2.2 for a detailed outline).

Climate adaptation seeks to develop measures that aim at reducing the vulnerability of a system and moderating climate change impacts. Since these are based on climate projections, it calculates with the anticipation of climate-related events employing traditional "predict and prevent" approaches (Tyler & Moench 2012; da Silva et al. 2012; Nelson et al. 2007).

In contrast, resilience implies "*the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks*" (Walker et al. 2004). Accordingly, it looks at phenomena and their wider repercussions in a system and its sub-components. Instead of prescribing a specific set of adaptation options, it explores how proposed activities feedback positively or negatively into the whole system through time (Nelson et al. 2007). Resilience addresses a multitude of stressors a city can be exposed to and should be equipped to deal with. Climate change is only one of them (Leichenko 2011; Tasan-Kok et al. 2013).

Since change is accepted as an inherent feature of the system, developing the adaptive capacity of its constituents (i.e. the urban system) to deal with slow and radical changes is the starting point for building resilience (Davoudi 2012; Eraydin & Taşan-Kok 2013a). In the scientific literature, such adaptive capacity is reflected in the ability to self-organize, learn and adapt (Carpenter et al. 2001; Tompkins & Adger 2004; Smit & Wandel 2006).

This paper opts for and is based on integrating a resilience approach into climate adaptation strategies. For a better understanding of the process of resilience-building through informed climate adaptation plans a conceptual framework is provided below (Fig. 1.1). It draws on contributions on resilience-oriented urban planning from Eraydin & Taşan-Kok (2013) and Tyler & Moench (2012). By employing resilience mechanisms in the design of climate adaptation plans the resilience of the urban system can be improved in order to be better able to respond and adapt to external and internal pressures (Wardekker et al. 2010; Eraydin & Taşan-Kok 2013a).

Three major benefits are expected by taking a resilience approach towards climate adaptation.

First, it supports the digression from the traditional predict and prevent planning approach of traditional climate adaptation towards integrating the element of uncertainty. The suitability of the latter has increasingly come

under scrutiny due to uncertainties in climate change predictions and unpredictable urban trends and developments (Tyler & Moench 2012; da Silva et al. 2012). A resilience approach is specifically geared to develop the underlying adaptive capacities of a system to deal with surprises and eventualities of any kind rather than solely preparing according to predictions.
Second, it widens up the scope of potential climate adaptation measures to address a holistic picture of intersections with different system components. With climate adaptation being a concerted effort that operates at multiple urban dimensions across different sectors, this aspect is highly salient. Thus, it requires the collaboration of a variety of stakeholders across levels and scales for a successful implementation of activities (Folke et al. 2005; Betsill & Bulkeley 2006). An awareness absence of resilience's underlying intersections across different policy domains and sectors might propel isolated, inefficient sectorial planning and impedes the joint development of a feasible climate adaptation package.
Third, employing a resilience approach in climate adaptation strengthens the overall robustness of cities by rendering them capable of coping with a variety of shocks that can seriously affect the livelihoods of its inhabitants (Arup 2014a).

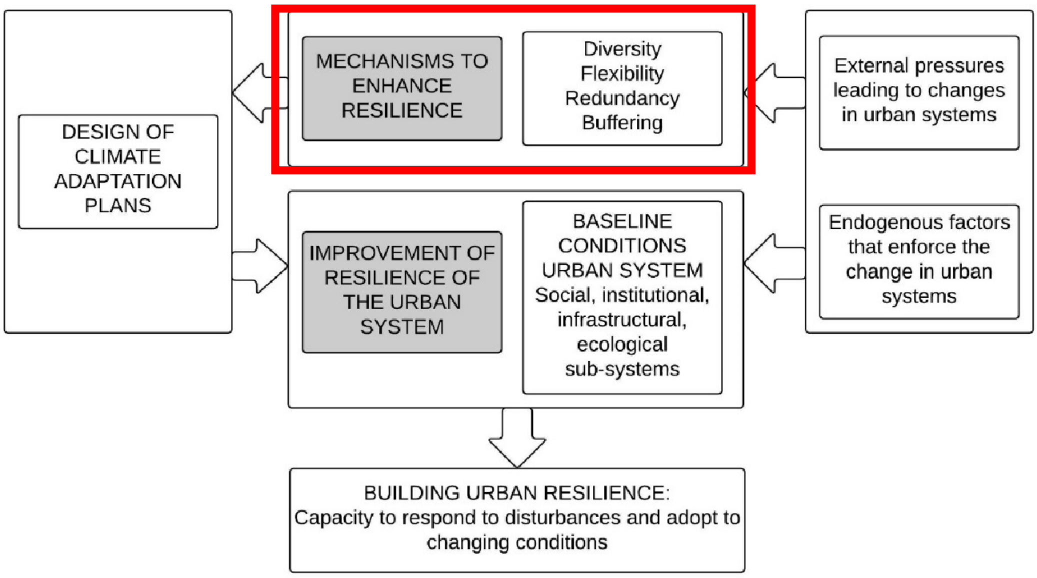

Fig. 1.1: Conceptual framework climate adaptation plans and resilience enhancement
(based on Eraydin & Taşan-Kok 2013a; Tyler & Moench 2012)

1.4 Knowledge gap: operationalizing resilience-building

A variety of mechanisms through which a system can be made resilient were established in the scientific literature (thereafter referred to as principles), such as innovation, flexibility or diversity (Adger et al. 2005; Folke et al. 2005; Godschalk 2003; Eraydin & Taşan-Kok 2013a; Carpenter et al. 2001; Walker et al. 2004; Wardekker et al. 2010). However, limited scientific progress was made in operationalizing resilience in a consistent and comprehensive way, and identifying appropriate ways to assess it (see Biggs et al. 2012; Biggs et al. 2014; Tyler & Moench 2012; da Silva et al. 2012; da Silva 2014).
The underlying problem is two-fold. First, resilience is an emergent system property and can therefore only be measured in terms of decline, namely a disturbance that was previously absorbed suddenly creates a regime shift (Gunderson 2009). Second, there is a lack of conceptual clarity of resilience in the scientific domain, represented in its inconsistent use and grounded in a scientific disagreement on its underlying characteristics

(Eraydin & Taşan-Kok 2013a; Davoudi et al. 2013; Leichenko 2011; Davoudi 2012; Meerow et al. 2016). As a result, the scientific output is mostly confined to disciplinary isolated ad-hoc lists of characteristics, missing how the latter relate to each other or overlap.

This has major ramifications for resilience-guided policy making. It is believed that (climate adaptation) plans can only embody efficient resilience-enhancing measures and actions when its underlying complex mechanisms and their intersections across policy domains are properly understood by decision-makers. So far, there is a lack of understanding on behalf of policy-makers and planners of how these mechanisms contribute to and influence urban resilience. This hampers its practical integration and consistent strategy development. It remains unclear how specific actions can be derived from existing concepts and how resilience on a city level can be assessed with a set of indicators (Tyler & Moench 2012; Cutter et al. 2008; Arup 2014b). Thus, "*for city-level planners and professionals to deliberately build urban climate resilience, they need a framework that provides guidance for what resilience means in practice and points to how it can be strengthened*." (Tyler & Moench 2012, p.312).

1.5 Research objective: creating an urban resilience framework

So far, no attempt has been made to synthesize resilience principles and indicators discovered across different disciplines into a holistic analytical framework with instructive value for practitioners.
Thus, the major aim of this paper is to develop a diagnostic tool for strategic urban (climate) resilience-building by which policy-makers can assess the current or projected state of urban resilience (after the implementation of climate adaptation plans). It is geared to policy-makers operating in climate adaptation as well as a broader set of stakeholders aiming at improving the resilience of their organizations or programs. Indicators are used as a means to break down principles into respective actions and provide guidance for required steps. By applying the tool, current weaknesses (through principles not being covered yet) and room for improvement can be detected.

The tool serves a two-fold purpose:
(1) Evaluating resilience baseline conditions, i.e. determine the extent of resilience of current conditions in the city, including involved organizations, infrastructure etc.
(2) Scanning existing and emerging adaptation plans for their fulfillment of (all) required criteria in order to establish or improve resilience (checklist)

After building the tool, its practicality is tested on the particular domain of flood risk management in London and Rotterdam. Focusing on one issue area of climate resilience illustrates a way to tailor abstract resilience principles to a particular field. Along these lines, the structure of the paper differentiates between two major blocks: building the diagnostic tool and the practical testing of the latter on the two illustrative case studies of London and Rotterdam.

Building the diagnostic tool will consist of the following five steps (see Fig. 1.2):
(1) Influential resilience definitions and concepts are explored
(2) Based on these definitions, four major resilience features are elaborated.
(3) These features are translated into and operationalized as distinctive resilience phases and potential policy directions.
(4) An in-depth literature review across different disciplines, such as system dynamics, economic resilience, adaptive governance, urban planning and disaster risk management is conducted to compile resilience principles (i.e. mechanisms that are stated to enhance general resilience). Subsequently, these are critically

evaluated, and those commonly identified in several strands of literature synthesized and integrated into the tool by allocating them to the respective phase.

(5) The same stock of literature including contributions from flood risk management and integrated, adaptive water management (following IAWM) is scanned for indicators tailored to the resilience domain of flood risk management and added to the framework.

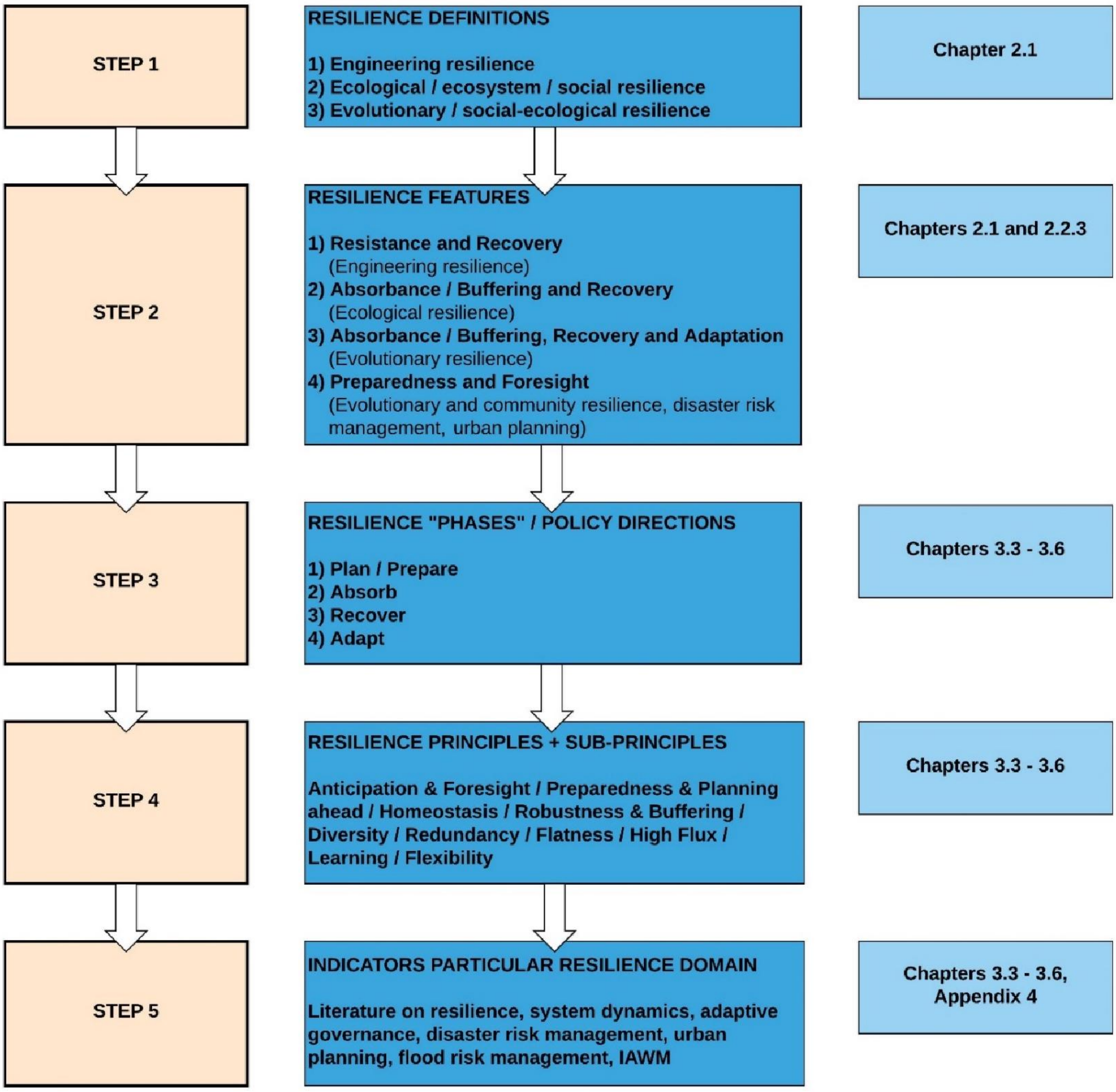

Fig. 1.2: Research framework and steps

Following, the tool is tested on two the two European cases of Rotterdam and London which both have long-term experience with flooding events and highly developed prevention and adaptation strategies. An in-depth analysis of respective policy documents along with (semi-)structured interviews with key actors and stakeholders is conducted in each city. By doing so, the ways in which institutional structure, culture and measures make reference to the resilience principles are assessed.

The testing of the tool serves two major purposes:

(1) Explore whether the framework itself and the elaborated principles are practical for policy-makers (difficulty of translating science into practice-related concepts)

(2) Find out whether the principles are translatable into concrete policy actions according to examples of their integration and application in respective organizations. These inform the refinement of the indicators.

With the development of the diagnostic tool forming the focal part of this paper, the central research question can be established as follows:

How to design a diagnostic tool to evaluate the resilience of cities and their climate adaptation plans

Answering the central question will be rooted in following supportive sub-questions:

1. *What are the major resilience characteristics and underlying mechanisms identified in the scientific literature of different disciplines?* (Step 1 and 2)
2. *How can these characteristics be operationalized for and applied to flooding events in urban areas and flood risk management?* (Step 3, 4 and 5)
3. *What indicators can enhance the applicability of the framework in policy-making?* (Chapter 5.1, 5.3, 6.1 and 6.3)

1.6 Scientific and societal relevance

This paper exhibits both, a scientific agenda in advancing resilience research theoretically and empirically, as well as a societal dimension by providing a concrete tool for resilience-building in cities.
It was previously argued that there is an "*apparent gap between the advocacy of social- ecological resilience in the scientific literature and its take-up as a policy discourse on the one hand, and the demonstrated capacity to govern for resilience in practice on the other*" (Wilkinson 2012, p.319). It is mostly rooted in conceptual difficulties and challenges in measuring the actual impacts of resilience (Biggs et al. 2012).
This research attempts to bridge this gap in different ways.
First, the framework strongly builds on the theoretical underpinnings of resilience. It draws on the scientific literature of the field and mainstreams perspectives from a multitude of different disciplines such as system dynamics, disaster resilience, community resilience, or ecological resilience in one comprehensive tool[1]. By doing so, this research unifies the different resilience perspectives while thoroughly describing their overlaps and thereby advances conceptual clarity of resilience.
Second, pursuing a societal and scientific agenda, it actively supports the capacity to govern for resilience by assessing the practicality of resilience principles and improving their functionality for policy-makers. With the diagnostic tool the researcher proposes a way to operationalize and assess resilience on a city-scale. Knowledge about the comprehensiveness of the indicators and principles along with options for their attainability is generated during field research which is used to improve its practicality.

From a societal dimension, the empirical findings shed light on issue areas and management gaps in building resilience for each city. By doing so, a starting point for future action to strengthen urban resilience along with

[1] The diagnostic tool elaborated in this paper will form the base for the forthcoming article "A diagnostic tool for urban resilience to climate change" by Wardekker et al. and the illustrative case studies will support the therein attempted development of a score card/matrix for evaluating municipal adaptation plans on their contribution to enhancing urban resilience.

recommendations how to do so is provided, which benefits the entire population. Resilience also strongly builds on the self-directing capacity of individuals to prepare themselves and adjust behavior if required. Therefore, several principles of the tool specifically touch on actions to improve community resilience, such as community awareness, preparedness, social networks or options for autonomous response. With the diagnostic tool, these come to the forefront of the attention of policy-makers and have a greater chance to inform action taken in future programs.

2 Theoretical background

The theoretical chapter will outline the following steps addressed in the research framework (see Fig. 2.1):
Step (1): Exploring influential resilience definitions
Step (2): Identification of resilience features

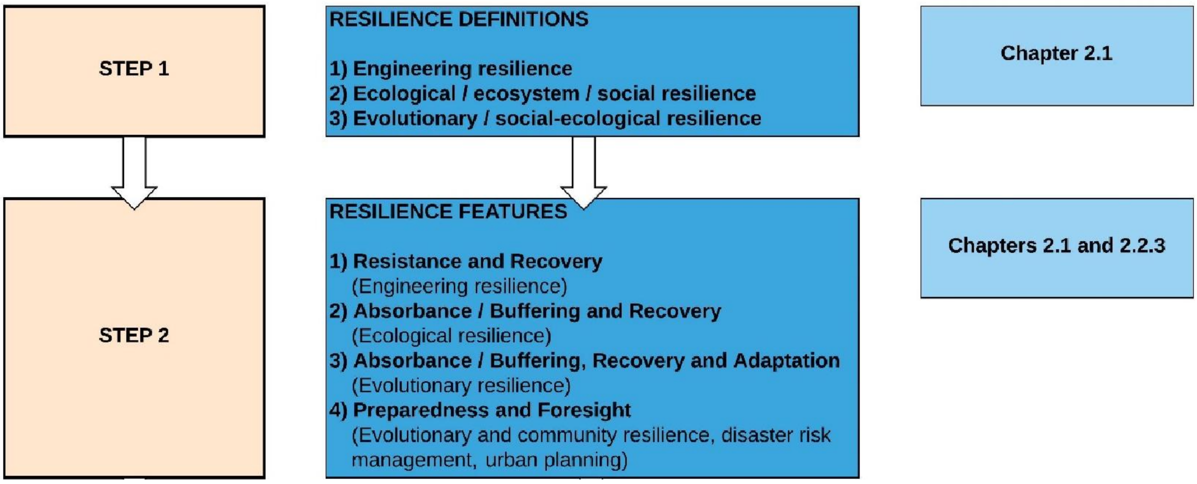

Fig. 2.1: Steps of the research framework addressed in the following chapters

2.1 Defining the features of resilience

To operationalize urban resilience, it is required to delve first into its conceptual base and definitions, and determine its most important underlying characteristics and properties identified in the scientific literature. The evolution of the term and meaning of resilience can be divided into three sequential concepts moving from its application to ecological to combined social-ecological systems (following SES): engineering resilience, ecological resilience and social-ecological resilience (Folke 2006; Wardekker et al. 2010). All of these three concepts build the foundations of the modern resilience discourse.

2.1.1 Engineering resilience: recovery and return time

Resilience was initially introduced and termed by Holling (1973) and originates from population and landscape ecology with a strong foundation in system dynamics, mathematics and modelling. The original interpretation

of engineering resilience refers to the ability of a system to return to an equilibrium or steady state with fully restored functionality after a disturbance (Davoudi et al. 2013). The underlying assumptions of engineering resilience are the existence of one single equilibrium that a system can return to, a stable, predictable environment which allegedly can be kept under control and the capacity of nature to self-repair into equilibrium after experiencing external disturbance (Folke 2006; Liao 2012). This view is largely supported by environmental and natural resource management and is still prevalent in ecology and disaster studies (Davoudi et al. 2013; Folke 2006). Its focus is on the recovery ("bouncing back") and efficiency of the system and resilience is measured according to a system's return time. The idea that a system can bounce back to a previous state is rooted in its resistance towards disturbance and change (Folke 2006). Accordingly, a disturbance is perceived as a threat since it poses a deviation from the system stability and ideal system functionality (Liao 2012).
The engineering approach has limited applicability to SES.
First, its primary focus on returning to an optimal, pre-disaster state is problematic when applied to communities and urbanized floodplains. These are dynamic, constantly evolving systems where flooding events are affected by a multitude of factors, such as climate, socio-economic trends, the built environment and natural, riverine processes. Consequently, they refrain from returning to a pre-determined state. In addition, quickly returning to such as state is at times neither desirable since replicating initial system characteristics that have been vulnerable is counterproductive (Liao 2012).
Second, due to its focus on stable systems with low failure probability or quick recovery to normal function it does not offer any trajectory for a system's inability to resist a disturbance and therefore leaves us with an incomplete picture for combined human-nature contexts such as cities. Likewise, Walker et al. (2004) criticize engineering resilience for its sole focus on return time as an insufficient measure for the different ways a system might fail to resume its functions.

2.1.2 Ecological / ecosystem or social resilience: the capacity to absorb disturbance

Ecological resilience (also termed ecosystem or social resilience) is claimed to be a more suitable concept for cities and flood risk management. It acknowledges the system being in a constant state of flux where instabilities can flip it from one state to another. It also embraces the concept of multiple possible equilibria as new states to which a system can either bounce back or forth (Adger et al. 2005; Davoudi et al. 2013). Empirical research of ecologists showed that ecological resilience more appropriately reflects the behavior of ecosystems and accompanying complex structural and functional changes observed during and after disturbances (Gunderson 2009). On a wider scale, this equilibrist view of bouncing back or forth has become highly influential across a variety of disciplines, such as economic geography, environmental planning or disaster risk management and shaping the types of responses (Davoudi 2012).

The differentiation between recover (returning to a pre-disaster state) and renew (turning into something different) is one of the major distinctive features between engineering and ecological resilience. After experiencing a major disturbance, in many cases the system turns out transformed while possibly still exhibiting similar elements (Gunderson 2009).
Furthermore, in addition to return time, ecological resilience addresses the capacity of a system to absorb change. Thus, it defines resilience in terms of the magnitude of disturbance a system can undergo and the ability to still persist when changed and continue functioning before crossing the threshold to a different regime. The focus is therefore on the persistence of a system (Folke 2006). A regime can be visualized with one or more basins of attraction (equilibrium states) in which a system can reside. Due to internal and external conditions, the regime constantly moves with the confines of these basins, which together with their boundaries constitute the so-called stability landscape (see Fig.2.2) (Walker et al. 2004).

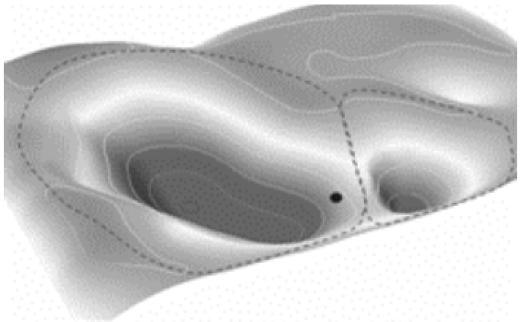

Fig. 2.2: 3D illustration of stability landscape with two basins of attraction (Walker et al. 2004)

This reflects on the previously mentioned criterion in which ecological resilience differs from engineering resilience. Due to the acknowledged dynamics in a system, constant fluctuations are perceived as normal in the former (Liao 2012).

The underlying idea of both engineering and ecological resilience is returning to "normal" after a disturbance, stressing the buffer capacity (i.e. ability to absorb disturbance) and robustness of a system to withstand external shocks (Walker et al. 2004; Davoudi 2012; Folke 2006; Tasan-Kok et al. 2013). As such, it is applicable both to ecological as well as social systems, when perceived as the capacity of communities to withstand external shocks. However, as Davoudi et al. (2013) state, such a narrow focus on persistence and robustness has a rather deterministic tone that doesn't allow for human ingenuity to develop new ways of dealing with disturbances and thereby improving their state of preparedness. Instead, she suggests evolutionary resilience as the concept to follow for SES.

2.1.3 Social-ecological or evolutionary resilience: the capacity to adapt following disturbance

Social-ecological or evolutionary resilience implies an advance in the concept of resilience by introducing a paradigm shift from traditional assumptions of returning to normalcy, a system's predictability and mechanic functioning, to discontinuity and uncertainty thinking (Davoudi 2012). The latter is rooted in the development of the adaptive cycle and panarchy described by Holling in 1986. It constitutes a heuristic model that illustrates the dynamics of an SES through influences and interactions across the levels of a system (scales) over time and space in order to explain system change over time (Walker et al. 2004; Resilience Alliance 2010). According to the adaptive cycle[2], slow, broad variables (macro-scale) interact with fast, small variables (micro-scale) to control the dynamics and determine the pathways of change in an SES, either in a top-down or bottom-up way (Gunderson 2009). In this constant state of flux, resilience is no "*fixed asset*" but "*a continually changing process;*

[2] According to the adaptive cycle, a system passes through four characteristic phases of rapid growth and exploitation (r), conservation (K), collapse or release ("creative destruction" Ω), renewal and reorganization (α) which exhibit different degrees of resilience. Brief periods with major changes, such as collapse (low but increasing degree of resilience) and reorganization (high resilience) are interspersed with long, slow processes occurring during exploitation (high but decreasing resilience) and conservation (low resilience) with minimal change and relative predictability of system dynamics. Ω is the phase of collapse following a disturbance during which attributes or components of the system can be lost. It is followed by renewal and reorganization (α) during which novelties and innovations can emerge (e.g. new ideas, policies, institutions) (Carpenter et al. 2001; Gunderson 2009; Walker et al. 2004). These cycles are not subject to a fixed sequence and in addition they occur simultaneously at different scales, with mutual influence and interactions (so-called panarchies).

not [as] a being but [as] a becoming" (Davoudi 2012, p.304) and a function of slow and fast variables acting at different scales. Consequently, regime shifts do not solely result from external perturbation but can also be triggered by internal stresses without a clear traceability of cause and effect (Davoudi 2012).

Most importantly, evolutionary resilience allows for change to happen due to human agency and system intervention in response to stresses, a fundamental aspect from a policy-making perspective (Nelson et al. 2007). It acknowledges the capacity of SES to self- or re-organize as a decisive condition for a whole system to deal with change. Self- and reorganization entails adjusting themselves through interactions among their components, creating novel creations and initiating adaptive processes (Folke 2006; Resilience Alliance 2010). From this perspective, disturbance turns from a threat to opening up opportunities for system renewal and new trajectories.

Thus, from an evolutionary resilience perspective the third added key aspect of resilience is the capacity for adaptation following the disturbance, in addition to quick recovery from disturbance (engineering resilience), and the ability to persist disturbance (ecological resilience) (Davoudi et al. 2013; Folke 2006; Davoudi 2012). This inherent element of dynamic change is best reflected in Walker et al. (2004) resilience definition as "*the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks*".

For above mentioned reasons, evolutionary resilience is deemed the most appropriate resilience concept for characterizing urban contexts with multiple dynamics at different scales leading to unpredictable development. Therefore, the researcher adopts this concept along with its three outlined key features. In line with its line of thinking, this paper will therefore follow Carpenter et al.'s (2001) interpretation of evolutionary resilience along its three major properties:

1. The amount of change the system can undergo and still retain the same controls on function and structure.
2. The degree to which the system is capable of self-(re)organization to accommodate external changes.
3. The ability to build and increase the capacity for learning and adaptation.

2.1.4 General versus specified resilience

A frequently discussed issue in the resilience literature that deserves attention is the differentiation between specified and general resilience. It unravels fundamental questions, such as to what type of disturbance an urban system should be resilient, and whether resilience is viewed in a long-term or short-term dimension. As such, the type of resilience employed determines the nature of required interventions and the principles to be included in the urban resilience framework, and will therefore be clarified at this point.

Specified resilience responds to the question of "resilience of what and to what" (for instance the resilience of an urban system to flooding events) and thus implies resilience of a particular part of a system (exhibiting a specific control variable) to a specific disturbance or event. Thereby it focuses merely on short-term adaptation to a specific, known disturbance (Meerow et al. 2016).

General resilience, on the other hand, refers to resilience towards all kind of shocks, including yet unknown ones. It adopts a long-term perspective on adaptation to uncertain scenarios through emphasizing adaptive capacities of the system (Resilience Alliance 2010; Godschalk 2003). Meerow et al. (2016) warn against focusing solely on specified resilience for the danger of lock-in and becoming too specialized on short-term adaptation at the expense of general adaptability to uncertain, unexpected threats (Meerow et al. 2016; Godschalk 2003).

Therefore, this research attempts to combine both approaches. The output of this research and the diagnostic tool itself is intended to apply to a wide range of climate-related impacts in the near and distant future and therefore addresses both short-term sudden events (e.g. cloudbursts, riverine flooding, surface water flooding) and long-term stresses (e.g. coastal sea level rise). Since it concentrates on one issue area, it unavoidably falls within the definition of specified resilience. Due to the necessity to limit the scope of the empirical research the focus will further be narrowed down to the illustrative domain of flood risk management when testing the tool and developing tailored indicators. However, to accommodate general resilience and avoid shortsightedness, the principles underlying the diagnostic tool are based on general adaptive capacities, such as diversity, flexibility or redundancy.

2.2 Locating evolutionary resilience in the urban context

This chapter will explore the intersections between evolutionary resilience and urban resilience and thereby take a closer look at the feasibility of a social-ecological resilience approach for the urban context of climate adaptation. The urban planning discipline will be shown to equally contribute to enriching the concept of evolutionary resilience with an additional resilience feature that is overlooked in the traditional resilience approach: the aspect of planning and preparedness. Finally, the translation of the discovered resilience features to concrete building blocks of urban climate resilience will be made to set the base for elaborating the diagnostic tool.

2.2.1 Intersection between evolutionary and urban resilience

With resilience being a concept that has recently gained momentum especially in regards of cities, the array of definitions of urban resilience is constantly growing. Definitions vary in detail and focus, ranging from broad definitions, such as the one of Leichenko (Leichenko 2011, p.164) who perceives it as the "*the ability … to withstand a wide array of shocks and stresses*" to more elaborate ones, such as the one of Meerow et al. (2016, p.45). They refer urban resilience *"to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity."*
Despite the variety of definitions the common tenor is a replication of the aspects of evolutionary resilience. The reoccurring elements are the capacity of urban systems to absorb changes, reorganize, develop adaptive capacity and strategies to cope with change while maintaining vital functions (Tasan-Kok et al. 2013). Due to its comprehensiveness this research adopts the following definition of urban resilience elaborated by Wardekker et al. (2010, p.988) as "… *a system that can tolerate disturbances (events and trends) through characteristics or measures that limit their impacts, by reducing or counteracting the damage and disruption, and allow the system to respond, recover, and adapt quickly to such disturbances*".

Definitions of "urban resilience" conceptualize cities as complex adaptive SES in which ecosystems are integrated with human society (Kernaghan & da Silva 2014; Tasan-Kok et al. 2013).
They consist of flows of goods, services and people with interdependent sub-systems under constant influence of external fluctuation and disturbances (e.g. infrastructure, economic, technological, cultural system). According to the adaptive cycle, these constantly evolve and respond to internal and external influences over different scales and time frames (da Silva et al. 2012; Resilience Alliance 2010; Gunderson 2009). Consequently,

unpredictable, non-linear feedback processes at multiple scales occur, which can give rise to abrupt changes, that also lie at the heart of evolutionary resilience (Folke et al. 2005; Folke 2006; Davoudi 2012).
Due to their inherent unpredictability the analysis of complex, adaptive systems is challenging. It is therefore common to characterize them via systemic emerging properties, such as resilience and adaptive capacity (Gunderson 2009).
An additional feature of cities that lends itself to the concept of evolutionary resilience is their refusal to return to a previous equilibrium state after disruption. This notion corresponds with the concept of several stable states a system can shift between following a disturbance (multiple-state equilibrium) supported by ecological resilience (Meerow et al. 2016). Due to the multiple feedback processes and the unstable nature of cities, returning to a previous state, as advocated by engineering resilience, might neither be possible nor desirable (Wardekker et al. 2010; Davoudi et al. 2013). The previous state could have disappeared and alternative pathways opened up which might have changed the whole trajectory of a system (Tasan-Kok et al. 2013).

Another aspect of evolutionary resilience that deserves further attention in relation to urban climate governance contexts is adaptability. Following Walker et al. (2004) adaptability in this paper is interpreted as "*the capacity of actors in a system to influence resilience*", which as an emergent property of the social component in SES, comes down to the capacity of humans to manage resilience and prevent a system from flipping into an undesired state or move back into a desirable one. Adaptability allows for human intervention into the system and therefore provides the foundation for strategic urban governance of climate adaptation.
"*Conscious interventions* [by human actors] *into the process, planned or otherwise, can diminish, sustain or enhance resilience* (Davoudi et al. 2013, p.312).
Against this backdrop, governance, as purposeful collective action (among state, private, and civil society stakeholders) can either sustain and improve a certain regime or trigger a transition of the system to a more preferable regime (Folke et al. 2005). Noteworthy, the type of resilience concept adopted by policy-makers determines the character of management approaches and available policy options. For instance, engineering resilience with its strong pronunciation of return time and resistance seeks to control and mitigate the impact of a disturbance. Cities that apply an engineering resilience approach will exhibit a strong tendency towards disaster risk management and emergency response along with a sole focus on short-term shocks and damage reduction at the expense of long-term gradual trends. In contrast, evolutionary resilience-driven approaches are more long-term focused and tend towards increasing the capacity of the system to cope with, adapt to and shape change (Tasan-Kok et al. 2013; Davoudi 2012). The framework to be elaborated in chapter 3 will address these different policy options for resilience-building in more detail.

2.2.2 Resilience and climate adaptation: intersections and differences

In the practitioners' discourse, resilience is often used synonymously with climate adaptation. Yet, resilience clearly goes far beyond the implications of climate adaptation by addressing a multitude of stressors a city should be equipped to deal with (Leichenko 2011; Tasan-Kok et al. 2013). Indeed, there are several intersections between the two concepts. It therefore seems important to clearly demarcate the two concepts, highlight potential overlaps and outline how the application of the resilience concept on climate adaptation can enrich the latter.

Both resilience and climate adaptation, though with different intensity, look at climate change-related impacts and seek ways to mitigate and moderate these impacts.
The resilience literature defines nature- or human induced changes leading to a disruption of a system as a disturbance which can either be gradual, long-term developments or sudden shocks (Resilience Alliance 2010).

From a resilience perspective cities are exposed to numerous such disturbances critical for human well-being, such as food and water scarcity, economic crisis or rapid urbanization. Thus, climate change impacts are acknowledged as a few out of a multitude of potential disturbances and can be discerned into sudden shocks and disasters (i.e. extreme weather events, heat stress) and gradual, disturbing trends (i.e. sea level rise) (Wardekker et al. 2010; Walker et al. 2004).

A major difference between the two concepts is the way they approach the mitigation or moderation of climate hazards.
Climate adaptation is understood as "*a process of deliberate change in anticipation of or in reaction to external stimuli and stress*" (Nelson et al. 2007, p.395). Thus, it focuses on actual or expected climatic stimuli whose impacts are moderated by designing response strategies and mechanisms (Smit et al. 2000). The base of climate adaptation are therefore the assessment of (known) climate-related vulnerabilities of and risks to the natural and human systems which it attempts to reduce (IPCC 2014). Following Nelson et al. (2007) vulnerability in the climate adaptation context is defined as a function of a system's exposure to hazards and its sensitivity to perturbations.
This builds a contrast to the theoretical underpinnings of unpredictability related to urban developments, potential climate change impacts and projections promoted in a resilience approach. Resilience-driven responses digress from the traditional predict-and-prevent planning approach prevalent in climate adaptation and acknowledge system vulnerabilities. Two major challenges arise from this "predict and prevent" and vulnerability approach. The reduction of vulnerability plays a paramount role, yet it cannot help to prevent or respond adequately to yet-not-known, unforeseeable disturbances. In addition, indirect effects, institutional or system flaws might be overlooked (da Silva et al. 2012; Tyler & Moench 2012).

This is where the adoption of the resilience concept in the design of climate adaptation strategies can make a major contribution. Instead of prescribing a specific set of adaptation activities, it starts from looking into how proposed activities feedback in a positive or negative way into the whole system through time (Nelson et al. 2007). By strategically integrating resilience criteria into climate adaptation strategies, cities can become capable of coping with a much broader variety of (unpredictable) shocks that might seriously affect its assets and the livelihoods of its inhabitants (Arup 2014a).
Furthermore, the application of the resilience approach enhances potential adaptation options. Instead of attempting to control disturbances, resilience aims at enhancing the capacity of a system to cope with them by purposefully managing resilience (Eraydin & Taşan-Kok 2013a; Folke 2006; Folke et al. 2005). The implied possibility to change the system state itself considerably widens the range of adaptation options beyond reactive response to disturbances to proactive planning and preparation (Nelson et al. 2007).
Introducing resilience-thinking into climate adaptation has another major implication: a shift in the traditional character of adaptation. The primary focus of the traditional adaptation approach is outcome-oriented in terms of reaching a state of adaptedness in which the urban system effectively deals with known hazards. However, seeking adaptedness in one domain might decrease resilience in another domain or might render a system too focused on one specific type of shock that it becomes vulnerable to other unknown ones. In contrast, adaptation from a resilience perspective entails promoting the underlying capacity of a system to deal with future change (Nelson et al. 2007). As a consequence, adaptedness can only be achieved temporarily and adaptation turns from an outcome into a continuous "work in progress" that constantly requires adjusting action, a process of continual learning and improving the capacity to handle hazards while maintaining the flexibility necessary to respond to change (Meerow et al. 2016; Nelson et al. 2007).

2.2.3 A fourth resilience feature: Preparedness and foresight

As outlined above, uniting evolutionary with urban resilience unravels a fourth feature of resilience in addition to absorb, recover and adapt, namely preparedness and foresight. Missed out on by the traditional, previously outlined resilience approach (chapter 2.1), it is endorsed by scholars across several disciplines.
In contrast to ecological systems, the human system has the capacity to recognize and anticipate disturbance, and deliberately manage it to a certain extent (Gunderson 2009; Holling 2001). According to Davoudi et al. (2013) who declare preparedness as a component of their resilience-building framework for urban planning, the intentionality of human agency and intervention is a major requirement for turning a crisis into an opportunity. Likewise, Holling (2001) states human intentionality and foresight to be a game changer in the adaptive cycle. Preparedness also finds replication across other disciplines such as disaster risk management, in pre-event measures to mitigate hazard-related impacts and losses where a major resilience focus lies (Cutter et al. 2008). Gunderson (2009) refers to it in the sense of anticipation and integrates it into her community resilience framework. She differentiates between the following phases: communities have the ability to anticipate disasters, manage vulnerabilities before disaster occurs, respond during a disturbance, and recover after natural disasters (Gunderson 2009).

The four detected resilience features which form the building blocks of the diagnostic tool are summarized in Table 2.1.

Resilience definition / concept	**Characteristics / Focus areas**	**Resilience Features**
Engineering resilience	Recovery to pre-disturbance, steady state, efficiency (return time), resistance, one single equilibrium	(1) Recover from disturbance
Ecological / ecosystem / social resilience	Robustness, persistence, buffer capacity, renew (recover), continuous internal system fluctuations, multiple equilibria	(2) Absorb disturbance without losing function
Social-ecological / evolutionary resilience	System renewal, transformability, adaptive capacity, learning, innovation, interplay disturbance and reorganization, sustain and develop	(2) Absorb disturbance without losing function, (1) Recover from disturbance by self-(re)organization, (3) Adapt to changing circumstances
Urban resilience	Human capacity to anticipate disturbance, intentionality of human agency, ingenuity to break and later the cycle	(4) Preparedness & Foresight

Table 2.1: Resilience definitions and features

2.2.3 Translating the four resilience features into building blocks for climate resilience

The four outlined resilience features all contain required elements for resilience-building but at this stage still remain rather abstract. They lack instructions for concrete policies or measures for resilience-building. All of them are potentially relevant for particular areas or components of the system and therefore represent a

continuum of actions required to be addressed by climate adaptation strategies supposed to enhance urban resilience (Meerow et al. 2016). For instance, persistence may be significant for the built infrastructure and structural interventions, such as dikes, flood barriers and storm walls. From a climate adaptation perspective, the outlined features can therefore be categorized as required steps, building blocks or phases of urban resilience which serve as the foundations of the framework to be elaborated in the following chapter.
The latter notion draws on the "event management cycle" employed in disaster risk management and emergency planning which structures required action before, during and after sudden shocks into consecutive phases (Linkov et al. 2014). Based on a National Academy of Sciences report on disaster resilience four functions of a resilient system are discerned: (1) planning and preparation, (2) absorption, (3) recovery and (4) adaptation (Linkov et al. 2013).

For the diagnostic tool these phases are not necessarily defined as consecutive phases or related to a certain temporal order of interventions. Sudden shocks (disaster risk management tradition) and slow trends have different requirements as regards the timing of required steps and policy actions. For the former, the sequence of action plays a major role, which is not the case for slow trends, where these phases can occur in parallel.
Also the importance and thus, emphasis of distinctive phases differs between slow-onset and sudden-onset stresses. For instance, sea level rise, can take a long time to build up and take effect. Incremental preparatory measures or in other words anticipatory adaptation that allows for absorbing the expected impacts (e.g. floating pavilions as a different, long-term strategy to deal with flooding or rising sea levels) might render the recovery phase irrelevant (Chelleri et al. 2015). Recovery, on the other hand is more salient for short-term shocks along with building foresight and enhancing preparedness in order to reduce damage from and trigger more efficient responses to known disasters and threats.
Since the framework shall unite applicability to sudden shocks and gradual trends, it needs to account for these different requirements. The use of the four functions a resilient system needs to perform facilitate this. Depending on the context of use, they can either be interpreted as consecutive phases or as parallel steps in terms of focal policy directions for resilience-building. Therefore they allow for a range of different pathways to enhance resilience depending on varying local contexts. This makes this framework particularly suitable as an assessment tool since different cities since might put varying emphasis on particular policy directions and related actions according to prevalent political, social and environmental conditions and also types of threats they are exposed to.

3 Design and operationalization of the urban climate resilience framework

The following chapters will outline the process of building the diagnostic tool for urban climate resilience which contains the following steps (see Fig. 3.1):
Step 3: Description of the phases/focal policy directions
Step 4: Operationalization of interdisciplinary resilience principles and allocation to respective phases
Step 5: Creating a general and specific set of indicators for flood risk management

For improved readability, information boxes were made with a short description of the phase/policy direction, principles and intermediate principles. The final list of indicators can be looked up in Appendix 3. In addition, a detailed outline of conceptual overlaps of terms and meanings across the reviewed resilience literature can be found in Appendix 2.

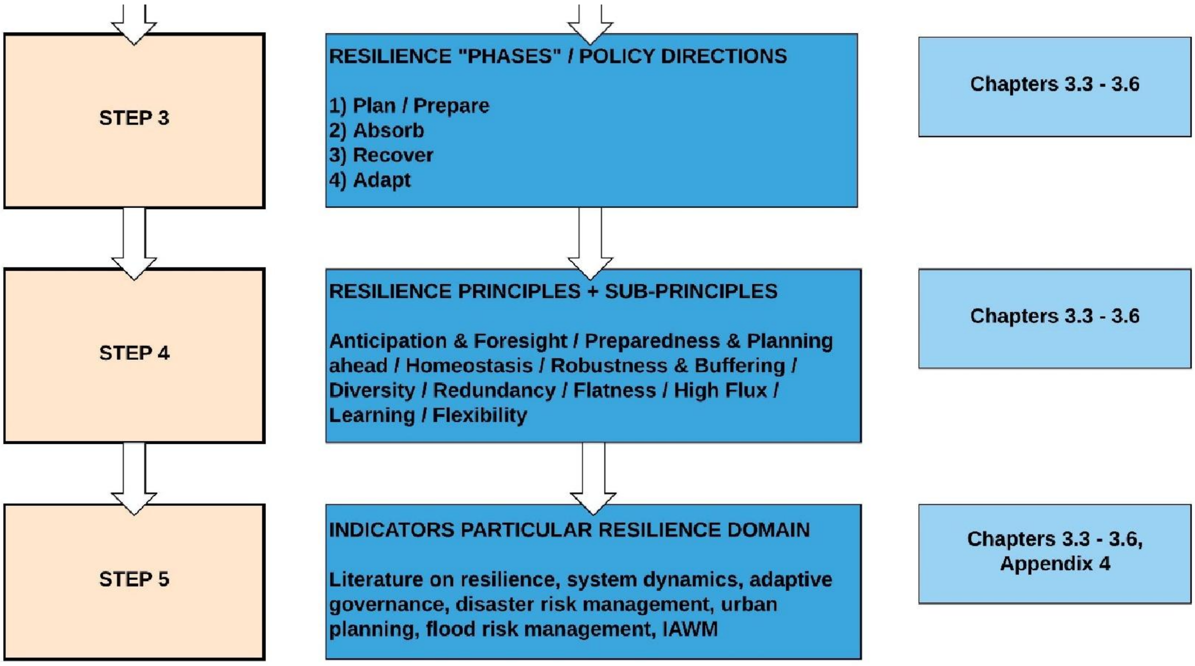

Fig. 3.1: Steps of the research framework addressed in the following chapters

3.1 The selection of resilience literature across disciplines

The literature on resilience is very broad and scattered across a range of different disciplines. Therefore, the existing theoretical and empirical body of resilience literature was reviewed and scanned for principles stated to enhance resilience in a system.
The principles offered by the scientific literature are often overlapping but do have slightly differing meanings according to discipline. Due to the temporal limitations of this research, not all sources providing such principles could be explored but a selection was made of particular disciplinary strands, which is outlined in more detail in this chapter. An overview of the literature and principles used can be found in Appendix 1. Subsequently, only principles were used that were at least pointed out by more than one strand of resilience literature.

Disaster resilience is one of the disciplinary strands the review included. Its emphasis is on the improving the capacity of cities, its inhabitants and infrastructure systems to recover quickly and effectively from man-made and natural disasters (Leichenko 2011). Two separate strands have evolved within the disaster resilience tradition: one replicating the line of thought of engineering resilience, and another one tending towards community resilience in terms of disaster preparedness and response (Cutter et al. 2010; Norris et al. 2008; Godschalk 2003).
The former focuses on critical infrastructure and the built environment with a set goal to limit damage to infrastructure (resistance), buffering potential impacts (absorption) and recovery to a previous state (Cutter et al. 2010). An aspect that is widely neglected by this strand is the social nature of communities. Yet it is increasingly compensated by the second strand of disaster resilience that focuses on community resilience. Proponents particularly focus on adaptive capacities that can be enhanced by policies and measures (Cutter et al. 2010). In addition, great emphasis is put on social capital, social networks, information management and sharing as well as public awareness of risk (Norris et al. 2008; Berkes & Ross 2013; Cutter et al. 2008; Godschalk 2003).

Another strand of literature that was investigated is **ecological resilience literature**, or **ecosystem management literature**. Following ecological, social or ecosystem resilience, it stresses the capacity to absorb disturbance (Leichenko 2011). In the reviewed literature of Gunderson (2011), common features of ecological and social systems are explored. The contribution of Ernstson et al. (2009) attempts to identify cross-scale interactions underlying the increase in vulnerability in two cities while pointing out the necessity for experimentation, learning and innovation. Other papers, such as the one of Biggs et al. (2012) propose concrete resilience principles based on ecosystem management. Despite differing focus areas, the underlying topics are the same: non-linearities, the ability of ecological and SES to self-organize and the perception of cities as complex, adaptive systems (Leichenko 2011).

The third body of literature considered in the review is **(adaptive) governance**. It focuses on the required underlying characteristics of the governance system to strengthen urban resilience and reduce the vulnerabilities of communities (Leichenko 2011). The prominent concept of adaptive governance is taken up by Folke et al. (2005) and formulated into an evaluative tool for governing institutions by Gupta et al. (2010). Learning and experimentation, polycentric, multi-level governance systems, flexible, transparent and accountable institutions, participatory and inclusive decision-making, social networks and capital are reoccurring elements in the governance literature (see Folke et al. 2005; Lebel et al. 2006; Buuren et al. 2015; Tyler & Moench 2012; da Silva et al. 2012).

Furthermore, the literature on **spatial and urban planning** was reviewed. Related contributions explore the capacities of cities to respond to and cope with uncertainties. Also mainstreaming resilience thinking into spatial planning, respective planning systems and policy design is a focal issue area (Eraydin & Taşan-Kok 2013a). Due to its early focus on preparation and mitigation actions for disasters which is influenced by the traditional land-use planning, the emphasis on a city's physical infrastructure and utilities and their robustness is still prevalent in this body of literature (Davoudi et al. 2013; Lu & Stead 2013; Godschalk 2003). Furthermore, connectivity is an element frequently taken up, both in terms of physical connections and interlinkages between vital services but also with regards to social and institutional relationships (Eraydin & Taşan-Kok 2013a).

Due its emphasis on the absorptive capacity of businesses, it was decided to also include the **economic resilience literature** into the review. Drawing on ecological resilience, economic geography and urban planning, this strand of literature looks at pre-disaster preparedness and post-disaster response. In regards of the former, mitigation processes to reduce potential direct and indirect (economic) losses are highlighted (Bruneau et al. 2003). Concerning the latter, attention is drawn to adaptive responses to hazards focusing on ingenuity and resourcefulness at household, company or market level during and after the event (Rose 2004; Leichenko 2011). These mostly consist of pre-disaster changes in structure, functions and behavior in order to resume vital key functions and performance in the face of a disturbance (Martin & Sunley 2014).

Finally, the literature on **flood resilience**, **flood risk management** and **IAWM** was scanned for indicators for the resilience domain at scope. The works form IAWM (see (Pahl-Wostl 2007; Huntjens et al. 2010) show conceptual overlaps with adaptive governance and capacity and were to support the specific indicators. Furthermore, comparative case study research by Raadgever et al. (2015) on flood risk management and governance was looked at to get a more thorough understanding of the available range of preparedness, prevention and response options for flooding events.

3.2 *Employing resilience principles and indicators*

Since the objective of this research is to make resilience more comprehensive and operational in order to become an integrative element in policy-making, it was decided to operationalize the concept by means of resilience principles, which are operationalized by means of indicators further on. In contrast to the more general resilience features outlined above, principles describe more specific mechanisms to generate resilience in a system and its sub-systems. Such principles were previously used by the Rockefeller Foundation, termed qualities of resilient cities (see Arup 2014a and da Silva & Morera 2014) or the Stockholm Resilience Centre (see Biggs et al. 2012 and Biggs et al. 2014). Furthermore, Wardekker et al. (2010) and Barnett (2001) employed such design principles to explore climate adaptation policy options.
According to Schipper & Langston (2015, p.12) principles have the advantage of providing easy guidance for achieving resilience since "*adherence to the 'qualities' or 'principles' of resilience should put one on the path toward resilience."* In addition, the principles are a comprehensive guide against which progress towards resilience can be assessed. Also da Silva et al. (2012) are in favor of of using these principles, or characteristics. They are argued to describe a desired state of a city's underlying networks and sub-systems which resemble the outcome of measures aimed at building urban resilience. Therefore, they offer a feasible pathway towards developing measurable resilience indicators that are easy to comprehend and apply.

An established set of principles originating from the ecological resilience and system dynamics literature lays the base of this framework. It was elaborated by Wardekker et al. (2010) and Barnett (2001) and previously applied and translated to climate adaptation options. It comprises **Homeostasis**, **Diversity** (termed omnivory), **Redundancy**, **Buffering**, **Flatness** and **High flux**.
It was found that the different strands of literature frequently allocate different meanings to the same or similar concepts. For this reason and due to the overall objective of the framework to be used as a diagnostic tool, it was decided that these broad principles require a sub-division into more concrete intermediate principles (for a schematic illustration of the framework components see Fig. 3.2).
Breaking down these principles into smaller categories has a two-fold advantage. From a theoretical perspective, it allows to integrate the respective notions related to these principles from the different strands of literature. From a practical perspective, it provides a more detailed guide which measures need to be taken for resilience-building and what specific components need to be fulfilled for each of these principles. This makes it easier for policy-makers to diagnose whether they are doing enough in each of these issue areas.
Based on the literature review four principles were found to be missing from the initial set proposed by Wardekker et al. (2010): **anticipation & foresight**, **preparedness & planning ahead**, **learning** and **flexibility**.

After identifying the principles and sub-principles, they are allocated to the respective phase / policy direction based on the particular resilience feature they address (i.e. Plan/Prepare, Absorb, Recover, Adapt). For some principles the scanned literature provides a clear indication which aspects are strengthened or supported which makes the assignment easy. For others there is no such indication and a clear picture of the mechanism and its eventual correlation with the underlying resilience feature needs to be painted. Again others enhance several aspects and therefore contribute to different phases. Following, these issues are addressed on a case to case base in the following chapters.

In a third step, sub-principles are operationalized by means of indicators. First, general indicators are developed based on the scanned literature. This supports the suitability of the diagnostic tool for a wide range of disturbances and its future application to other cases.
In addition to that, a more specific set of indicators tailored to the resilience domain of flood risk management is elaborated. There are no universal indicators to be applied consistently across all sectors and geographic

locations due to the localized and context-specific character of resilience and climate adaptation (Tyler et al. 2014). It is therefore worthwhile to focus on one particular domain of resilience, such as flood resilience and flood risk management and determine respective indicators while looking at the wider intersections with other sectors and policy areas.

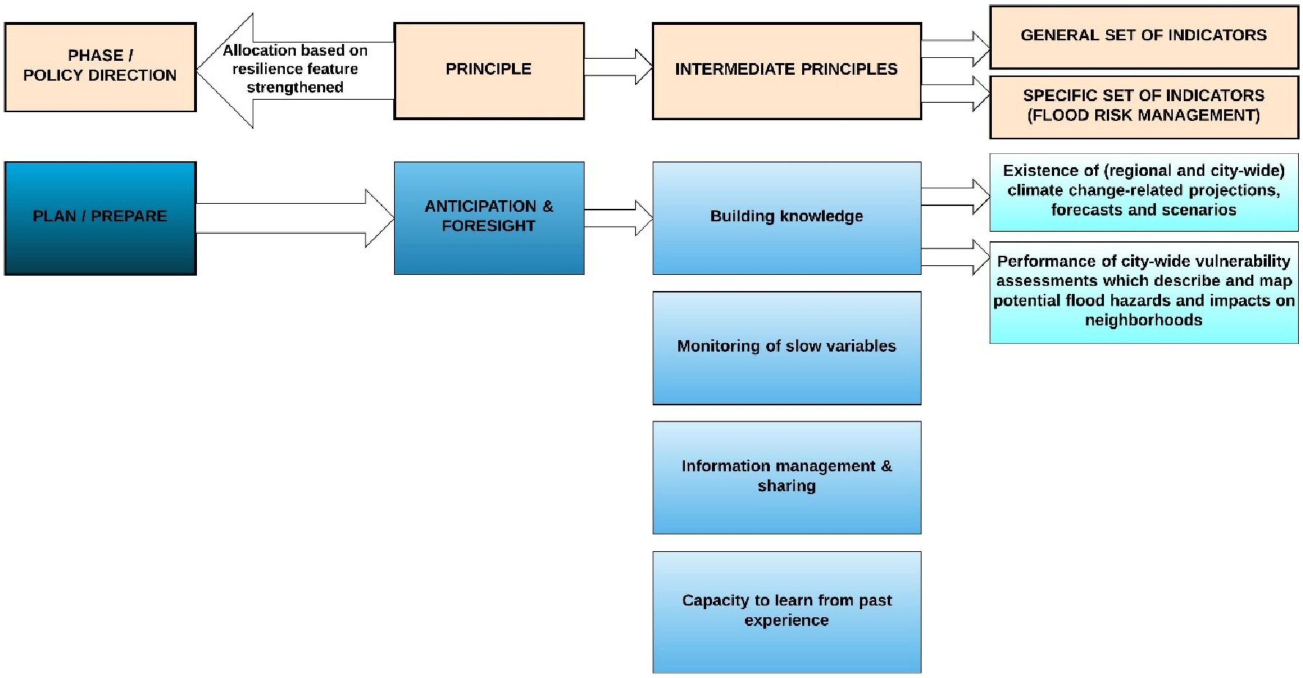

Fig. 3.2: Schematic illustration of framework development

The selection of indicators is guided by the underlying decision what is being measured. In this paper, resilience has previously been outlined to be interpreted as a process rather than an end state. Informed by the idea of resilience-building, the diagnostic tool will therefore mainly be based on process indicators, except for issue areas reflecting on system conditions which require output indicators for assessing the status quo (Schipper & Langston 2015). This differentiation is reflected in the pursued two-fold function of the tool: (1) assessing the state of resilience of the current system (population, institutions, infrastructure) and its configurations (mostly requiring output indicators), (2) assessing the coverage of resilience principles by current and emerging adaptation plans (mostly process indicators).
Noteworthy, the ability of indicators to measure such complex phenomena like resilience, resulting from systemic changes across a variety of dimensions and sectors, is a contested issue. It needs to be acknowledged that the whole spectrum of resilience cannot fully be represented by a few measures. Therefore, the limitation of indicators for only being proxies for the various manifestations of resilience needs to be kept in mind (Schipper & Langston 2015; Tyler et al. 2014).

3.3 Phase 1: Plan & Prepare

PLAN / PREPARE

The capacity to plan, prepare for and anticipate known shocks and stresses. It is represented in proactive action, pre-emptive measures or preparedness activities aimed at mitigating or reducing exposure or minimizing vulnerability to particular threats.

Fig. 3.3: Description of Plan/Prepare

Following the idea of cities continuing to function under adverse circumstances without losing their main characteristics, several disciplines, such as urban planning, disaster risk management and social sciences focus their attention on the “process of preparing the system” for known events. Adequate preparation and planning ahead for eventual adversities make systems better absorb these events and fasten the recovery process by improving recovery capacity (de Bruijn 2004). It is important to mention that this phase involves enhancing the capacities of a system to plan and prepare for disturbances, not setting concrete structural mitigation measures, which is a major difference to subsequent phases.

Planning and preparedness have different implications across various disciplines.
The disaster resilience perspective puts its emphasis mainly on known risks and shocks. As such, planning and preparedness implies having the right system elements and services for disaster response in place that enhance responsiveness, such as early warning systems or communication channels for public information on flood hazard (Tyler & Moench 2012; Schelfaut et al. 2011; Godschalk 2003; Norris et al. 2008; Tanner et al. 2009). This perspective has major overlaps with the flood risk management approach, which apart from effective emergency management, stresses public and institutional awareness of flood risk (de Bruijn 2004; Raadgever et al. 2015; Zevenbergen et al. 2008).
Due to major focus of this phase/ policy direction on known disturbances and threats, reactive learning becomes a decisive aspect for short-term shocks. In accordance with the tenor of the governance literature on resilience, this mainly consists of (1) gathering knowledge (to enhance the predictive capacity of when and where a disaster might occur), especially related to past experience with shocks and (2) the identification of vulnerabilities (Davoudi et al. 2013; Gunderson 2009).
For gradual, long-term trends however, the widely emphasized ability to understand and maintain environmental conditions becomes more salient (Davoudi et al. 2013; Tyler & Moench 2012; Lu & Stead 2013). This notion is closely intertwined with Folke’s et al. (2005) and Biggs et al. (2012;2014) recommendation to foster the understanding of ecosystem dynamics, and underlying changes in slow variables and of SES as complex adaptive systems continually evolving in response to internal system feedbacks. Monitoring mechanisms safeguard that slow-onset developments and subsequent changes are spotted on time and responded to proactively.

3.3.1 Anticipation & Foresight (plan/prepare)

Anticipation & Foresight is solidly rooted in the previously mentioned integration of the human element in SES. This brought about an acknowledgement of the human capacity to anticipate disturbances to a certain degree and design preparatory interventions through adaptation (Holling 2001; Gunderson 2009; Boyd et al. 2015; Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2010; Davoudi et al. 2013). Notably, this

is a specific characteristic of SES, since for ecological systems there is no evidence that the can recognize nor manage disturbances ahead (Gunderson 2009).
Anticipation is based on the ability to imagine different futures and thereby enriches the consideration of possible outcomes (Davoudi et al. 2013; Boyd et al. 2015). In Boyd et al.'s (2015) words, "*such anticipatory practice, in situations of noteworthy and alarming change, are conceivably highly beneficial to imagine how to elucidate complexity and decipher 'wicked' problems, and engage with new mechanisms to harness the future*."
Against this backdrop, foresight has been stated to be closely intertwined with learning processes. Davoudi et al. (2013) even declares it a product of a two-fold learning process: (1) **active learning in terms of developing knowledge** and detecting system vulnerabilities and (2) **learning from previous experience** (which is often referred to as social learning). Both criteria have been taken up as intermediate variables of foresight and anticipation. The two which have further been added, namely monitoring of critical slow variables and information management and sharing are prerequisites for learning.
Monitoring is a criterion rooted in ecosystem management and adaptive governance (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005) that supports the learning process about environmental feedback mechanisms and is useful for identifying early warning indicators for regime thresholds that can be acted upon.
Information management and sharing originates from the community resilience literature (Berkes & Ross 2013; Norris et al. 2008) and the IAWM literature (Pahl-Wostl 2007). Relevant knowledge has both to be built but also stored effectively over time in order to establish institutional memory (Tyler & Moench 2012) that can be harnessed as an information source and shared with other parties.

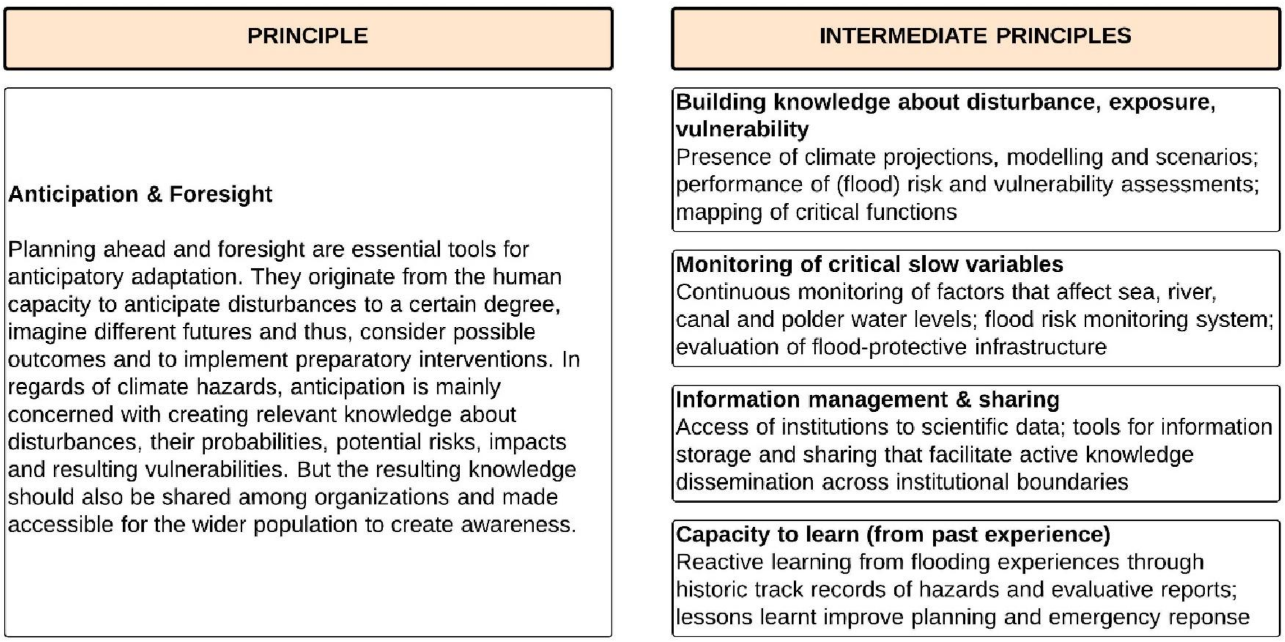

Fig. 3.4: Overview principle Adaptation & Foresight and intermediate principles

3.3.1.1 Building knowledge about disturbances, exposure and vulnerability

A major component of anticipation and foresight is building knowledge about complex adaptive systems and ecosystem dynamics for an anticipatory response to feedback mechanisms and harmful changes therein (see Holling 2001; Gunderson 2009; Boyd et al. 2015; W. N. Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014). A thorough knowledge about potential threats and risks faced enhances the chance for anticipation and can make a system adequately act on them.

Managing a SES towards a desired trajectory is based on understanding a system's resilience and its inherent conditions and characteristics that allow the system to cope with an event and absorb impacts (Biggs et al. 2012; Biggs et al. 2014). This requires a broad set of insights and specialized knowledge, which from a resilient system point of view are co-produced by stakeholders from different scientific disciplines.

Regional climate projections, scenarios and modelling form the base for predicting trends and patterns (Lu & Stead 2013; Arup 2014; Godschalk 2003, Gunderson 2009). Equally important is the identification of vulnerabilities[3] of the system, and information about the city's capacity to respond to threats (Tyler & Moench 2012; Lu & Stead 2013; Linkov et al. 2014; Cutter et al. 2008; Davoudi et al. 2013). This encompasses knowledge about climate-related hazards, the system's exposure to this harzard and the probability of risks and disturbances.

Specifically for flooding events, such knowledge can be accumulated through the performance of regular vulnerability assessments / analysis of the city towards disturbances (flooding events) which describe and map potential hazards and impacts on neighborhoods (Cutter et al. 2008; Lu & Stead 2013; Linkov et al. 2014; Tyler & Moench 2012; Godschalk 2003), along with the creation of flood hazard and risk maps (Gersonius et al. 2011). In addition, mapping of economic assets, critical functions (hospitals, police stations etc.) and commercial establishments in flood-prone areas provides a food estimation of potential flood risk and impacts (Godschalk 2003).

Noteably, the degree of possible anticipation and foresight of events depends on the type of disturbance. There is a major difference between sudden shocks and long-term gradual trends. In contrast to the former, slow-onset threats leave enough time to build knowledge and evidence about the change and its feedback mechansims on the human and natural system. As a consequence, there is time for informed anticipatory adjustments or adaptation. This is not the case for rapid-onset hazards where a system's resilience only becomes apparent when it strucks and cannot be evaluated upfront, other than relying on assumptions drawn from previous experience with the same or a similar hazard (Schipper & Langston 2015).

3.3.1.2 Monitoring of critical slow variables

Monitoring is an important tool for learning about SES, social-ecological dynamics and adequate ways to manage them in order to keep them from slipping into a different regime. Sudden shocks, such as storms, earthquakes, flooding events or long-term gradual trends that build up over time, such as sea level rise are often tipping points that push a system over the edge into another state. Yet, it is usually the combination of a shock (e.g. cloudburst, rainstorm, storm surge) with slow variables, which makes the system approach potential thresholds and potentially collapse.

Slow variables can be of socio-economic, governance-related or ecological nature (Biggs et al. 2012; Biggs et al. 2014; Ernstson et al. 2010). For short-term shocks like cloudburst events or riverine flooding, variables like rainfall patterns, soil type (e.g. clay vs. absorptive soil composition), groundwater levels, the extent of impermeable surfaces in the city (loss of green spaces, building activities) or sewerage capacity are relevant (van de Ven et al. 2014). For long-term gradual changes like sea level rise, land elevation and subsidence, coastal welands deterioration or a low maintenance of levee or dike systems are among these slow variables (Ernstson et al. 2010). Yet, in practice the understanding of slow variables is limited since thresholds cannot be exactly located or identified unless after a system transformation occurred (Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2010; Nelson et al. 2007). Therefore, monitoring is especially relevant for spotting slow-onset trends (Schipper & Langston 2015).

[3] The vulnerability of a system is a function of both, exposure to a disturbance (e.g. flooding, heat stress) and the sensitivity of a system (degree of potential harm to people and sites) (Biggs et al. 2012; Cutter et al. 2008).

(Real-time) monitoring and subsequent identification of slowly changing variables provide for a better understanding of ongoing processes and facilitate anticipation of possible events provided that observed patterns continue. It also helps to identify early warning indicators for thresholds (e.g. through changes in statistical behavior) (Biggs et al. 2012; Biggs et al. 2014; Boyd et al. 2015; National Academy of Sciences 2012). From a system perspective, monitoring is a particular type of feedback, that by detecting changes in SES, provides information to actors and thereby enables the development of (long-term) adaptation strategies but also anticipatory, preventive response to these changes (Biggs et al. 2012).
With regards to flood risk management, three issue areas proof important for continuous monitoring and inspection: Factors that affect sea level, river, canal and polder water levels (Carpenter et al. 2001), the conditions and safety standards of flood-protective infrastructure (Chelleri et al. 2015; Davoudi et al. 2013; Lu & Stead 2013), and the periodic analysis of crucial infrastructure, such as electricity or transport networks (de Bruijn 2004).

3.3.1.3 Information management & sharing

As much as the generation of climate hazard-related knowledge, creating effective information management, storage and sharing mechanisms are a prerequisite for social and organizational learning (Tyler & Moench 2012). The latter safeguard that knowledge can independently and swiftly be accessed and disclosed if required and serve as an institutional memory (Tyler & Moench 2012).
The aspect of information management and sharing has been widely discussed from different angles in the resilience literature. Literature on community resilience stresses the importance of (legal) public access to information to enhance transparency and accountability of policy-making. It also stresses its importance for fostering the capacity of communities to act and react independently in the face of disturbances (Tanner et al. 2009; Berkes & Ross 2013; Norris et al. 2008). Since this aspect is paramount for community preparedness, it will be picked in detail at a later stage, together with public awareness, risk communication and training and education (chapter 3.3.2.1) and with regards to public autonomous response in the face of disturbance (see chapter 3.5.1.3).
In support of anticipation and foresight, the focus is mostly on access to important (scientific) data such as climate projections on behalf of governance units or organizations for them to set adequate action and make strategic policy choices (Tyler & Moench 2012). This perspective is put forward by the adaptive governance literature (see Gupta et al. 2010, Tyler & Moench 2012, Moench 2014) and by representatives of IAWM (see Pahl-Wostl 2007). Questions asked are about information integration, management and storage, accessibility within institutions and institutional memory, across scales and institutional boundaries. Pahl-Wostl (2007) highlights two key aspects in regards of information management: information should be available to the system and the system should be able to process it. The first dimension can be achieved by open, shared information sources that facilitate integration (Pahl-Wostl 2007). Other, more intangible forms of knowledge exchange might also happen through platforms of exchange among actors across institutional boundaries, such as workshops, brainstorming sessions (van den Brink et al. 2013; Moench 2014).

3.3.1.4 Capacity to learn from past experience

Noteworthy, this type of reactive learning from and preparing for adverse events is oriented on short-term shocks, events that have already been encountered before and that are predictable to a certain extent. Its nature is in stark contrast with the type of learning relevant for long-term adaptation which exhibits a proactive approach in dealing with uncertainty instead of attempting to reduce it.

Since learning entails gaining a greater understanding and awareness of potential risks and threats, past experience with adverse events can be harnessed as learning ground in order to come out stronger than before (Schipper & Langston 2015). It fosters anticipation of when and where a disaster occurs and respective impacts on communities and offers insights into system failures in order to avoid their repetition (Gunderson 2009; da Silva et al. 2012). The capacity (of individuals, groups or institutional patterns) to learn effectively from past experience and disasters in order to avoid repeated failures and improve performance is termed social learning or single loop learning (Tyler & Moench 2012; Folke et al. 2005; Rockefeller Foundation 2015; Gupta et al. 2010). If used effectively, the knowledge gained through antecedent revovery and adaptation processes influences has the potential to enhance the inherent resilience of a system for the next event (Cutter et al. 2008).

More specifically for the issue of flooding, it entails the ability to learn from each flooding event and adding new insights into the experience portfolio, which might facilitate infrastructural, physical, institutional or behavioral adjustments to enhance preparedness.

This requires internal documents such as reports or event evaluation documents where comprehensive lessons learnt are formulated. Also historical or geological track records of disasters along with the knowledge about the physical processes triggering a disturbance form the base for such learning processes (National Academy of Sciences 2012).

Yet, promoting lessons learnt in a system alone is not sufficient, since the internalization of past experience needs to occur, both in the social as well as in the organizational realm to bring about the required changes. It is therefore paramount that past experiences inform future decisions in a way that lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms (Folke et al. 2005; Tyler & Moench 2012; Cutter et al. 2008; Davoudi et al. 2013; Adger et al. 2005; da Silva & Morera 2014; Schipper & Langston 2015). Or in other words, when "*beneficial impromptu actions are formalized into institutional policy for handling future events*" (Cutter et al. 2008, p.603). New policy implementation, both in terms of a refinement of internal procedures and externally-oriented policies, might become unavoidable in the face of failure of previous policies or approaches to solve the problem unraveled during a shock (Gunderson 2009).

3.3.2 Preparedness & Planning ahead

Notions of preparedness and planning ahead are found in disaster resilience, but also in flood risk management, urban planning and the governance literature (see Cutter et al. 2008; Cutter et al. 2010; Cutter et al. 2013; Godschalk 2003). The latter two mostly emphasize learning processes and preparatory measures to minimize disturbances (see Davoudi et al. 2013; Eraydin & Taşan-Kok 2013b; Lu & Stead 2013). As a common baseline among these contributions, preparedness & planning ahead aim at improving a city's coping responses before a disaster occurs and thereby designing systems that are able to maintain their function in case of a disturbance (Boyd et al. 2015; Gunderson 2009; Davoudi et al. 2013; Wardekker et al. 2010).

Based on the transdisciplinary literature review, three key dimensions of preparedness & planning ahead have been identified (see Figure 3.5):

(1) Public flood risk awareness and trainings which form the base for adequate, autonomous response capacity.

(2) Response & emergency management which involves having the right system elements and services for disaster response in place that enhance responsiveness. These range from early warning systems, communication means for public information on flood hazard to evacuation routes (Tyler & Moench 2012; Schelfaut et al. 2011; Godschalk 2003; Norris et al. 2008; Tanner et al. 2009).

(3) Preparedness of businesses for adverse events:
Business resilience is poorly featured in the scanned resilience literature but it constitutes an important agenda in climate adaptation and disaster preparedness. It consists of providing businesses with scientific data to factor climate change into their business practice, as well as preparatory measures on behalf of companies, such as business continuity plans.

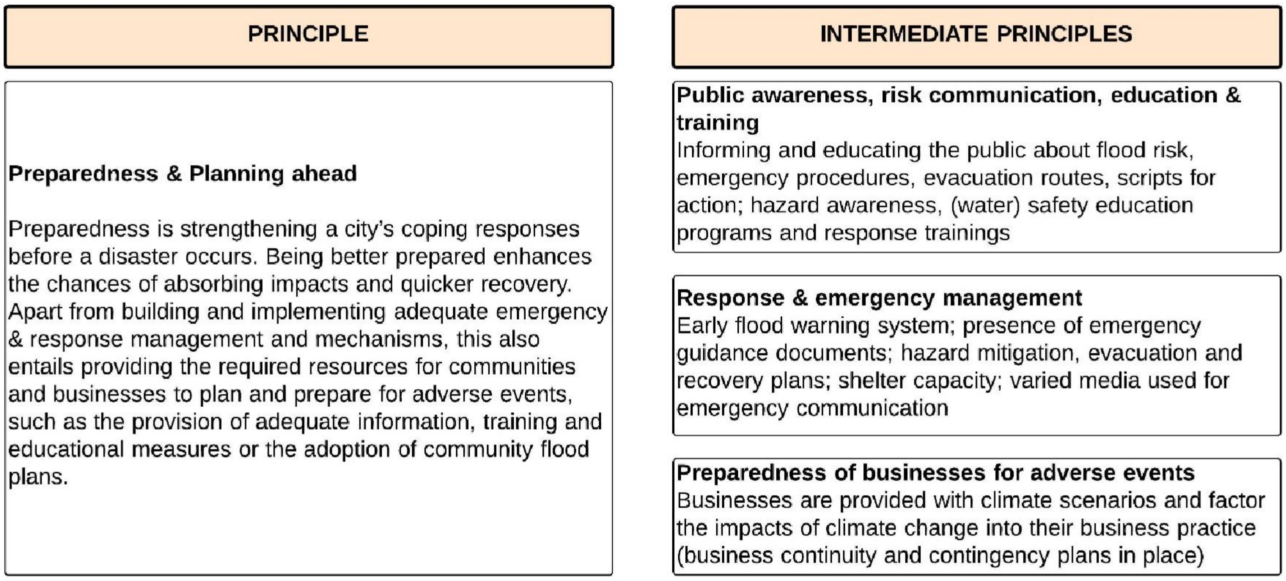

Fig. 3.5: Overview principle Preparedness / Planning ahead and intermediate principles

3.3.2.1 Public awareness, risk communication, education & training

According to community and disaster resilience approaches, a resilient city develops the capacity of their communities to anticipate and respond to disaster (Godschalk 2003). It is argued that access to and an understanding of changing social, political and economic circumstances form the base for people to reduce their own exposure to climate events (Schipper & Langston 2015). Consequently, citizens should know and understand disturbance in order to be able to act and react independently in the face of a disturbance and recover quicker after a disturbance (see also chapter 3.5.7.3). (Tanner et al. 2009; Berkes & Ross 2013; Norris et al. 2008; Cutter et al. 2013).

Therefore, awareness creation on flood risk and water safety and flood risk education among the potentially affected population, communities and businesses are pivotal (Schelfaut et al. 2011; de Bruijn 2004). Creating awareness by communicating flood risk and response strategies even during long periods of absent flooding renders response capacity during events more effective (Raadgever et al. 2015; Godschalk 2003). Public awareness can be fostered by disseminating flood risk information via various channels, such as websites or online learning systems (Lu & Stead 2013). On these channels, for instance GIS maps of hazard areas and emergency contacts could be published (Godschalk 2003).
People should also know whether they should stay, home, leave their properties and area or move to a local safe zone, like a shelter (Raadgever et al. 2015). The provision of plans and scripts for action fosters the ability of individuals to act, or act according to plan (Gupta et al. 2010). Several scholars point out the importance of providing sufficient and accurate information about appropriate actions to take in case of a flooding event or where to turn to for assistance since public adherence to recommendations is not a given (de Bruijn 2004; Norris et al. 2008; Rockefeller Foundation 2015).

Apart from communication, hazard mitigation capability can be actively fostered through effective and broad flood risk training measures for neighborhoods.

3.3.2.2 Response & emergency management

Concerning short-term shocks, planning and preparedness also involves having effective emergency management structures and flood management tools in place. Rooted in community and disaster resilience, this intermediate principle has no applicability to long-term, gradual trends. It is owed to their mere character that they build up slowly over time and therefore have no urgent, sudden momentum like disasters. Much more salient for slow-onset trends and changes are previously mentioned processes of building knowledge and monitoring of slow variables.

An early (flood) warning system is essential to provide for enough lead time to prompt action and extend the window of opportunity in which important decisions can be taken (Raadgever et al. 2015). In addition, the presence of hazard management and mitigation plans as well as emergency response plans are pivotal (Schelfaut et al. 2011; Cutter et al. 2008). Especially in times of crisis, it needs to be clear to all parties involved who has authority over decision-making, what the individual responsibilities and required actions are, and with whom to communicate. Guidance documents are therefore key for a structured, on-time, coordinated emergency response, especially where a smooth collaboration of many different stakeholders is required, such as water management, public safety, municipalities, fire brigade, police and emergency services (Raadgever et al. 2015). Furthermore, the presence of plans for mobilizing supplies (e.g. mutual aid) and personnel can facilitate quicker response and recovery (Bruneau et al. 2003). Another element of effective emergency response is the presence of evacuation plans and the designation of respective evacuation routes (da Silva & Morera 2014; van den Brink et al. 2013; de Bruijn 2004).

Lastly, emergency measures must be communicated to the wider public to facilitate timely response and action (Gupta et al. 2010). The base are reliable and a variety of available communication technologies (ICT) to be harnessed for disseminating information during emergencies concerning hazard alerts, emergency decisions, adequate behavioral responses and dangers (da Silva & Morera 2014; Schelfaut et al. 2011; Norris et al. 2008).

3.3.2.3 Preparedness of businesses for adverse events

The aspect of preparedness of businesses for adverse events includes anticipatory adaptation for expected slow-onset future trends (e.g. sea level rise) as well as preparedness for acute shocks in order not to lose of not lose operational function and/or quickly resume function. Though in many aspects being a new challenge, climate adaptation does have overlaps with already prevalent business practice, such as risk management or business continuity planning and is therefore not an entirely new concept but needs to be mainstreamed into existing risk management processes practice (Lonsdale et al. 2010).

The principle of preparedness of businesses is mainly rooted in disaster, community and economic resilience literature. Both suggest ways to reduce potential direct and indirect business interruption impacts and losses with a specific focus on the human operation of businesses and organizations (Rose 2004). Some indicators were also drawn from the literature about organizational change and detected traits of well-adapting organizations (Lonsdale et al. 2010).

Several measures concerning proactive preparation of financial institutions and companies have been suggested to reduce potential business interruption impacts. A starting points is providing companies with information about climate-related impacts and threats (e.g. climate scenarios) (Godschalk 2003). This creates an understanding of what climate change means for the organization and the extent of exposure based on local impacts which may serve as entry points for adaptation action (Lonsdale et al. 2010). An important driving force in this regard are bridging organizations or partnerships. The participation in formal or informal networks can facilitate the spread of this information and the support of others broaden the picture of potential action (Lonsdale et al. 2010).

3.3.3 Homeostasis

As previously outlined, slow variables determine the structure of an SES. Dynamics therein arise from interactions and feedbacks between fast variables responding to the conditions generated by slow variables (Biggs et al. 2014). Resilience-building implies the strategic management of feedbacks in a system in order to prevent regime shifts. Its base is the identification of key slow variables that maintain the current social-ecological regime along with critical thresholds that can trigger a regime shift. Such regime shifts can be the result of a shock (e.g. extreme rainfall) of a gradual change in a slow variable (e.g. sea level rise). This requires solid knowledge about the SES, its slow and fast variables (Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2010; Nelson et al. 2007).
Homeostasis is one such mechanism to strategically engineer a system. It relates to the implementation of multiple feedback loops that counteract disturbances (dampening feedback) and/or stabilize the system in order to maintain a particular SES regime when facing external stresses (Wardekker et al. 2010). It can therefore be interpreted as a preparation for acute disturbances and gradual, slow trends.
Despite the difficulties to determine decisive slow variables in an SES, some insights about Homeostasis-related measures in a city's ecological, social, governance and spatial components can be drawn from the resilience literature which will be further explored below. Noteworthy, Homeostasis is highly context specific and determining all possible pathways is impossible. This research therefore only focuses on a few aspects with broad applicability (see Fig. 3.6). Not all of these intermediate principles refer to planning and preparedness. Some exhibit absorption mechanism such as the preservation & restoration of regulating ecosystem services, others are related to several phases, such as the quick notification of disturbances or inclusiveness & equity standards (plan, prepare; absorb; recover). With the planning and preparedness component prevalent in almost all of them, the decision was made to allocate it to this phase.

PRINCIPLE	INTERMEDIATE PRINCIPLES
Homeostasis Dynamics in a SES arise from interactions and feedbacks between fast variables responding to the conditions generated by slow variables. Strategic management of feedbacks to prevent regime shifts (caused by disasters or slow trends) is therefore crucial. One way to do so is through implementing multiple feedback loops that counteract disturbances (dampening feedback) and/or stabilize the system to maintain a particular SES regime.	**Preservation and restoration of regulating ecosystem services** Policies for natural areas and ecosystem conservation are in place, additional green spaces are created along with the restoration of natural floodplains and water retention areas
	Integrated planning, coordination & collaboration Presence of bridging mechanisms that link and align strategies which can refer to the coordination of emergency plans or mainstreaming of water policies with other sectorial policies (e.g. land use, urban development)
	Inclusiveness & equity standards Supportive resources and services for vulnerable groups; legally enshrined rights and entitlements to use resources and services; equitable policy processes and outcomes of adaptation measures representing all interests at stake
	Clearly defined responsibilities of actors / institutions Responsibilities for water and sewerage system, flood protection and prevention are clearly defined and allocated (statutory responsibilities) and all parties are aware of their roles in flood protection, response, recovery.
	Quick notification of disturbances Flood and weather forecasting, monitoring and early warning system are present to generate timely information and a variety of communication channels is used for warnings

Fig. 3.6: Overview principle Homeostasis and intermediate principles

3.3.3.1 Preservation and restoration of regulating ecosystem services

In ecology, slow variables are frequently linked to regulating ecosystem services, such as climate or flood regulation. The presence of green space and natural habitats can act as buffer for flooding events in urban areas by providing additional water storage and reducing surface water run-off. Coastal wetlands have the capacity to also absorb tidal surges (Depietri et al. 2012; Gómez-Baggethun & Barton 2012; van den Brink et al. 2013; Wardekker et al. 2010). The preservation or restoration of regulating ecosystem services is therefore argued to have a stabilizing effect towards maintaining a desirable regime and preventing critical thresholds (Biggs et al. 2012; Biggs et al. 2014; Ernstson et al. 2010).
Several policy options and planning measures can be applied such as conservation of natural areas and ecosystems, the creation of green space (parks, public space), green roofs, urban tree canopy cover, or the (re)implementation of urban floodplain wetlands or coastal wetlands (Biggs et al. 2012; Wardekker et al. 2010; da Silva & Morera 2014).
On the other hand, urbanization and land conversion cause the fragmentation and isolation of ecosystems and thereby erode their capacity to provide these services. In regards of flooding from rainwater, sealed surfaces of built-up areas impede water infiltration and amplify flooding impacts (Depietri et al. 2012). The percentage of impervious surface area is therefore chosen as one of the indicators (Godschalk 2003).

3.3.3.2 Integrated planning, coordination & collaboration

Integration and coordinated collaborative processes within and between urban sub-systems and across different operational scales are deemed efficient resilience-building mechanisms across disaster resilience, flood risk management, spatial planning and governance.
In disaster risk management the emphasize lies on collaboration in the development of calamity and crisis management plans. These shall generate quicker, more efficient and coordinated response across the different parties involved in emergency management (Raadgever et al. 2015; Godschalk 2003).
The IAWM perspective, drawing on adaptive governance, considers multi-level and multi-sector integration to have a positive influence on acceptance of decisions and on compliant implementation on the ground (Pahl-Wostl & Knüppe 2013). For flood risk management and governance especially in urban areas, the aspect of mainstreaming of water policies with other sectorial policies (drainage, land use etc.) is salient. Mainstreaming involved the integration of water safety issues or adaptation objectives into existing sectorial policies and practices such as municipal, spatial planning and development (Runhaar et al. 2009; Uittenbroek et al. 2013). Notions of mainstreaming are put forward in the wider governance and climate adaptation literature and acknowledge that "*the whole point of the work on adaptation processes is to have risks (and opportunities) associated with climate change (or other environmental changes) actually addressed in decision-making at some practical level*" (Smit & Wandel 2006, p.285). Linking climate adaptation with urban (re-) development, planning processes, maintenance programs and other ongoing projects (road maintenance and public area development) is described as one way to do so (In Dutch *Meekoppelen*) (Wardekker et al. 2010; Smit & Wandel 2006).

The common tenor of these different disciplinary contributions is that policies, plans and measures are of integrative character, meaning that they address several issue areas, and are developed in a collaborative way with all relevant parties involved.
Bridging mechanisms, which can consist of actors, policies, laws or other instruments are found to have a positive effect on linking and aligning strategies (Raadgever et al. 2015). In this respect, a frequently stressed issue associated with integrated development and planning is a common underlying vision. Such a vision is argued to "*promote consistency in decision-making and ensures that all investments are mutually supportive to a common outcome*" (da Silva & Morera 2014, p.5). It is even deemed more powerful if formulated into concrete development plans or regulations that safeguard the alignment of projects and programs.

Another important component of integrated planning and coordination is cross-sector and cross-institutional collaboration. Relevant processes triggered by collaboration mentioned in the literature are information exchange that supports quick response by shortening feedback loops and additional benefit creation due to shared resources (da Silva & Morera 2014; Rockefeller Foundation 2015). This criterion will be touched on in several other instances in more detail (see chapter 3.4.2.4 and 3.5.1.2) and will therefore not be given further emphasis at this point.

3.3.3.3 Inclusiveness & equity standards

Slow variables can also refer to the social or governance realm, like social cohesion or socio-economic inequality (Wardekker et al. 2010). Likewise, Ernstson et al. (2010) identify socio-economic inequality as a slow variable giving rise to the deterioration or urban ecosystem services and thereby enhancing vulnerability of socially marginalized people.
It is widely acknowledged that lower income classes are less robust towards disaster stress than groups with higher socio-economic status, exhibit lower capacity to absorb impacts and recover less quickly due to experienced psychological consequences from asset loss. Moreover, they are deemed less successful in

mobilizing support following a disturbance (Norris et al. 2008). Inequity has different facets and cuts across the three phases of preparedness, absorption of impacts and recovery.

First, it manifests in unequal access to resources and means. Therefore, governmental and municipal assistance for achieving equity for vulnerable groups is pivotal. Such assistance can target hazard safety levels in such neighborhoods, entail tailor-made mitigation programs after determining the specific needs of these groups. Furthermore, supportive resources and services fostering quicker recovery are feasible, such as relocation into safe locations or the implementation of community-safety education programs (Godschalk 2003). Also, legal rights and entitlements, which represent the way that institutions shape how individuals are able to claim access to resources and services are crucial. As such, institutions can play a key role in limiting or facilitating access of (marginalized) groups (Tyler & Moench 2012). Equity also expands to equitable post-disaster resource distribution and access (Norris et al. 2008), an aspect, which will be dealt with in more detail in High Flux (see chapter 3.5.2.1).

A second dimension of equity worthwhile mentioning in this context are transparent, equitable policy processes and outcomes of adaptation measures that take account of unequal societal circumstances (Gupta et al. 2010). In the scientific literature, this notion is closely intertwined with concepts of accountability of governing authorities (van den Brink et al. 2013; Gupta et al. 2010; Lebel et al. 2006; Leichenko 2011; Folke et al. 2005). Accountable and just authorities make policy-making processes and financial expenditures transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits. Apart from enhancing the adaptive capacity of vulnerable groups and society at large, such authorities are stated to reduce destabilizing conflicts and strengthen weak links in society and thereby exhibit a stabilizing effect (Lebel et al. 2006). Accordingly, accountable and just municipalities or decision-makers would look into distributional consequences of adaptation projects, such as uneven spatial impacts of environmental change (Adger et al. 2005).

3.3.3.4 Clearly defined responsibilities of actors and institutions

A definite allocation of responsibilities among actors and institutions involved forms another aspect of accountability and is argued to serve as a stabilizing mechanism by governance and flood risk management literature (Gupta et al. 2010; van den Brink et al. 2013; Raadgever et al. 2015; Mees et al. 2014; Buuren et al. 2015). Ambiguous responsibilities in municipal, institutional, emergency management and water management processes can aggravate the magnitude of disruption experienced in hampering on-time, coordinated response (Wardekker et al. 2010; Tanner et al. 2009).

For this paper, relevant responsibilities range from evident financial liability in the case of flooding, intergovernmental division of labor for performing emergency response activities (e.g. search and rescue), to the definite allocation of tasks in water management, such as solving water problems or the sewage system (Bruneau et al. 2003; van den Brink et al. 2013; Gupta et al. 2010; Wardekker et al. 2010). In addition, it is also crucial that citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery (Raadgever et al. 2015; de Bruijn 2004). Specifically with regards flooding events, statutory responsibilities for flood prevention and protection laid down in policy documents can render response mechanisms more efficient (Wardekker et al. 2010).

3.3.3.5 Quick notification of disturbances / shocks

With respect to preparedness the importance of reliable and multiple available communication technologies to disseminate information to the wider public in the run-up and during shocks was previously mentioned (see chapter 3.3.2.1).

Specifically for Homeostasis, the rapidity of information transmission gains importance. It facilitates a timely response and action on behalf of citizens, emergency responders and officials and might therefore prevent losses. The rapidity of delivering messages about potential hazards is greatly influenced by the type of disturbance itself and its level of predictability.
Early anticipation of disturbances, such as a tidal wave or extreme precipitation by means of sophisticated weather forecasting, flood forecasting and an early warning system is beneficial since it widens the window of opportunity for appropriate policy decisions to be made (i.e. vertical or horizontal evacuation).

Noteworthy, quick notification of disturbances does not apply to all types of disturbances since the prerequisite of predictability exclude unknown events, which struck suddenly without prior warning or indications of their occurrence.

3.4 Phase 2: Absorb

ABSORB

The ability to withstand a disturbance, endure its impacts and cope with it to a certain extent while not being degraded by its effects or lose function. It is a function of actions taken to mitigate, better absorb impacts and enhance response capacity to an event.

Fig. 3.7: Description Absorb

The capacity to absorb a hazard is dependent on the magnitude of disturbance a system can undergo before crossing a threshold and its ability to persist and continue functioning when facing disturbance. In a SES, it can be influenced by reinforcing mechanisms spanning across the ecological, infrastructural, social and governance sphere. As such, it is a function of the actions taken to (1) avoid or prevent impacts before a disaster occurs and (2) the ability to respond to an event in terms of absorbing impacts when it occurs (Gunderson, 2009).
In the scientific literature, the prevention of and protection from impacts is covered by several, yet partly overlapping concepts. In disaster risk management, urban planning and economic resilience pre-event measures directed towards avoiding and reducing risk or damage to people, property, and resources are referred to as mitigation. Mitigation is argued to increase a system's resilience to disturbance (Tasan-Kok et al. 2013; Cutter et al. 2008). Disaster risk and traditional flood risk management approaches focus mainly on the properties of cities' physical infrastructure and utilities such as persistence and robustness. These concepts also find wider recognition as important resilience characteristics, especially in the ecological resilience literature. Interpreted as the ability to withstand a certain level of stress they play a paramount role during and in the aftermath of a disturbance (Davoudi et al. 2013; Folke 2006; Walker et al. 2004).
Yet, approached from an engineering perspective, robustness runs danger of obtaining a negative connotation of rigid, static, short-term protective measure against losses from a long-term adaptation perspective. Especially when applied to other system components of a SES, such as institutions, robustness and persistence could support a rigid and inflexible culture that counteracts adaptability and innovation (Davoudi et al. 2013). This explains the placement of robustness in the absorb phase as one potential short-term strategy to buffer impacts.
Also Liao (2012) highlights the danger of excessive reliance on flood control measures and ways of artificially promoting environmental stability. She points out their contradiction with resilience underpinnings and the inherent danger of eroding resilience of a system. Instead, she proposes that "*flood hazard management based on resilience theory would begin with acknowledging periodic floods as inherent environmental dynamics*".

Thereby she refers to the second major aspect the framework seeks to integrate: absorbing impacts.
From a flood risk management perspective, there are two elements that fall within this category that both intersect with spatial planning: flood risk prevention and flood risk mitigation. The former aims at reducing the consequences of flooding by decreasing exposure of people and property. This could be administered by prohibiting (property) development in flood-prone areas. In contrast, the latter focuses on measures inside flood-prone areas to reduce the magnitude or consequences of a flooding such as zoning or building codes or creating additional water storage capacities (Raadgever et al. 2015). The spectrum of measures in this category is covered in the following chapter by "creating buffer capacity" and "impact- and risk-reducing planning & planning practice".

3.4.1 Robustness & Buffering

Building on the various dimensions of Robustness & Buffering identified in the scientific resilience literature, three major dimensions can be discerned (see Fig. 3.7):
(1) Robustness through infrastructure, representing approaches of prevention and flood risk mitigation by keeping threats out before they occur, mainly by flood-protective infrastructure.
(2) Creating buffer capacities which implies measures inside flood-prone areas to reduce the magnitude or consequences of a flooding.
(3) Impact- and risk-reducing planning & planning practice aiming at preventing flood risk, for instance by prohibiting property development in flood-prone areas, or reducing flood impacts via flood-proofing buildings or issuing construction standards according to flood risk.

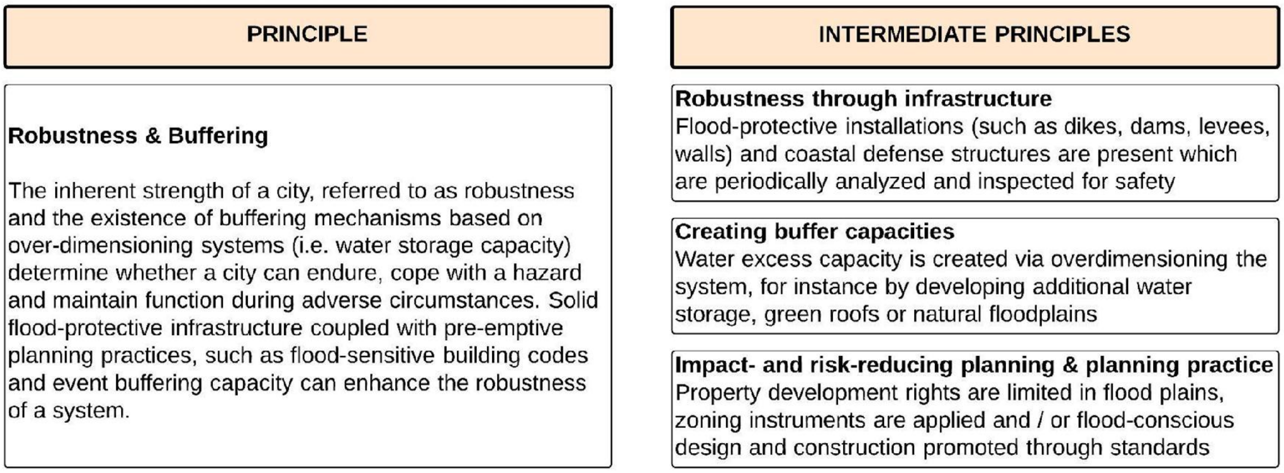

Fig. 3.8: Overview principle Robustness & Buffering and intermediate principles

3.4.1.1 Robustness through infrastructure

One way to make a system robust against a disturbance is preventing the disturbance entirely by implementing structural measures that can resist its impacts and thereby limit exposure (de Bruijn 2004; Godschalk 2003; van den Brink et al. 2013). Therefore, the focus here is on the inherent physical strength of (critical) infrastructure to withstand the impacts of a disturbance without suffering a loss of function (Davoudi et al. 2013; Liao 2012; Kernaghan & da Silva 2014; Tasan-Kok et al. 2013).

Such pre-event protective structural measures involve storm surge barriers, flood walls, levees, dams, dikes, embankments, locks or coastal defense structures (Raadgever et al. 2015; Godschalk 2003). As a short-term option they are suited for containing both, sudden stresses such as storm surges or high river levels following precipitation, and slow-onset changes like sea level rise though dike systems along the coast.
To keep this infrastructure robust, sophisticated construction based on (formalized or legally enshrined) water safety standards and dike norms is required in order to make failure predictable and safe (da Silva & Morera 2014). This requires specialized knowledge on engineering, hydraulic conditions and geotechnical features (Raadgever et al. 2015). In addition, flood protective infrastructure requires continuous maintenance and management to maintain its function. Thus, periodic assessments and improvements of barriers, dikes, locks and dams are crucial (Cutter et al. 2013).

3.4.1.2 Creating buffer capacities

Another way of strengthening a system's robustness towards adverse events going beyond structural interventions is creating buffer capacities. The term buffering originates from system dynamics and accommodates a wide range of potential policy options for moderating impacts of disturbances or disasters. These touch on construction design, urban development, spatial measures and environmental management (Wardekker et al. 2010).
Buffering is defined as the ability of a system to absorb disturbances to a certain extent, which is administered by over-dimensioning essential capacities so that critical thresholds are less likely to be crossed (Wardekker et al. 2010). Such a system is considered resilient since existing capacities exceed needs and can be relied on in times of need (Barnett 2001). The notion of buffering is also found in ecological resilience where it is associated with robustness and community resilience, namely the ability of a society to absorb disturbance (Gunderson 2009; Tompkins & Adger 2004; Folke 2006).
Concerning flood risk management, three different dimensions of buffering can be established based on the scanned literature. For sea level rise, coastal flooding (for instance by a storm surge) and river flooding creating buffer capacity consists of the implementation of levees, canals and (additional) water arms (Gunderson 2009). For flooding from rainwater following extreme precipitation (also termed cloudbursts in the remainder of this paper) buffering measures involve creating more space for rainwater to be attenuated, by increasing (rain)water storage and capture (Wardekker et al. 2010; McBain et al. 2010). Examples are the implementation of rainwater harvesting installations, water retention ponds or the use of low-lying areas as water retention space (which also applies to flooding from the river) (Wardekker et al. 2010; McBain et al. 2010). A natural way of increasing rainwater attenuation, previously assigned to Homeostasis, is the restoration of urban floodplain wetlands and the (re-)creation of urban green space (Godschalk 2003; da Silva & Morera 2014; van den Brink et al. 2013; Biggs et al. 2012; Biggs et al. 2014).
Limited water drainage capacity due to combined sewer systems is a paramount issue for many (old) cities. Therefore, another way of improving the buffer capacity of the urban water system is by designing drainage networks for exceedance, for instance by installing oversized pipes or attenuation tanks in the drainage network (McBain et al. 2010).

3.4.1.3 Impact- and risk-reducing planning & planning practice

Reducing a system's vulnerability by diminishing the magnitude of hazard-related consequences inside the vulnerable area constitutes a third pathway for making a system more robust (Godschalk 2003; Raadgever et al. 2015). This can be administered by employing impacts- and risk-reducing planning and planning practice. Conceptually, this falls within the notion of mitigation promoted across disaster resilience, urban planning and

economic resilience (Cutter et al. 2008; Tasan-Kok et al. 2013; Rose 2004). Also intersections with previously mentioned flood risk prevention and mitigation approaches can be noticed (Raadgever et al. 2015; Zevenbergen et al. 2008).
Practical measures in this category refer mostly to impact-reducing spatial planning, strategic land-use planning where flood risk is used as a design parameter for spatial planning and building codes for private and public property development (Sheltair Group 2003; Zevenbergen et al. 2008; Tasan-Kok et al. 2013).
In regards of the former, options include limiting development rights or entirely prohibiting development in flood-risk areas, for instance by employing flood zoning tools. Also relocating property from flood-prone areas and inhibiting new developments are mentioned in the literature (Tyler & Moench 2012; Raadgever et al. 2015; Zevenbergen et al. 2008; van den Brink et al. 2013; Godschalk 2003). In addition, the ground level of flood-prone areas could be elevated (Wardekker et al. 2010).
Concerning building codes, proposed measures involve flood-proofing of existing and new structures and public facilities based on construction or design codes (Godschalk 2003; Zevenbergen et al. 2008; van den Brink et al. 2013). Furthermore, water-proofing functions can be implemented within buildings, for instance by locating non-essential functions at the ground-level of buildings (Wardekker et al. 2010; Zevenbergen et al. 2008).

3.4.2 Diversity

Notions of diversity, variety and flexibility are closely intertwined, and mentioned in the literature as mechanisms to enhance resilience (see Biggs et al. 2012, 2014, Adger et al. 2005, Godschalk 2003, Tyler & Moench 2012, Carpenter et al. 20012, Folke et al. 2005, Walker et al. 2004; Barnett 2001; Wardekker et al. 2010). In the transdisciplinary literature diversity is stated to support both, the absorption of impacts (phase 2) and recovery from disturbances (phase 3). Since no clear-cut distinction can be made it will be integrated in both phases.

Diversity in the sense of absorptive capacity is taken up by system dynamics, disaster resilience, ecological resilience / ecosystem management and governance. Here, diversity focuses on the response capacity and functional diversity created by different system components and the ways in which disturbance effects are absorbed and modified by them (Biggs et al. 2012; Biggs et al. 2014).
According to scholars, the diversification of resources and means by which those resources are delivered can reduce a system's vulnerability. Due to its heterogeneous components performing different functions, the system is not equally vulnerable in all parts and some of them will still be operational during disturbance. Consequently, such a system can better accommodate external shocks (Wardekker et al. 2010; Barnett 2001). This aspect termed **functional and response diversity** is represented in the first intermediate principle (see Fig. 3.9).

More general, case studies suggest that systems with many different components are more resilient than their counterparts with only a few (Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2016). In SES, diversity can be exhibited by species, habitats, communities, livelihood strategies or governing authorities (Biggs et al. 2012).
This notion of diversity is taken up by the intermediate principles: **actor & stakeholder diversity** and **institutional diversity**.

Finally, **spatial diversity of critical functions** is adopted as an intermediate principle due to its mentioning by several experts (Pahl-Wostl 2007; Tyler & Moench 2012; SheltAir Group 2003). The underlying concept is the same as for functional diversity. Due to their spatial distribution across the city, critical infrastructure and assets differ in exposure and therefore vulnerability to disturbances. As a result, vital functions will be able to be maintained.

Different functions can also be interpreted in terms of multiple ways to fulfill existing or emerging needs. They create the benefit that essential tasks can still be performed under a wide range of (climate) conditions and that important functions are maintained under adverse circumstances. This is argued to enhance a system's flexibility, but mainly comes into play for recovery (and will therefore be dealt with in chapter 3.5.2.3) (Biggs et al. 2012; Biggs et al. 2014; Carpenter et al. 2001; Tyler & Moench 2012; Godschalk 2003). The view of diversity to enhance the recovery capacity of a system is represented in the governance, economic resilience and ecosystem management literature.

PRINCIPLE	INTERMEDIATE PRINCIPLES
Diversity Systems with many different components are more resilient than their counterparts with only a few. Diversification of resources and means can reduce a system's vulnerability by generating heterogeneous components performing <u>different functions</u> and thus facilitating a diversity of responses to threats. Furthermore, the prevalence of multiple ways of needs fulfillment (also called functional diversity) facilitates performing essential tasks and maintaining functions under a wider range of climate conditions and thus, enhances a system's flexibility.	**Functional & response diversity** Energy, food supply, transport options (multiple modes for transporting goods and people), land-use types and the economic landscape are diversified; in addition different flood management approaches are employed cutting across preparation, prevention, adaptation, response
	Spatial diversity of critical functions Vital functions and services (financial institutions, hospitals, crisis centres, refugee centres, water pumping facilities, flood protective infrastructure) are physically distributed across the city to balance risk
	Actor & stakeholder diversity Involvement of diverse administrative levels, actors and stakeholders with different backgrounds and knowledge in decision-making, planning and implementation processes which allows for different problem frames and solutions for flooding events
	Institutional diversity, multi-level governance systems and linkages Governing authorities differ in size, structure and culture, there are various water governing authorities at different scales (national, regional, local) with overlapping roles so that they can take over in the case of one's failure

Fig. 3.9: Overview principle Diversity and intermediate principles

3.4.2.1 Functional & response diversity

Functional diversity is understood as engineering systems towards having many functionally different components that serve as a protection against threats (Godschalk 2003).
There are two underlying assumptions for functional diversity. First, the components' differences in size, scale, and reaction to disturbances make up their particular strengths (and weaknesses) in case of disruption and distribute risk (Biggs et al. 2014). Second, through the different system elements and the means they provide there is a variety of options for achieving a service provision or performance of a particular function which supports maintaining functions when facing disturbances.
According to the scientific resilience literature, this criterion applies to a variety of urban sub-systems, spanning from the societal, ecological, technological sphere to the provision of services and goods.

In the societal realm it implies a heterogeneous population exhibition a wide range of expertise, occupations and education (Walker et al. 2004; Martin & Sunley 2014). In the natural realm, the emphasis is on multiple species that according to different physical traits or timing of contribution to ecosystem services respond differently to disturbances. As a result, some of the elements will withstand it and keep on delivering their functions (Biggs et al. 2012; Biggs et al. 2014; Folke 2006; Carpenter et al. 2001; SheltAir Group 2003).
From an ecological perspective, spatial heterogeneity of landscape patches leaves certain areas unaffected and thereby maintains their capacity to produce crucial ecosystem services (Biggs et al. 2012; Biggs et al. 2014; Adger et al. 2005). Thus, one of the indicators is the parallel existence of different land-use types in cities (Gunderson 2009).
In regards of services and resources, attention is specifically directed to critical functions and resources, such as energy, water, food and transport where dependence on a singular supply source should be prevented (Wardekker et al. 2010; Resilience Alliance 2010; SheltAir Group 2003; Liao 2012). Thus, the following indicator is created: Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people) (Liao 2012; Wardekker et al. 2010; Resilience Alliance 2010).
Economic resilience contributions stress economic variety as a key for absorbing disturbances via a diversified business landscape accommodating different industries and sectors (Martin & Sunley 2014). From this perspective, another indicator results: The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated (Martin & Sunley 2014).

3.4.2.2 Spatial diversity of critical functions

Another dimension of diversity relates to spatial diversity of critical functions. It involves the geographical and physical distribution of a system's key aspects and functions so that not all of them are simultaneously affected in the case of disturbance (Tyler & Moench 2012). A strategic geographic and spatial distribution of the latter safeguards their functioning even when system connections are lost or limited in the face of disturbance (Tyler & Moench 2012; SheltAir Group 2003).
From a disaster resilience and spatial planning perspective, spatial diversity is mostly applied to critical functions and services, such as distributed infrastructure networks and resource reserves (da Silva & Morera 2014). As such it entails hospitals, financial institutions, crisis centers, shelters, food and drinking water sources. From an IAWM perspective, a decentralized flood-protective infrastructure gains salience (Pahl-Wostl 2007).

3.4.2.3 Actor & stakeholder diversity

From a social perspective, the principle of Diversity can apply to actors, management approaches and problem solutions (Biggs et al. 2012). Actor and stakeholder diversity contributes to the diversification of resources and means and reduces a system's vulnerability. Notably the notion of actor and stakeholder diversity has overlaps with "Broad stakeholder participation and engagement", a sub-component of Flatness (see chapter 3.5.1.2).

The benefits of actor and stakeholder diversity in policy realms are two-fold.
First, especially in regards of ecosystem management, broad stakeholder participation and collaborative processes are maintained to promote the understanding of SES, their underlying system dynamics and behavior based on the available transdisciplinary knowledge. This serves as the base for developing respective models, an in-depth analysis of disturbances and a system's capacity to identify critical thresholds (Biggs et al. 2012; Biggs et al. 2014; Resilience Alliance 2010). Therefore, foresight and anticipation of disturbances and slow trends can be improved (Biggs et al. 2012; Folke et al. 2005). Thanks to differing disciplinary or professional backgrounds of the stakeholders, exchange among them might help to fill knowledge gaps, spot challenges, find links or develop novel approaches to known problems (Biggs et al. 2012; Folke et al. 2005; Berkes & Ross 2013). In a

policy setting, such a constellation can best be captured by: a variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process (Gupta et al. 2010; van den Brink et al. 2013; Biggs et al. 2012; da Silva & Morera 2014) (Biggs et al. 2012; Da Silva & Morera 2014).

Second, scholars of ecosystem management and adaptive governance point out the value of actor diversity in the variety of perspectives brought to the table. The admission of different problem frames and perspectives engenders different approaches, strategies, solutions and ultimately, responses to threats (Biggs et al. 2012; Biggs et al. 2014; van den Brink et al. 2013; Gupta et al. 2010; Leichenko 2011). Such a constellation not only enriches problem-solving but also the exchange of different management approaches, triggers learning processes and creates understanding for best practice (Biggs et al. 2012; Folke et al. 2005).

3.4.2.4 Institutional diversity, multi-level governance systems & linkages

With regards to governance, diverse institutional and organizational forms (e.g. NGOs, community initiatives, governmental departments) with overlapping domains of authority and roles (also see chapter 3.4.2.1) facilitate response and functional diversity and thereby safeguard that functions are maintained in the face of disturbance (Biggs et al. 2012).
The idea of diversity in governance systems is related to three key components:
First, institutional diversity which refers to the prevalence of diverse institutional and organizational forms and arrangements that respond differently to changes. Variety in institutions and organizations entails different actor groups such as governmental and non-governmental, but also varying cultures, internal structure or size of governing authorities (Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Tyler & Moench 2012; Kernaghan & da Silva 2014; van den Brink et al. 2013; Resilience Alliance 2010; Walker et al. 2004).

Second, multi-level and multi-layered governance systems , also termed polycentric governing systems (Biggs et al. 2012) or polycentric, multilayered institutions (Lebel et al. 2006). They exhibit various governing authorities at different scales made up by a diverse group of actors with different roles and overlapping functions (Biggs et al. 2012; Biggs et al. 2014; Gupta et al. 2010; Folke et al. 2005). This notion goes hand in hand with the previously mentioned actor and stakeholder diversity (see chapter 3.4.2.3) and therefore generates the same benefits of admitting a variety of perspectives, opinions and problem definitions which translates into enhanced problem-solving strategies, learning and the development of multiple policy options as solutions (Biggs et al. 2012; van den Brink et al. 2013; Leichenko 2011; Gupta et al. 2010). Notably there are intersections of indicators occurring in Flatness (Institutional decentralization & autonomy), when it comes to shared responsibilities and management authorities among responsible institutions across scales and the distribution of governing authorities across scales (see chapter 3.5.1.1).
Specifically with regards to flood risk management, building distributed flood response capacity on a household, community and municipal level to create a diversity in sources and failure compensation would also fall into the category of multi-layered governance (Liao 2012).
The third key component are institutional linkages between the different governing authorities which are best represented by the level of interaction, exchange and collaboration among the diverse stakeholders operating at different levels (Folke et al. 2005). This can best be operationalized with formal and informal partnerships among governing authorities, academia, firms and NGOs (da Silva & Morera 2014) or the participation in meetings or other platforms of exchange, such as workshops, brainstorming sessions (van den Brink et al. 2013). Noteworthy, linkages between actors are equally relevant for other principles, such as Homeostasis (Integrated planning, coordination and collaboration) or High Flux (Collaboration, Social & Institutional Networks).

According to Biggs et al. (2012) there is a caveat with institutional and actor diversity. Too little of it might give rise to brittleness, whereas too many actors and institutions involved might slow down processes, when based on joint consideration, and cause unintegrated and poorly streamlined approaches. Since this could have unintended side effects on the principle “Integrated Planning, coordination & collaboration”, a balance needs to be found.

3.4.3 Redundancy

Due to their conceptual similarity, omnivory is frequently mentioned with redundancy since their combination is expected to enhance system resilience. Noteworthy, there is a thin line especially between functional redundancy and diversity, a clear allocating to one or the other is not always possible due to their similarity in effect.

In contrast to omnivory which implies creating multiple different functions, redundancy describes the presence of multiple SES elements or replication of components or pathways in order to have multiple instances available that perform the same function which can fully substitute each other and therefore prevent system failure in case one component fails. This is usually referred to as functional redundancy (Wardekker et al. 2010; Biggs et al. 2012; Tyler & Moench 2012; Godschalk 2003).

Redundancy is an acknowledged resilience mechanism across diverse fields such as engineering, disaster risk management, system dynamics, ecosystems management and governance. As such it offers a wide range of applicability to different system components.

From a resilience-building perspective it implies the strategic creation of systems that have multiple nodes, connected components or back-up systems that prevent failure in the face of extreme pressures or disruption (Eraydin & Taşan-Kok 2013a; Tyler & Moench 2012; van den Brink et al. 2013; Gupta et al. 2010). Applying an ecological perspective, functional redundancy implies biodiversity (Gunderson 2009).

Four major dimensions of redundancy are identified which give rise to the following four intermediate principles:

(1) Overlapping functions and roles in social, organizational or governance contexts, such as those represented by multi-level governance systems with several distributed layers of authority, can help better absorb disturbance and spread risk since higher levels of governance can compensate for failure of lower levels.

(2) Functional redundancy in important functions and services based on a replication of functionally similar components, subsystems or SES elements which can fully substitute each other and thereby prevent system failure.

(3) Spare capacities and back-up resources for contingency situations when demand rises and resource flows are disrupted, which can consist of vital resources (such as water, medicine and food) or energy and electricity back-ups.

(4) Compartmentalization & modularity are mechanisms employed in flood risk management and networks design to locally contain flood impacts and/or prevent cascading effects to other parts of the system.

PRINCIPLE	INTERMEDIATE PRINCIPLES
Redundancy Describes the presence of multiple elements or replication of components or pathways in order to have multiple instances available that perform the same function. These can fully substitute each other and therefore prevent system failure in case one component fails. From a resilience-building perspective it implies the strategic creation of systems that have multiple nodes, connected components and spare capacities that prevent failure in the face of extreme pressures or disruption, and maintain service delivery. It applies both to technological (power grid, infrastructure) as well as to social systems (large social networks that offer different problem-solving options).	**Overlapping functions and roles** Redundancy of actors, actor groups, overlapping roles and multiple alternative connections at local to global scale through multi-level governance systems help maintain functions under adverse circumstances **Functional redundancy in important functions and services** Components of the urban system are duplicated to provide substitute services when another component is disrupted (flood protective infrastructure, electricity networks, water systems, multiple routes of supply, energy, transport) **Spare capacities & back-up resources** Purposely created spare capacity and back-ups for contingency situations with rising demand, such as alternative power, water and energy supplies for critical infrastructure and businesses or stocks of food, medicine, drinking water **Compartmentalization & Modularity** Mechanisms to locally contain flood impacts and prevent cascading effects are compartmentalization dikes or basing communication, transport networks, infrastructure grids and other vital functions in cities on a modular network structure

Fig. 3.10: Overview principle Redundancy and intermediate principles

3.4.3.1 Overlapping functions and roles

Overlapping functions, roles and responsibilities among institutions, actors and actor groups provide one way of generating redundancy in social, organizational and governance contexts. With regards to their function to absorb disturbance and spread risks, they have been pointed out to act as important safety mechanisms when parts of the system fail by maintaining the provision of services and tasks (Norris et al. 2008; Buuren et al. 2015; Low et al. 2003).

From a governance perspective, the redundancy of actors, actor groups and their overlapping roles are hypothesized to enhance adaptive capacity since they positively contribute to the stock of institutional memory (Folke et al. 2005). Different organizational forms prevalent in a governance system (i.e. NGOs, community groups, government departments) can overlap in function and provide a diversity of responses. This notion also extends to communities that are well-linked and exhibit overlapping functions which engender creative solutions and adaptability (Biggs et al. 2014).

Overlapping measures and the possibility for higher levels of governance to compensate for failure of lower levels are additional benefits mentioned in regards of this type of redundancy (Gupta et al. 2010; Biggs et al. 2012). Polycentric, multi-level governance systems along with decentralized decision-making structures are recognized as a manifestation of overlapping roles and functions (Biggs et al. 2012; Norris et al. 2008). On a practical level, this includes shared responsibilities, rights and management authorities among actors and responsible institutions across scales (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005).

Another form of redundancy are different organizational forms sharing the same or similar issue areas. Examples are civic organizations or NGOs with focus and issue areas overlapping with those dealt with at a more official level or local level conservation actions that step in when respective institutions at national or international level fail (Biggs et al. 2012).

Yet, the practical application of this mechanisms is limited which also explains its scarce coverage in the scientific literature that lacks an indication of specific indicators. The reason for that is that this type of redundancy is associated with perceptions of unnecessary administrative costs, inefficiencies, fragmentation in political realms or duplicating authorities (Biggs et al. 2012; Folke et al. 2005).

3.4.3.2 Functional redundancy in important functions and services

Functional redundancy is represented across ecosystem management, ecological, economic, disaster and community resilience (see Biggs et al. 2012; Biggs et al. 2014; Adger et al. 2005; Gunderson 2009; Godschalk 2003; Martin & Sunley 2014). Despite slight variations in interpretation, there is broad consensus in describing it as the replication of functionally similar components, subsystems or SES elements which can fully substitute each other. By doing so, they prevent system failure and sustain system functioning even when single elements fail (Wardekker et al. 2010; Biggs et al. 2012; Godschalk 2003; Martin & Sunley 2014; Barnett 2001).

The difference in ways the resilience literature refers to functional redundancy is its application to different system scales. On a micro-scale it entails the <u>duplication of the same or similar elements to provide safety mechanism for system failure</u>, often termed safe failure mechanisms (Tyler & Moench 2012; Godschalk 2003). These can for instance be found in production systems, water systems, or infrastructure systems. In the context of disaster risk management special emphasis is put on maintaining vital function, such as transport, communication networks, food and drinking supplies (Cutter et al. 2008; Cutter et al. 2010; Wardekker et al. 2010; Tyler & Moench 2012). For flood risk management and defense, redundancy could come down to a variety in (flood protective) infrastructure, such as several dikes, storm surge barriers that reduce failure probability (Cutter et al. 2008; Cutter et al. 2010).
From an economic resilience perspective, redundancy mechanisms in the production system and supply chains of businesses gain importance (Martin & Sunley 2014).

Based on that, the two following three indicators are established:
<u>Multiple access / evacuation routes, multiple routes of supply, electricity, sewage removal</u> (Cutter et al. 2010; Cutter et al. 2008; Wardekker et al. 2010)
<u>Several transmission towers to sustain communication</u> (Tyler & Moench 2012)
<u>Multiple counterparts for vital functions</u> (Wardekker et al. 2010)

3.4.3.3 Spare capacities & back-up resources

Another dimension of redundancy is the store-up of buffer stocks and the presence of back-up resources.
Buffer stocks serve as a spare capacity for contingency situations when demand rises and resource flows are disrupted. They involve <u>medicine, drinking water, food supplies, water pumps from household, company to city-wide level</u> related to emergency preparation (da Silva & Morera 2014; da Silva et al. 2012; Tyler & Moench 2012; Wardekker et al. 2010).
Equally important is the implementation of back-up systems that allow operations to be switched to other network parts during an event and thereby ensure continuity (Biggs et al. 2012; Biggs et al. 2014; Godschalk 2003; Tyler & Moench 2012; Wardekker et al. 2010; da Silva et al. 2012). These could consist of <u>alternative power</u>

or water supplies for key businesses and critical infrastructure, but also energy back-up generators to keep crucial services running (Bruneau et al. 2003; Tyler & Moench 2012).

3.4.3.4 Compartmentalization & modularity

A fourth way of adding redundancy to a system and its sub-components is via compartmentalization or modularity. Both are able to prevent cascading effects into other parts of the system and thereby prevent complete system collapse by containing disturbances.
It is frequently mentioned that a fully connected system with tightly interacting subcomponents that are loosely connected equips part of the system with the capacity to reorganize and resume function while being affected by a disturbance to a limited extent (Resilience Alliance 2010; Biggs et al. 2014; Janssen et al. 2006; Sheltair Group 2003). Such a constellation is captured by modularity, a term that is frequently described in connection with redundancy and outlined by scholars from ecosystem management, system dynamics, governance and disaster risk management.
A modular system structure implies a network with "*subsets of densely connected nodes that are loosely connected to other sub-sets of nodes*" (Biggs et al. 2012, p.428) which can be visualized with a tree structure. In such a structure, subsystems are functionally autonomous while closely integrated into the city fabric. Consequently, effects of a disruption remain contained locally while cascading of wider impacts on the whole system is prevented which reduces the system's vulnerability (Martin & Sunley 2014; Biggs et al. 2012; Resilience Alliance 2010; SheltAir Group 2003). This gives a worthwhile indication for a potential resilient set-up and how to organize communication networks, transport networks, (critical) infrastructure grids, land use arrangements, ecosystems or sectorial and organizational components of the economy (SheltAir Group 2003; Martin & Sunley 2014; Resilience Alliance 2010; Biggs et al. 2012; Gunderson 2009).
Another term frequently used in water management and systems that builds on a similar mechanism as modularity is compartmentalization. By dividing a system up into compartments and creating boundaries, it contains disturbances within certain confines and stops them from spreading to other parts of the system. Examples from flood risk management are dike rings, compartmentalization dikes, temporary dams or flood defenses that prevent flooding from spreading to other regions or to locally contain them (Gersonius et al. 2011; Wardekker et al. 2010).

3.5 Phase 3: Recover (Reorganize / Renew)

RECOVER

The ability to rapidly recover from an experienced disturbance, timely reorganize within desired boundaries and resume function by fostering fast response mechanisms and autonomous, self-directed (public) action.

Fig. 3.11: Description Recover

Based on the adaptive cycle, recovery and renewal[4] is the alpha phase immediately following a creative destruction, or disturbance (omega phase) in which a new system emerges. Recovery involves immediate,

[4] The acknowledgement that the process of recovery is always unique and the resulting state never exactly the same, has led scientists to use the terms of renewal or re-organization as an equivalent to recovery (Folke 2006).

reactive responses to and coping mechanisms with disturbances with a short-term horizon (Zevenbergen et al. 2008; Lu & Stead 2013). For flooding events these could entail emergency response and rescue services, pumping away water, damage repairs of property, assets and critical infrastructure and the provision of financial support for recovery (Raadgever et al. 2015; Lu & Stead 2013).
According to engineering and ecological resilience there are two possible pathways in this phase: the system can either recover or renew, and thus, either return to a similar state to pre-disturbance, or into something quite novel and different. From a social-ecological perspective this phase is referred to as "window of opportunity" for a pathway change and new configurations since social systems in contrast to ecological ones have the ability of anticipation and can therefore predevelop recovery plans (Gunderson 2009; Nelson et al. 2007).

However, a system's success in making use of this opportunity depends on the degree to which a system is able to self-(re)organize (without being mere subject to outside forces) (Folke 2006). The latter has been previously outlined as a major resilience characteristic and is widely acknowledged as an emergent property of complex adaptive systems (Carpenter et al. 2001; Tyler & Moench 2012). A system capable of self-organization manages to maintain and re-define its identity, buffer impacts from other systems and persist without aid (Carpenter et al. 2001; Lebel et al. 2006). In the following chapters, the self-organizing capacity of a system is shown to be associated with decentralized, supportive institutions that employ participatory decision-making structures and are able to provide the room for autonomous change required for the public to act and react appropriately.

A second criterion for recovery frequently mentioned in the resilience literature is the speed of recovery, termed rapidity (Tasan-Kok et al. 2013; Kernaghan & da Silva 2014; Norris et al. 2008; Godschalk 2003). From an ecological resilience perspective this implies "*flexibility* [of a system] *to rearrange itself into a stable state"* after a disturbance (Lu & Stead 2013, p.201). For flooding events it is associated with the speed of return from when flood impacts are noticed to a state of normal or improved livelihoods compared to a situation without a flood (de Bruijn 2004).
In the scientific literature several mechanisms are stated to improve the speed of recovery.
For instance flexibility which is understood as the capacity to quickly respond to disturbances by initiating reactive, immediate and temporary changes at localized, small scales in a city's subsystems (Liao 2012). This involves the ability to produce alternative responses beyond standard such as the temporary repurposing of available resources (Rockefeller Foundation 2015). Specifically for flooding events, such responses could involve the set-up of demountable defenses, the use of sand bags, turning schools or gym facilities into temporary shelters, or a quick switch from land-based to water-based public transport (Raadgever et al. 2015; Liao 2012).
The rapidity of recovery further depends to a great extent on the availability of and access to resources on behalf of governing authorities and the wider population. The more options they have, the quicker they can access and mobilize resources (such as financial recovery services), the sooner they can resume normal livelihoods (Schipper & Langston 2015; Tyler & Moench 2012). These two mechanisms will be looked at in more detail in the following chapters.

3.5.1 Flatness (recover)

The capacity to self- and reorganize has been previously established as a major driving force in the recovery process by determining whether a system can maintain and re-define its identity.
Flatness is a means of enhancing the frequently mentioned resilience criterion of self-organization. It refers to the way a system is or should be governed. The whole system should not be organized in a hierarchical, top-down mode. The absence of a local formal competence to act on behalf of the population, as well as on lower policy levels along with lengthy decision-making and bureaucracy processes makes the system too inflexible and

too slow to cope with changes and thus, ineffective in response (Wardekker et al. 2010; Wardekker et al. 2016). Consequently, the ability to self-organize depends to a great extent on governing institutions and their ways of developing and sustaining the capacity of people to deal with change (Holling 2001).

In the course of the literature review, three major aspects of flatness (intermediate principles) were identified which are outlined in the following chapters.
First, a system's capacity to self-organize is associated with a **decentralized governance structure** that allows for autonomous, locally-informed policy-making at lower levels of governance.
Second, **participatory decision-making structures**, along with active and **early engagement of a variety of stakeholders** in the management and governance process are crucial for creating an atmosphere of proactive public behavior (Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2010).
Third, the **room for autonomous change** provided by institutions plays a decisive role in shaping the capability of actors to self-organize measures and seize opportunities when they arise. By incentivizing social actors to improvise and offering them the chance to experiment during crises, quicker recovery is likely (van den Brink et al. 2013; Gupta et al. 2010).

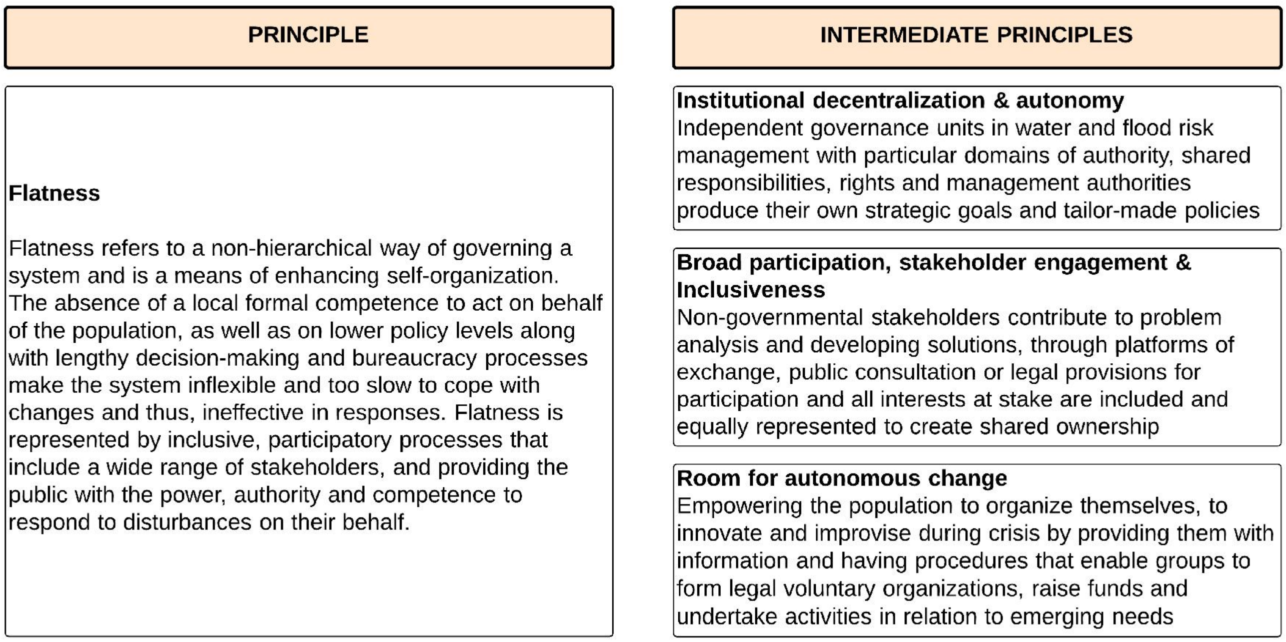

Fig. 3.12: Overview principle Flatness and intermediate principles

3.5.1.1 Institutional decentralization & autonomy

The decentralization of a governance system works against inefficient, lengthy and inflexible system structures and service provision. Several scholars establish that shared responsibilities, rights and management authorities, such as those prevalent in a decentralized system are one of the major ingredients of resilience-building (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005).
The level of (de)centralization of a governance system sheds light on the autonomy and capacities of lower governance levels (e.g. municipal level) to make autonomous decisions, authorize plans and legislate policy. Thus, it affects the level of control governing authorities possess to integrate new factors and approaches (Tanner et al. 2009). Autonomy in this sense refers to the relationship with other levels of governance and government, financial independence and the ability to autonomously develop own strategic goals, tailor-made policies and measures (Lebel et al. 2006; Pahl-Wostl & Knüppe 2013).

The notion of decentralization and autonomy of independent governance units is closely interrelated with the presence of multi-level governance arrangements. They are best described as "*nested, quasi-autonomous decision-making units operating at multiple scales*" with a particular domain of authority within a designated geographic area (Folke et al. 2005, p.449). Multiple governance levels imply a certain degree of autonomy, shared responsibility and power and thereby contribute to Flatness (Folke et al. 2005; Biggs et al. 2012).
Whereas centralized systems benefit from legislative power and resources, the adaptive capacity is argued to be higher in decentralized governance systems and they are more prone to develop tailor-made solutions (Raadgever et al. 2015; Lebel et al. 2006). Polycentric arrangements allow for policy-making tailored to the local situation. With their decentralized structure they are better able to appropriately respond to the scale of the problem by applying knowledge suitable for particular social-ecological, geographical and environmental contexts. In that way, they can develop locally-informed, level-specific action and management interventions (Biggs et al. 2012; Lebel et al. 2006; Tanner et al. 2009; Folke et al. 2005).

3.5.1.2 Broad participation, stakeholder engagement & inclusiveness

An important supportive element of Flatness is the active engagement of a variety of stakeholders in the management and governance process, or in other words participatory policy-making (Biggs et al. 2012; Biggs et al. 2014; Wardekker et al. 2010).
Participation can range from merely providing information to stakeholders, to the joint identification of problems, and policy implementation (Biggs et al. 2012). Frequently it is measured according to the access to and influence on the policy process of relevant stakeholders (Mees et al. 2014). In this paper it is operationalized as the active involvement of a variety of stakeholders, actors and administrative levels in all the phases of a project or program, namely design, planning-, governance- and implementation processes (da Silva & Morera 2014; Biggs et al. 2012; Biggs et al. 2014; van den Brink et al. 2013).
Active co-production of (non-governmental) stakeholders in agenda setting, analyzing problems and the development of solutions has proven most successful when it comes to the creation of a shared understanding of issues (Biggs et al. 2012; Biggs et al. 2014; Huntjens et al. 2010). Such a shared understanding is the result of constant joint deliberation of issues and the frequent exchange among stakeholders and lies at the heart of any coordinated action, mobilization of resources and self-organization in general (Lebel et al. 2006).
Moreover, joint understanding of issues can translate into the feeling of shared ownership which safeguards ongoing sustained action and the maintenance of projects by communities after their implementation. Arguably, this requires a strategic actor involvement right from the start. Feasible tools are early public consultations and information evenings in which problem perceptions of and alternative solutions by the local communities are actively sought. Also, deliberative forums or platforms of exchange between actors such as policy officials, municipality representative, project coordinators and the local population before and during the implementation of projects account for that (van den Brink et al. 2013; Mees et al. 2014). When it comes to the implementation of projects, Godschalk (2003) and Norris et al. (2008) among others recommend for city staff to work together with each neighborhood to design appropriate mitigation approaches in accordance with local needs that mitigate vulnerability to disturbances.

In the context of broad stakeholder participation several scholars plead for "inclusiveness" or "inclusion" which they refer to governance arrangements that seek active inclusion, empowerment and mobilization of marginalized groups of citizens most vulnerable to climate disturbances. (da Silva & Morera 2014; Tompkins & Adger 2004; Elmqvist 2014; Elmqvist et al. 2013; Resilience Alliance 2010). Apart from equity criteria that have been previously mentioned (see chapter 3.3.3.3) such inclusive governance systems are argued to aim at open, transparent decision-making processes that include and equally represent all interests at stake (Mees et al. 2014; Tyler & Moench 2012).

3.5.1.3 Room for autonomous change

According to Wardekker et al. (2010) one of the two major components of Flatness is strengthening the capacity of the population to self-organize and self-regulate by equipping them with the competence, authority and power to respond to disturbances on their behalf. This requires institutions to "*permit social actors to autonomously adjust their behavior in response to environmental change*", referred to as "*room for autonomous change*" (Gupta et al. 2010, p.463). The ability to self-organize autonomous, preventive measures is argued to enhance adaptive capacities of actors. In addition, such conditions facilitate quicker response to changing conditions, seizing opportunities when they arise and heighten the chance of reorganization within desired boundaries (van den Brink et al. 2013; Gupta et al. 2010; Folke et al. 2005). Such a scenario can be described as follows: citizens immediately react to moderate damage, and quickly reorganize due to their capability to autonomously fix damage and clean-up after the event without requiring external assistance (Liao 2012).

A valuable operationalization of room for autonomous change was made by Gupta et al. (2010) which will be adopted by this paper. Focusing on supportive governance conditions, they propose for institutions to fulfill the following three conditions in order to establish room for autonomous change:
(1) Continuous access to information both within the institutional and public realm
(2) Enhance the capacity of actors to act according to plan, by providing scripts for action and plans in the face of disasters
(3) Promote the capability of the public to improvise (during crisis) by fostering innovation and social capital

Some of these indicators have already been taken up in previous chapters and will therefore not be further elaborated at this point. Access to information was looked at with respect to planning and preparedness, both in the institutional and societal realm. For the former with regards to information management, storage and sharing in organizations (see chapter 3.3.1.3), for the latter in terms of ways to enhance public (flood) risk awareness (see chapter 3.3.2.1). Providing the public with plans and scripts for action and train them in appropriate disaster response has also been previously indicated (see chapter 3.3.2.1). An additional indicator is added: the affected population is provided guidance on flood-resilient construction and how to prepare their homes for flooding (Schelfaut et al. 2011)

Procedures that enable groups to form legal voluntary organizations, raise funds and undertake activities in relation to emerging needs (Tyler & Moench 2012) are mentioned as a driver for the capability of the public to improvise. Not being directly related to Flatness but also contributing to flexibility in response, others will be added in High Flux (chapter 3.5.2.3).

3.5.2 High flux (recover)

The principle of High Flux is rooted in the concept of perceiving urban processes to happen in "systems of cities", consisting of social and ecological networks with dynamic interlinkages (panarchies) (Ernstson et al. 2010). High Flux represents a fast rate of movement of resources through the system that ensures a fast mobilization of these resources to quickly respond to threats and changes (Wardekker et al. 2010). The underlying idea is that the faster the rate of movement of resources, the more resources are available at a given point in time to deal with disturbance (Barnett 2001). Clearly this mechanism addresses the aspect of rapidity by seeking ways and implementing conditions to maximize promptness in response. In the literature review, four sub-dimensions of High Flux are identified which will be described in the following chapters:

(1) Availability of and access to basic financial and human resources are deemed crucial in determining the capacity of individuals and organizations to respond to events and make provisions for resuming normal life (Gupta et al. 2010; van den Brink et al. 2013).

(2) During post-disaster recovery, **networks** are recognized to confer resilience to ecological and social systems by creating bridges between system components (Folke et al. 2005; Gunderson 2009; Janssen et al. 2006; Tasan-Kok et al. 2013; Biggs et al. 2012; Godschalk 2003). In the societal and institutional realm, they generate a flow of resources, ideas and materials which contributes to response and resource diversity and thereby shortens recovery time (Janssen et al. 2006; Folke 2006; Gunderson 2009; Carpenter et al. 2001).

(3) Flexibility in response is also identified as a driving force for recovery. It is associated with a variety of options available to citizens to adapt to change. The notion of options is closely intertwined with perceptions of (economic and resource) diversity which determine an actor's ability to (quickly) modify behavior and adopt alternative strategies in response to disruption (Schipper & Langston 2015).

(4) With regards to planning and physical infrastructure, **connectivity** describes the physical and spatial links between transport-, communication networks and vital infrastructure (Davoudi et al. 2013). While connectivity is a desirable system attribute for recovery, interconnectivities require careful identification and management due to potential cascading effects across the system (Biggs et al. 2012). From an ecosystem perspective, the connectivity of landscape patches (ecological corridors) safeguards required links to sources of ecosystem recovery after disturbance (Biggs et al. 2012).

PRINCIPLE	INTERMEDIATE PRINCIPLES
High Flux The principle of High Flux is rooted in the concept of perceiving urban processes to happen in "systems of cities", consisting of social and ecological networks with dynamic interlinkages (panarchies). High Flux represents a fast rate of movement of resources through the system that ensures a fast mobilization of these resources to quickly respond to threats and changes. This mechanism addresses rapidity by seeking ways and implementing conditions to maximize promptness in response. The underlying idea is that the faster the rate of movement of resources, the more resources are available at a given point in time to deal with disturbance.	**Availability of & access to resources** Financial support for recovery is provided through contingency or damage compensation funds and payout of these funds or insurances is quick; supportive resources and assistance are arranged for vulnerable groups
	Social & institutional networks Formal or informal cross-sector partnerships and networks between governing authorities, academia, firms and NGO and a broad web of social ties can fasten recovery by accessing resources of others
	Flexibility in response / resourcefulness Citizens have the choice and options to modify behaviour and adopt alternatives strategies if required, such as modifying structures, changing physical location or temporary repurposing of resources, means and spaces
	Managing connectivity of critical sectors, infrastructure and natural habitats Interconnectivities between sectors, critical functions along with potential cascading effects are identified and connections between natural habitats and water bodies are established

Fig. 3.13: Overview principle High Flux and intermediate principles

3.5.2.1 Availability of and access to resources

Scholars from economic resilience, governance, ecological resilience and flood risk management point out the importance of availability of and access to resources for individuals, businesses and organizations in order to respond to disturbances and reorganize quickly thereafter.

The provision of financial resources through payout of insurances or national compensation funds is argued to constitute a critical factor for economic, business and citizens' recovery (Raadgever et al. 2015; Martin & Sunley 2014). Pre-event arrangements for governmental reimbursement, such as national contingency funds or damage compensation payments out of national, regional or municipal funds are therefore considered salient (Bruneau et al. 2003; da Silva & Morera 2014; van den Brink et al. 2013; Tyler & Moench 2012).
Furthermore, it is commonly agreed that required financial funds to restore assets or communication should be delivered quickly (de Bruijn 2004). Accordingly, priorities should be given to quick financial provision mechanisms after a shock along with a quick payout of insurances to facilitate housing reconstruction (Bruneau et al. 2003; Arup 2014a).

Several scholars across different disciplines also stress the availability of municipal budgets for successful recovery and reorganization. Gupta et al. (2010) and van den Brink et al (2013) refer to financial investments in climate adaptation measures, whereas Tanner et al. (2009) expand on the overall municipal capacity to finance emergency and recovery services and flood preventive infrastructure. To compensate for eventual financial bottlenecks, institutions should withhold financial resources for required public hazard-related expenditures (i.e. road reconstruction, drainage and sewage repair and improvement) (Wardekker et al. 2010; Godschalk 2003).

When it comes to the individual level, it has already been outlined that the ability to recover, raise funds for reconstruction and damage repair depends to a great extent on socio-economic factors. Low-income groups with limited or no savings nor insurance are argued to have a limited capacity to recover successfully after a disturbance (de Bruijn 2004; Norris et al. 2008). Therefore, is imperative that supportive resources and assistance are specifically arranged for vulnerable groups in high-risk areas (e.g. relocation housing programs) (Godschalk 2003).

3.5.2.2 Social and institutional networks

The intermediate variable of social and institutional networks is rooted in the concept of connectivity. It is linked to High Flux due to its interpretation as "*the structure and strength with which resources, species or actors disperse, migrate or interact across patches, habitats or social domains in social-ecological systems*" (Biggs et al. 2012, p.n.a.). More concretely, it implies the direct linkages between the nodes of a network or interactions between components, that facilitate the exchange of material, information and other resources (Biggs et al. 2012; Tasan-Kok et al. 2013).

High levels of connectivity are fostered by promoting social and institutional networks that establish a multitude of connections between actors and institutions. Accordingly, Gunderson (2009) among others describes formal and informal networks as pivotal sources of resilience for ecological and social systems in post-disaster recovery. They actively enhance actors' access to information, communication, assets and finances and thereby facilitate and fasten the recovery process. In addition, accessing assets of others (through collaboration) can contribute decisively to the capacity to mobilize assets and resources (e.g., physical, social, financial, environmental, information, technology) in order to take action (Tyler & Moench 2012; da Silva et al. 2012).

Institutional networks are described to engender diverse solutions, policy options and responses which shorten recovery time. Additionally, pre-existing organizational networks can rely on their established structure to quickly mobilize support or emergency service for survivors (Norris et al. 2008). They also allow for flexibility in problem-solving since different types of knowledge and disciplinary backgrounds can be harnessed (Folke 2006; Gunderson 2009; Carpenter et al. 2001). Several scholars for that reason particularly stress cooperation structures to include bodies from different sectors (Huntjens et al. 2010; Folke et al. 2005). Thus, the following indicator is created: Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs (Davoudi et al. 2013; Folke et al. 2005; Huntjens et al. 2010).
In institutional realms networks can also be more intangible, associated with the presence of platforms of exchange among actors, such as workshops, congresses or city labs (van den Brink et al. 2013; Moench 2014).

With respect to the social realm, a broad web of social ties among groups and actors engenders information sharing, the development of trust as well as a flow of resources and ideas among people (Janssen et al. 2006; Biggs et al. 2012; Biggs et al. 2014). Thus, actors embedded in such constellations are more likely to receive important information (such as an evacuation notice) through their social support network and receive it quickly (Norris et al. 2008).
Scholars frequently connect the underlying idea of resource diversity created by social networks and multiple, alternative connections (that allow for a wider set of problem-solving options) in social and institutional contexts with aspects of social redundancy (Elmqvist 2014; Norris et al. 2008).
Against this backdrop social support, often termed social capital is described as a prominent driver for self- and reorganization after disruption in and beyond community resilience and governance literature (Tasan-Kok et al. 2013; Gunderson 2009; de Bruijn 2004). Understood as "*the bridging and bonding links between people in social networks*" (Folke et al. 2005, p.460) its mobilization during crisis triggers informal decision-making processes, self-organization (e.g. organizing reconstruction) and improvisation (Eraydin & Taşan-Kok 2013a; Folke et al. 2005). Therefore, the level of social cohesion and inter-group contacts among population groups (de Bruijn 2004) is taken up as an indicator.

3.5.2.3 Having options for flexibility in response

One aspect taken up by several scholars across disciplines is having multiple options to choose from. With respect to diversity and functional redundancy the availability of various options is stated to support the ability to adopt alternative strategies through the provision of multiple pathways. Furthermore, the prevalence of multiple ways of needs fulfillment facilitates performing essential tasks and maintaining functions under a wider range of climate conditions. In all these ways flexibility supports a system's capacity to recover from disturbance (Biggs et al. 2012; Biggs et al. 2014; Carpenter et al. 2001; Tyler & Moench 2012; Godschalk 2003).

In essence, diverse options should result in the capacity to mobilize resources. In the scientific literature these range from monetary resources for shifting livelihoods and modifying social and physical structures (Tyler & Moench 2012), convertible assets and skills (Moench 2014), to information or technological resources (Bruneau et al. 2003). The following two indicators summarize these contributions: Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required (Schipper & Langston 2015; Tyler & Moench 2012); Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it (Moench 2014; Tyler & Moench 2012; Rockefeller Foundation 2015)

The value of diversity for flexibility is also acknowledged in economic and community resilience. A diverse economy with different combinations of industries is stressed to reduce vulnerabilities and counteract widespread economic collapse or decline by providing employment and safeguarding economic growth (Martin & Sunley 2014). In addition, it enhances the resilience of livelihoods since it enables people to shift to other occupations and activities should changing circumstance require it. This applies both to quicker recovery from short-term shocks, but also long-term gradual changes (Biggs et al. 2012). Accordingly, community resilience scholars point out the danger in relying on one particular economic strand, often generating dependency on a narrow range of resources that might be affected by a disturbance and thus disrupt many people from their livelihood base (Norris et al. 2008). The following indicator is therefore formulated: Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes (Martin & Sunley 2014).

Yet, resilience literature hardly goes beyond describing the results of these actor capacities and availability of options while lacking clear indicators how these evolve.

3.5.2.4 Managing connectivity of critical infrastructure, services and natural habitats

The prominence of the concept of connectivity for system resilience has already been pointed out in support of recovery with regards to social and institutional networks (see chapter 3.5.2.2). Yet, connectivity is also described in terms of critical linkages between different spatial layers of a system potentially impacted by a disaster or used do denote intersections between critical sectors, such as transport or communication networks (Davoudi et al. 2013; Zevenbergen et al. 2008; da Silva & Morera 2014). Thus it is applicable to a much wider set of physical and ecological system components and has implications for spatial planning, infrastructure networks and critical services (Tasan-Kok et al. 2013).

It needs to be mentioned that high connectivity is not a desirable attribute for all (sub) systems. When all system elements are closely connected, disturbances and their effects may quickly spread through the system, which are often referred to as cascading effects. Against this backdrop, the identification and in-depth analysis of intersections with other sub-systems gains importance along with their strategic management.

A two-step approach can be taken to do so: Investigating into factors that contribute to failure of water, sewerage, transport and food system infrastructure that cause major disruptions, and locating where system failure have major impacts (Moench 2014). The second or parallel step entails the identification of critical linkages between different spatial layers, critical physical and spatial links between transport networks, ICT networks and vital infrastructure that might be affected by a disaster (Davoudi et al. 2013; Zevenbergen et al. 2008).

From an ecosystem perspective, connectivity is crucial for maintaining ecological diversity which is highly salient for ecosystem recovery after a disturbance (Gunderson 2009; Biggs et al. 2012; Biggs et al. 2014; Folke 2006). In general, according to empirical evidence ecological and biotic diversity is stated to promote stabilizing ecosystems after a disturbance and enhance the recovery of ecosystem functions thereafter (Gunderson 2009; Holling 2001; Carpenter et al. 2001; Walker et al. 2004). Connecting landscape and habitat patches safeguards the required links to sources of ecosystem recovery after disturbance (Biggs et al. 2012; Biggs et al. 2014). Consequently, in urban contexts preserving and implementing well-connected habitat patches (Biggs et al. 2012) and connecting webs of green and ribbons of blue (Biggs et al. 2012; Sheltair Group 2003) are beneficial spatial planning measures.

3.6 Phase 4: Adapt

ADAPT

The flexibility to seize arising opportunities and the capacity to initiate informed, deliberate, long-term changes in the system (e.g. organizational change, new policies) in response to changing conditions in order to maintain desired functions in the future.

Fig. 3.14: Description Adapt

Whereas recovery is the phase immediately following disturbance, focusing on rapid, reactive short-term responses, adaptation can be considered the extension of recovery in a long-run. It is a proactive phase where the ground for a future directory of dealing with change and disturbances is laid.
Notably, adaptation has two potential dimensions and time horizons. In the meaning of anticipatory adaptation, it refers to preparatory measures set in response to projected changes in the plan / prepare phase. These become especially salient for slow-onset, gradual trends, provided that they are spotted in time. For instance with regards to sea level rise, anticipatory adaptation is key to finding new ways for living with higher water levels in the future and trigger innovations and new concepts such as building whole villages on water.
Yet, adaptation can also refer to actions taken in response to actual changes (such as disasters) directed at reducing adverse impacts in the future but also seizing opportunities that open up (Tompkins & Adger 2004).
In both cases, adaptation consists of management processes to improve system resilience. Namely, new adaptive strategies to cope with change, strategic adjustments in parts of the system or the development of whole new system configurations (Linkov et al. 2013; Tasan-Kok et al. 2013). Manifestations involve institutional or organizational changes (i.e. new routines), structural measures including the redesign of the built environment (e.g. reinforcement of dikes, dams, floodwalls), the implementation of new policies or management decisions in urban development or environmental management (to solve experienced problems) (Linkov et al. 2013; Gunderson 2009; Schmitt et al. 2013; Nelson et al. 2007).

Whereas the above mentioned developments outline the output of the adaptation process, this paper is more interested in elaborating the underlying mechanisms that facilitate these developments, namely the capacity to deal with change and continued development (Zevenbergen et al. 2008).
The two respective mechanisms addressed in the scientific resilience literature are flexibility and learning. Learning and flexibility were found to constitute paramount resilience criteria cutting across all different strands of literature and were therefore added to the framework (see Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; da Silva et al. 2012; Cutter et al. 2008; Godschalk 2003; Carpenter et al. 2001; Gupta et al. 2010; Nelson et al. 2007; Liao 2012; da Silva & Morera 2014; Buuren et al. 2015; Schipper & Langston 2015). Their importance results primarily from the element of surprise inherent in complex, adaptive systems and the necessity to deal with uncertainty alongside a system's robustness (Folke et al. 2005; Biggs et al. 2012; da Silva & Morera 2014; Nelson et al. 2007; Davoudi et al. 2013). Both are considered an integrative element of adaptive capacity and governance and are elaborated in more detail in the following chapters (Folke et al. 2005; Liao 2012; Nelson et al. 2007; Cutter et al. 2008).

3.6.1 Learning & Reflectivity

Since SES constantly underlie uncertainty, surprise and unexpected changes, learning provides an integral part of their successful management. Adaptive management and governance all build on learning as a pivotal factor for developing new adaptive strategies to cope with change and performing strategic adjustments in parts of the system and thus, for adaptive capacity (Folke et al. 2005; Tasan-Kok et al. 2013; Linkov et al. 2013; Zevenbergen et al. 2008; Carpenter et al. 2001; Biggs et al. 2012). While both social and ecological systems possess the capacity to self-organize and adapt, learning is an essential human capacity (Schmitt et al. 2013).
What opposes this type of learning from the one outlined in the plan/prepare phase is the element of uncertainty. In phase 1 the major goal is to reduce uncertainty by learning more about potential disturbances and attempting to predict them. In contrast, when directed towards proactive long-term adaptability, a certain amount of uncertainty is accepted for which mechanisms are created to better deal with it.

Two dimensions of learning are identified to be relevant in the context of adapting to changing circumstances:

(1) Institutional learning capacity: As a continuous process of updating, testing and adjusting understanding, learning shapes the ability of individuals and organizations to deal with new developments and initiate timely adjustments, such as the modification of standards or the development of new policies when required. To be prepared to do so institutions should adopt this principle with regards to their institutional culture and decision-making processes (Holling 2001; Folke et al. 2005; Carpenter et al. 2001; da Silva & Morera 2014; Liao 2012; Moench 2014).

(2) Experimentation & Innovation: Institutions that actively foster experimentation in terms of learning-by-doing and innovation are better apt to develop novel solutions suited to expected future changes (Carpenter et al. 2001; Liao 2012).

PRINCIPLE	INTERMEDIATE PRINCIPLES
Learning & Reflectivity Under conditions of uncertainty and unexpected changes, learning becomes pivotal for affecting actual change. It is the most important driver for strategic adjustments in part of the system and new strategies to cope with change. It depends on the capacity and willigness of organizations and individuals to apply new knowledge, adopt novel, alternatives strategies in response to changing circumstances and change set goals if a new context requires it.	**Institutional learning capacity & reflectivity** Plans, strategies and policies are periodically revised and updated based on emerging information and research and continuous, participatory co-learning approaches are being applied (information networks, workshops, webinars) **Experimentation & innovation** Small-scale policy experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts are present and financially supported, and informal, safe space to experiment and innovate is provided

Fig. 3.15: Overview principle Learning & reflectivity and intermediate principles

3.6.1.1 Institutional learning capacity & reflectivity

Institutions and institutional arrangements are argued to play a paramount role in acting as a barrier or facilitator for (social) learning. By fostering knowledge-sharing mechanisms, they determine access of parties to lessons learnt and they set the base for joint reflection on experiences, ideas and values by admitting collaborative, participatory processes (Biggs et al. 2012; Biggs et al. 2014; Gupta et al. 2010; Tyler & Moench 2012). Yet, in practice the capacity to learn in organizations is often limited by its internal structure and culture which impede the flow of information or trans-institutional collaboration (Moench 2014).

The literature differentiates between two distinct modes of learning. Single loop learning refers to a change in skills, practices, actions and routines based on learning form past experiences while leaving goals unchanged (see chapter 3.3.1.4). In contrast, double loop learning brings about more fundamental change with respect to existing norms and in the assumptions underlying actions and institutional patterns. Such changes can be informed by questions about the impacts of actions on the system (Biggs et al. 2012; Biggs et al. 2014; Gupta et al. 2010; Lonsdale et al. 2010). Results are the adoption of new routines, patterns of interaction, collaboration or new management decisions based on shifts in perceptions of feasible strategies as new knowledge is gained (Linkov et al. 2013; Gunderson 2009; Schmitt et al. 2013; Nelson et al. 2007; Gupta et al. 2010). The latter are also indicators for institutional flexibility, therefore there are overlaps between the two categories.

The adaptive governance literature identifies several features of well-adapting organizations that actively drive processes of learning and change within and beyond their own realms.
First, monitoring and evaluation is stated to form an integrative part of learning and reflection. For institutions, this implies internal monitoring of activities and the continuous critical evaluation of implemented policies (Cutter et al. 2013; Gupta et al. 2010; Lonsdale et al. 2010; Huntjens et al. 2010) Monitoring is required to establish knowledge about the feasibility of strategies and subsequently improve them via policy and management change (Pahl-Wostl 2007). This is especially salient for dealing with complex problems like climate adaptation that require an acceptance of occasional failure or policy adjustments (Lonsdale et al. 2010).
Second, scholars state willingness and ability to reflect on experiences to constitute an additional requirement for learning (Moench 2014; Rockefeller Foundation 2015; Schipper & Langston 2015). Learning is a characteristic of so-called reflective systems attuned to uncertainty and change which refrain from implementing permanent solutions but rather modify standards and norms in accordance with emerging knowledge. Consequently, mechansims for iteration and incorporation of new information in strategies, policy development and amendments along with iteratice decision-making are paramout, however ways to get there are only poorly researched at this point (Moench 2014; Lonsdale et al. 2010; Gupta et al. 2010; Tyler & Moench 2012; Nelson et al. 2007; Liao 2012; Gunderson 2009).
Third, pro-active participatory co-learning approaches with available space for learning and exchange are a feature of well-adapting organizations. Such learning spaces could involve information networks, knowledge data bases but also joint workshops or webinars (Lonsdale et al. 2010). Thus, broad stakeholder participation and institutional linkages (see chapters 3.4.2.4 and 3.5.1.2) are a crucial condition for such learning approaches to occur.

3.6.1.2 Experimentation & innovation

In the face of knowledge about SES always being incomplete, experimentation is of great significance for resilience-building (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005).
From a governance perspective, institutions that incorporate resilience features should provide room for experiments, apply and facilitate learning-by-doing approaches. Scholars especially point out the importance of allowing failures and having the opportunities to make discoveries in order to create innovation (Biggs et al. 2012; Carpenter et al. 2001; Liao 2012; Knüppe & Pahl-Wostl 2011). In this regard, Lonsdale et al. (2010) refer to the creation of and support for “informal space” to experiment and innovate.
Following this line of thought, there is mentioning in the governance and IAWM literature of policies to be perceived as experiments from which to learn. Against this backdrop continuous testing and evaluation of alternative management approaches and adpatation strategies play a crucial role (Resilience Alliance 2010;

Folke et al. 2005; Biggs et al. 2012). Accordingly, several scholars across different fields stress the presence and financial support of small-scale policy experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts (Resilience Alliance 2010; Folke et al. 2005; Biggs et al. 2012; Huntjens et al. 2010; Zevenbergen et al. 2013).
From an ecosystem management perspective, experimentation entails management experiments in order to learn about SES responses to management actions or disturbances and their overall dynamics. This proves crucial for designing and planning appropriate adaptation in response to SES changes (Biggs et al. 2012).

3.6.2 Flexibility

Flexibility in adaptation is opposed to the short-term, immediate flexibility required for recovery. It manifests in the ability (and willingness) of organizations or individuals to change, apply new knowledge or adopt novel, alternative strategies in response to changing circumstances (Carpenter et al. 2001; Folke et al. 2005; Godschalk 2003; Rockefeller Foundation 2015; Eraydin & Taşan-Kok 2013a).
From a system governance perspective, Nelson et al. (2007) especially point out the aspect of managing systems for flexibility rather than stability to achieve resilience. Managing for flexibility has various dimensions and in this paper will be applied to the following three most apt for organizational contexts of governing climate adaptation:

(1) Institutional flexibility: the way institutions are organized, perform their daily activities and their decision-making processes have an influence on their flexibility to react to changing circumstances and adapt quickly.
(2) Flexibility in spatial planning looks at the extent of flexibility in the use of space and land-use based on current spatial planning practice and urban structure in order to determine whether a city can accommodate required spatial adjustments in the future.
(3) Flexibility in measures: the extent to which current climate adaptation measures limit the range of possible options for the future and their suitability for a variety of possible climate scenarios.

PRINCIPLE	INTERMEDIATE PRINCIPLES
Flexibility Uncertainty requires flexible planning, spontaneous responses and adopting flexible elements that are apt for several scenarios to come. From an institutional perspective, flexibility in structure and processes is crucial to be operational under fast-changing conditions. Flexibility in spatial means refers to creating anticipatory physical "structural elbowroom" for future adjustments, extensions or retrofitting. Flexibility can also be perceived as a design principle for adaptation measures according to reversibility, and avoiding limitations on the range of possible future mesaures.	**Institutional flexibility** Institutions have flexible decision-making processes where a change in speed and actor composition is possible, allow for changes in goals, strategies and time horizons, and have flexible procedures and cooperation arrangements **Flexibility in spatial planning** Flexible elements in spatial planning and physical interventions are applied that allow for future adjustments, retrofitting and/or extension (examples are broader dike foundations, modular elements in buildings) **Flexibility in measures** Measures taken now exhibit a mixture of small-, large scale, structural and non-structural measures and do not limit the range of possible future measures; preferably they are reversible (multi-functional dikes)

Fig. 3.16: Overview principle Flexibility and intermediate principles

3.6.2.1 Institutional flexibility

Lonsdale et al. (2010) among others argue that organizational learning calls for flexible structures, decision-making processes and goal management.

In addition, scholars of adaptive governance, ecosystem management and IAWM under the umbrella term of adaptive and flexible management all stress institutional flexibility and decision-making to be a prerequisite for staying operational during and appropriately responding to fast changing circumstances such as those related to climate change or socio-economic conditions (Pahl-Wostl 2007; Resilience Alliance 2010; Walker et al. 2004). With regards to water and flood risk management, building more flexibility into rules and procedures is stated to counteract observed path dependency in planning and governing institutions. The current focus is often on long-term, large-scale flood protection infrastructure which poses the danger of lock-in and leaves limited room for introducing change (van den Brink et al. 2013; Pahl-Wostl 2007).

A comprehensive operationalization of institutional flexibility is provided by Buuren et al. (2015) which will be adopted in this paper. To determine the underlying characteristics of flexible institutions they use the term flexible arrangements. They argue that adjusting policy strategies in response to changing insights, circumstances and continuously added knowledge "*is only possible when actors can also easily adjust the ways of collaboration, the mutual agreements, and the rules of collaboration.*" (Buuren et al. 2015). Such flexible arrangements are characterized along the three dimensions of flexibility of (interaction) processes, flexible content and flexible organizational structures of collaboration. These can be translated into the following indicators:

Decision-making processes allow for a change in speed, actor composition (Buuren et al. 2015)

Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon, goals of strategies and activities (Buuren et al. 2015)

Institutions offer room for changing procedures and cooperation arrangements if required (Buuren et al. 2015)

3.6.2.2 Flexibility in spatial planning

With spatial adaptation being a prominent concept in climate adaptation, flexibility in terms of "*enabling minor shifts in how systems function or spaces are used*" becomes salient in the context urban climate adaptation (Sheltair Group 2003, p.5). The aggravation of climate change impacts and other unexpected disturbances will require a transformation of the spatial landscapes of the city (Sheltair Group 2003). Spatial flexibility allows for a "structural elbowroom" for the functional rededication of spaces, required future adjustments, add-ons, extensions or easy-to-perform changes in a densely built urban fabric. A case study performed in Vancouver using the notions of convertibility and expandability offers a valuable operationalization for putting spatial flexibility into policy practice.

Convertibility implies the strategic design of urban structures and systems for versatility, in order to be apt for other multiple uses and functions (simultaneously) in the long run. As a result, required transformation can be performed more easily and at lower cost. Therefore, the case study argues in favor of convertible structures and multi-use spaces that allow for short- and long-term shifts in the use of space, parcels or buildings (Sheltair Group 2003). In this category also falls the use of modular elements in buildings that facilitate a quick re-dedication and modification (Wardekker et al. 2010), or dual-use options of buildings (e.g., watertight parking garage to be used for water storage, elevated roads still to be used in contingency situations) (Zevenbergen et al. 2008).

Expandability refers to "*facilitating additions (or deletions) to the quantity of land or space dedicated to particular uses*" (Sheltair Group 2003, p.5). An example from flood risk management is the construction of dikes with wider-than necessary foundations for easy retrofitting at a later stage (Wardekker et al. 2010).

Convertibility and expandability can be supported and enhanced by respective spatial regulations for land use, spatial functions or by legal provisions (such as the water law) (see chapter 3.4.1.3). With regards to urban planning policy, a supportive mechanism for convertibility is shortening the life-cycles and planning horizon of buildings and infrastructure (Zevenbergen et al. 2008; Wardekker et al. 2010). The rapid rate of substitution of structures and buildings facilitates a quicker modification of spaces. One possible way to foster expandability consists of restricting developments in areas or leaving areas completely without development (Wardekker et al. 2010; van den Brink et al. 2013; Raadgever et al. 2015; Tyler & Moench 2012).

3.6.2.3 Flexibility in measures

One of the goals of adaptive governance and management is to create strategies that are suited to a broad range of potential future (climate) scenarios and can be modified if required (Raadgever et al. 2015). The scientific literature describes several features of measures that account for these criteria.

A well-reported term in the context of resilient decision-making are no-regret measures. These are measures that do not require substantial financial investment, prove effective for a broad range of possible future scenarios and are therefore feasible to implement irrespective of climate change (Stead & Tasan-Kok 2013; de Bruin et al. 2009; Raadgever et al. 2015).

It is further argued, that flexibility is provided by measures taken now or envisaged for the near future that do not limit the range of possible future measures and therefore exhibit features of reversibility. Therefore, solutions for short-term problems should be assessed against causing problem in the far future (Huntjens et al. 2010).

Reversibility might be safeguarded in financial terms, for instance by reducing irreversible commitment of financial resources (Wardekker et al. 2010) and favoring multiple non-structural small-scale approaches instead of putting the emphasis on costly large-scale structural measures such as flood defenses (Huntjens et al. 2010).

Against this backdrop the necessity to adopt a long-term planning horizon becomes evident, determined by the mere character of climate change (Zevenbergen et al. 2008). This includes the ability to estimate long-term consequences of policies and plans (Lu & Stead 2013). The necessity to develop long-term disaster risk reduction and resilience strategies based on planning ahead is also highlighted in the disaster resilience literature (S. Cutter et al. 2013).

3.7 Framework

PHASE / POLICY DIRECTION	PRINCIPLE	OPERATIONALIZATION	INDICATORS FROM THE SCIENTIFIC LITERATURE
	Anticipation & Foresight Planning ahead and foresight are essential tools for anticipatory adaptation. They originate from the human capacity to anticipate disturbances to a certain degree, imagine different futures and thus, consider possible outcomes and to implement preparatory interventions. In regards of climate hazards, anticipation is mainly concerned with creating relevant knowledge about disturbances, their probabilities, potential risks, impacts and resulting vulnerabilities. But the resulting knowledge should also be shared among organizations and made accessible for the wider population to create awareness.	**Building knowledge about disturbance, exposure, vulnerability**	**GENERAL** Existence of (regional and city-wide) climate change-related projections, forecasts and scenarios (Lu & Stead 2013; Arup 2014; Godschalk 2003, Gunderson 2009) Identification and assessment of climate-related hazards, probability of occurrence, system's exposure, city-wide impacts and associated risks (Tyler & Moench 2012; Lu & Stead 2013; Linkov et al. 2014; Cutter et al. 2008; Davoudi et al. 2013; Godschalk 2003) Mapping of economic assets, critical functions (hospitals, police stations etc.), commercial and manufacturing establishments in flood-prone areas (Godschalk 2003) **FLOOD-RESILIENCE SPECIFIC** Performance of city-wide vulnerability assessments which describe and map potential flood hazards and impacts on neighborhoods (Cutter et al. 2008; Lu & Stead 2013; Gersonius et al. 2011; Linkov et al. 2014; McBain et al. 2010; Tyler & Moench 2012; Godschalk 2003; Zevenbergen et al. 2008)
		Monitoring of critical slow variables	**GENERAL** Real-time data collection; monitoring of natural (geological, atmospheric, oceanic) phenomena (National Academy of Sciences 2012) Periodic analysis and inspection of crucial infrastructure, like transport networks, electricity networks, telephone lines, water supply, drainage systems (de Bruijn 2004b) **FLOOD-RESILIENCE SPECIFIC** Flood risk monitoring systems are in place (Biggs et al. 2012; Lu & Stead 2013) Continuous monitoring of factors that affect sea level, river, canal and polder water levels (Carpenter et al. 2001) Continuous monitoring, control and evaluation of dikes safety and of flood-protective facilities (Chelleri et al. 2015; Davoudi et al. 2013; Lu & Stead 2013)
		Capacity to learn (from past experience)	**GENERAL** Keeping track records and data archives on hazards (over time), disaster losses (National Academy of Sciences 2012; Tasan-Kok et al. 2013; Cutter et al. 2013) Lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms (Folke et al. 2005; Tyler & Moench 2012; Cutter et al. 2008; Davoudi et al. 2013; Adger et al. 2005; da Silva & Morera 2014; Schipper & Langston 2015) **FLOOD-RESILIENCE SPECIFIC** Presence of accessible long-term track records of previous flooding events and disturbances (National Academy of Sciences 2012; Tasan-Kok et al. 2013) Lessons learnt from previous flooding events are formulated into tangible, accessible reports
		Information management & sharing	**GENERAL** Access of government agencies and research institutions to global scientific information and important (scientific data) (Pahl-Wostl 2007; Tyler & Moench 2012) Tools and mechanisms for information storage and sharing (i.e. data archives, open access, reports, policy documents) accessible for all employees over time, across institutional borders and between public and private entities (Tyler & Moench 2012; Cutter et al. 2013; Tasan-Kok et al. 2013, Pahl-Wostl 2007, van den Brink et al. 2013) Presence of platforms of exchange among actors (e.g. policy officials, municipality representatives, project coordinators), such as workshops, brainstorming sessions (van den Brink et al. 2013)

PLAN / PREPARE

Preparedness & Planning ahead

Preparedness is strengthening a city's coping responses before a disaster occurs. Being better prepared enhances the chances of absorbing impacts and quicker recovery. Apart from building and implementing adequate emergency & response management and mechanisms, this also entails providing the required resources for communities and businesses to plan and prepare for adverse events, such as the provision of adequate information, training and educational measures or the adoption of community flood plans.

Public Awareness, Risk Communication, Education & Training

GENERAL

Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action during disasters (e.g. guidance for preparation and appropriate response) (Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004a; Gupta et al. 2010; Raadgever et al. 2015)

Applying risk communication strategies for affected residents, e.g. flyers, targeted campaigns (van den Brink et al. 2013)

Hazard awareness, (water) safety education programs and response trainings to neighborhood and community organizations (Godschalk 2003; Schelfaut et al. 2011; Pahl-Wostl 2007b)

FLOOD-RESILIENCE SPECIFIC

Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations (da Silva & Morera 2014; Eraydin & Taşan-Kok 2013; Lu & Stead 2013; Tyler & Moench 2012; Schelfaut et al. 2011; Norris et al. 2008)

Response & Emergency Management

GENERAL

Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies (da Silva & Morera 2014; Schelfaut et al. 2011; Norris et al. 2008)

Prevalence of hazard management plans, hazard mitigation plans, emergency response plans and contingency protocols (Schelfaut et al. 2011; Cutter et al. 2008; Linkov et al. 2013)

Prevalence of evacuation plans, designation of evacuation routes and presence of shelter capacity (Cutter et al. 2013; da Silva & Morera 2014; van den Brink et al. 2013; de Bruijn 2004b)

Training and capacity building on risk communication for responsible authorities (Schelfaut et al. 2011)

FLOOD-RESILIENCE SPECIFIC

Presence of a flood forecasting and early flood warning system (Raadgever et al. 2015; Schelfaut et al. 2011)

Preparedness of businesses for adverse events

GENERAL

Information provision of climate scenarios, climate-related impacts and threats (Godschalk 2003; Lonsdale et al. 2010)

Presence of issue-specific formal or informal networks for exchange of best practice and knowledge generation (Lonsdale et al. 2010)

Businesses have an understanding of potential climate change related threats, associated risks and vulnerabilities in the business operation as well as opportunities (Lonsdale et al. 2010)

Companies factor the impacts of climate change into their business practice (for instance by having business continuity and contingency plans in place) (Rose 2004; Lonsdale et al. 2010)

Homeostasis

Dynamics in a SES arise from interactions and feedbacks between fast variables responding to the conditions generated by slow variables. Strategic management of feedbacks to prevent regime shifts (caused by disasters or slow trends) is therefore crucial. One way to do so is through implementing multiple feedback loops that counteract disturbances (dampening feedback) and/or stabilize the system to maintain a particular SES regime.

Preservation & restoration of regulating ecosystem services

FLOOD-RESILIENCE SPECIFIC
Policies and plans for natural areas and ecosystem conservation
(Tompkins & Adger 2004; Godschalk 2003)
Increasing / creating urban green spaces, green roofs, urban tree canopy cover
(Biggs et al. 2012; Wardekker et al. 2010; da Silva & Morera 2014)
(Re) implementing urban floodplain wetlands, coastal wetlands
(Biggs et al. 2012; Wardekker et al. 2010; da Silva & Morera 2014)
Wetlands acreage and loss (Godschalk 2003)
Percentage of impervious surface area (Godschalk 2003)

Integrated planning, coordination & collaboration

GENERAL
Presence of bridging mechanisms (e.g. actors, policies, laws, tools and instruments) that link and align strategies (Raadgever et al. 2015)
Linking urban (re-) development, planning processes, maintenance programs and other ongoing projects (road maintenance and public area development)
(Wardekker et al. 2010; Smit & Wandel 2006)
Presence of a formalized, common vision underlying planning and implementation of projects
(da Silva & Morera 2014; Rockefeller Foundation 2015)
FLOOD-RESILIENCE SPECIFIC
Cross-sector collaboration, mainstreaminig of water policies with other sectorial policies (drainage, land use, urban development) (Runhaar et al. 2009; Uittenbroek et al. 2013)

Inclusivness & equity standards

GENERAL
Legally enshrined rights and entitlements of citizens to use resources, urban systems and services (e.g. legal registration of residence coupled to receiving services) (Tyler & Moench 2012)
Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs) (Godschalk 2003)
Setting aside financial resources to make poor neighbourhoods safer from disturbances (Godschalk 2003)
Collaboration between municipalities and residents in neighbourhoods to determine their needs and set appropriate vulnerability-reducing measures (Godschalk 2003)
Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits (Lebel et al. 2006)
Assessments of distributional consequences and who wins and loses from the implementation of particular climate adaptation measures and impacts (Adger et al. 2005)

Clearly defined responsibilities of actors / institutions

GENERAL
Presence of specific divisions of accepted responsibilities (Raadgever et al. 2015)
Intergovernmental division of labour for performing emergency response activities (e.g. search and rescue) (Bruneau et al. 2003)
Transparency on responsibilities, tasks and rolse of governing authorities and stakeholders (De Bruin et al. 2009)

FLOOD-RESILIENCE SPECIFIC
Responsibilities are clearly defined and allocated for causing and solving water-problems, sewage systems (Gupta et al. 2010)
Statutory responsibility for flood prevention and protection is defined and determined in policy documents (Wardekker et al. 2010)
Legal responsibilities for property damage caused by flooding events are clearly defined and known by involved parties (Wardekker et al. 2010; de Bruijn 2004a; Schelfaut et al. 2011)
Insurability of private property against flood loss (Van den Brink et al. 2013; Godschalk 2003)
Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery (Raadgever et al. 2015; de Bruijn 2004a)

Quick notification of disturbances

GENERAL
Multiple, reliable communication and broadcasting technologies (internet, mobile phone, telephone, newspaper, TV etc.) to be harnessed for communicating flood warnings (da Silva & Morera 2014; Schelfaut et al. 2011; Norris et al. 2008)
FLOOD-RESILIENCE SPECIFIC
Presence of a flood and weather forecasting, monitoring and early warning system to generate timely information that facilitates anticipation (Raadgever et al. 2015; Schelfaut et al. 2011; Linkov et al. 2013a)

Robustness & Buffering

The inherent strength of a city, referred to as robustness and the existence of buffering mechanisms based on over-dimensioning systems (i.e. water storage capacity) determine whether a city can endure, cope with a hazard and maintain function during adverse circumstances. Solid flood-protective infrastructure coupled with pre-emptive planning practices, such as flood-sensitive building codes and event buffering capacity can enhance the robustness of a system.

Robustness through infrastructure

FLOOD-RESILIENCE SPECIFIC
Presence of flood-protective structural measures and installations (Godschalk 2003)
Presence of formalized water safety / dike standards that are regularly monitored (da Silva & Morera 2014; Raadgever et al. 2015)
Periodic assessment, optimization and improvement of flood-protective infrastructure (Cutter et al. 2013)

Creating buffer capacities

FLOOD-RESILIENCE SPECIFIC
Implementation of levees, canals and water arms (Gunderson 2009)
Increasing above and under-ground (rain)water storage and capture mechanisms (McBain et al. 2010; Zevenbergen et al. 2008; Wardekker et al. 2010)
(Re)creating open space as urban floodplain wetlands and as urban green spaces (parks) (Godschalk 2003; da Silva & Morera 2014; van den Brink et al. 2013)
Increasing the percentage of floodable area (Liao 2012)
Increasing the drainage capacity of the urban water system by designing drainage networks for exceedance (McBain et al. 2010)

Impact- and risk-reducing planning & planning practice

FLOOD-RESILIENCE SPECIFIC
Limiting development rights in flood plains and areas at risk from flooding (flood zoning) (Raadgever et al. 2015; Tyler & Moench 2012)
Prohibiting (property) development in flood-prone areas (Raadgever et al. 2015)
Introduction of permits in flood-prone areas (Schelfaut et al. 2011)
Relocating property from flood-prone areas and inhibiting new development (Godschalk 2003; Zevenbergen et al. 2008; van den Brink et al. 2013)
Flood-proofing and flood-resilient construction codes and standards for buildings and public facilities (da Silva & Morera 2014; Godschalk 2003; Zevenbergen et al. 2008; van den Brink et al. 2013; Liao 2012)
Elevation of ground level of urban flood-prone areas (Wardekker et al. 2010; Liao 2012)
Flood-risk conscious interior design and appropriate planning (Wardekker et al. 2010; Zevenbergen et al. 2008)

ABSORB DISTURBANCE

Diversity

Systems with many different components are more resilient than their counterparts with only a few. Diversification of resources and means can reduce a system's vulnerability by generating heterogeneous components performing <u>different functions</u> and thus facilitating a diversity of responses to threats. Furthermore, the prevalence of multiple ways of needs fulfillment (also called functional diversity) facilitates performing essential tasks and maintaining functions under a wider range of climate conditions and thus, enhances a system's flexibility.

Functional & response diversity

GENERAL
Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people) (Liao 2012; Wardekker et al. 2010; Resilience Alliance 2010)
Variety in energy systems using different energy sources which can be generated at different scales (local, regional, global) (SheltAir Group 2003)
Variety in food provision: maintain local capacity to produce food, while strengthening transnational trade networks (SheltAir Group 2003)
The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated (Martin & Sunley 2014)
Heterogeneous population covering a wide range of different expertise, occupations and education (Walker et al. 2004; Martin & Sunley 2014; Rockefeller Foundation & ARUP 2015)
Parallel existence of different land-use types in cities (Gunderson 2009)
Implementing measures for crop diversification (i.e. urban farming, homegardens (Moench 2014)
FLOOD-RESILIENCE SPECIFIC
A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization (Liao 2012)
Diverse sources of design for flooding protection infrastructure
(Pahl-Wostl 2007; Cutter et al. 2008; Cutter et al. 2010)

Spatial diversity of critical functions

GENERAL
Financial institutions, economic activities, hospitals, crisis centres, refugee centres, water pumping facilities etc. are physically distributed across the city (Tyler & Moench 2012)
Various, geographically and spatially distributed (drinking) water sources and reservoirs around the city (Sheltair Group 2003; Tyler & Moench 2012)
Food supplies are sourced from different geographic areas (Tyler & Moench 2012)
FLOOD-RESILIENCE SPECIFIC
Decentralized flooding protection infrastructure with diverse sources of design (Pahl-Wostl 2007)

Actor & stakeholder diversity

GENERAL
Variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process (Gupta et al. 2010; van den Brink et al. 2013; Biggs et al. 2012; da Silva & Morera 2014)
Actors and stakeholders involved in decision- and policy-making have differing professional and knowledge backgrounds (Biggs et al. 2012; Folke et al. 2005; Berkes & Ross 2013)
Different government and non-governmental stakeholders are involved in setting the TOR and/or consulted (Huntjens et al. 2010)
FLOOD-RESILIENCE SPECIFIC
Different problem frames and policy solutions for urban flooding (van den Brink et al. 2013)

Institutional diversity, multi-level governance systems and linkages

GENERAL
Organizations with different sizes, cultures, funding mechanisms, internal structures
(Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Tyler & Moench 2012; Kernaghan & da Silva 2014; van den Brink et al. 2013; Resilience Alliance 2010; Walker et al. 2004)
Various governing authorities at different scales made up by a diverse group of actors with different roles and overlapping functions
(Biggs et al. 2012; Biggs et al. 2014; Gupta et al. 2010; Folke et al. 2005)
Presence of formal and informal partnerships between governing authorities, academia, firms and NGOs (da Silva & Morera 2014)
Presence of platforms of exchange among actors, such as workshops, brainstorming sessions (van den Brink et al. 2013)
FLOOD-RESILIENCE SPECIFIC
Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)
(Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006)
Governing authorities involved in flood risk management differ in size, culture, internal structure (Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Tyler & Moench 2012)
Distributed flood-response capacity across levels (households, communities, municipalities) (Liao 2012)

Redundancy

Describes the presence of multiple elements or replication of components or pathways in order to have multiple instances available that perform the same function. These can fully substitute each other and therefore prevent system failure in case one component fails. From a resilience-building perspective it implies the strategic creation of systems that have multiple nodes, connected components and spare capacities that prevent failure in the face of extreme pressures or disruption, and maintain service delivery. It applies both to technological (power grid, infrastructure) as well as to social systems (large social networks that offer different problem-solving options).

Overlapping functions and roles	**GENERAL** Shared responsibilities, rights and management authorities among responsible institutions across scales (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005) Redundancy of actors and actors roles (Folke et al. 2005) Different organizational forms that share the same issues areas (Biggs et al. 2012) Polycentric, multi-level governance systems with decentralized decision-making structures (Biggs et al. 2012; Norris et al. 2008) **FLOOD-RESILIENCE SPECIFIC** Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level) (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006)
Functional redundancy in important functions & services	**GENERAL** Multiple access / evacuation routes, multiple routes of supply, electricity, sewage removal (Cutter et al. 2010; Cutter et al. 2008; Wardekker et al. 2010) Several transmission towers to upkeep communication (Tyler & Moench 2012) Multiple counterparts for vital functions (Wardekker et al. 2010)
Spare capacities & back-up resources	**GENERAL** Alternative power supplies and energy back-up generators for key businesses, critical infrastructure and services (Bruneau et al. 2003; Tyler & Moench 2012) Alternative water supplies for all key businesses and critical infrastructure (Bruneau et al. 2003) Maintaining stocks of food, medicine, water supplies in case of disruption (Tyler & Moench 2012)
Compartmenalization & modularity	**GENERAL** Presence of polycentric, multi-level governance systems (Biggs et al. 2012) Communication, transport networks, infrastructure grids and other vital functions and services in cities are based on a modular network structure (SheltAir Group 2003) Sectorial and organizational components of an economy are based on a modular network structure (Martin & Sunley 2014) **FLOOD-RESILIENCE SPECIFIC** Presence of compartmentalization dikes, dike rings, compartmentalized polders, temporary dams or flood defences that prevent floodings from spreading to other regions or locally retain substances (Gersonius et al. 2011; Wardekker et al. 2010)

PHASE / POLICY DIRECTION	PRINCIPLE	OPERATIONALIZATION	INDICATORS FROM THE SCIENTIFIC LITERATURE
RECOVER	**Flatness** Flatness refers to a non-hierarchical way of governing a system and is a means of enhancing self-organization. The absence of a local formal competence to act on behalf of the population, as well as on lower policy levels along with lengthy decision-making and bureaucracy processes make the system inflexible and too slow to cope with changes and thus, ineffective in responses. Flatness is represented by inclusive, participatory processes that include a wide range of stakeholders, and providing the public with the power, authority and competence to respond to disturbances on their behalf.	**Institutional decentralization & autonomy**	**GENERAL** Shared responsibilities, rights and management authorities among responsible institutions across scales (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005) Level of financial independence of governing bodies (Lebel et al. 2006) Municipal authorities have the autonomy to authorize plans and legislate policy (Tanner et al. 2009) Autonomous management capacity and ability to autonomously develop own strategic goals, tailor-made policies and measures (Lebel et al. 2006; Pahl-Wostl & Knüppe 2013) Independent governance units with a particular domain of authority within a designated geographic area (Folke et al. 2005; Biggs et al. 2012) **FLOOD-RESILIENCE SPECIFIC** Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level) (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006)
		Broad participation, stakeholder engagement & inclusiveness	**GENERAL** Presence of mechanisms for providing stakeholder and public input to decisions, (climate adaptation) programs and strategies (e.g. hearings, meetings, local consultations) (Davoudi et al. 2013; Tyler & Moench 2012) Non-governmental stakeholders contribute to agenda setting, analysing problems, developing solutions and governance process ("coproduction") (Biggs et al. 2012, 2014; Huntjens et al. 2010) Presence of open, deliberative forums or platforms of exchange between actors (policy officials, municipality representative, project coordinators, local population) before and during the implementation of projects (i.e. workshops, brainstorming sessions) (Mees et al. 2014b; van den Brink et al. 2013) Designing varied local and context-specific mitigation approaches based on neighborhoods consultation and collaboration and needs assessment (Godschalk 2003; Norris et al. 2008) Legal provisions concerning access to information, participation in decision- making (e.g. consultation requirements before decision-making) and access to courts (Huntjens et al. 2010) Decision-making processes are transparent and aim at including and equally representing all interests at stake (Mees et al. 2014b; Tyler & Moench 2012) Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits (Lebel et al. 2006)
		Room for autonomous change	**GENERAL** **Continuous access to information** All indicators below "Information management & sharing" + Applying risk communication strategies for affected residents, e.g. flyers, targeted campaigns (van den Brink et al. 2013) **Capacity to act according to plan** Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action during disasters (e.g. guidance for preparation and appropriate response) (Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004a; Gupta et al. 2010; Raadgever et al. 2015) **Capacity to improvise during crisis** Procedures that enable groups to form legal voluntary organizations, raise funds and undertake activities in relation to emerging needs (Tyler & Moench 2012)
			FLOOD-RESILIENCE SPECIFIC **Continuous access to information** Disclosure of credible and correct information on flood risk by respective governance institutions to households, and community organizations is imperative (da Silva & Morera 2014; Eraydin & Taşan-Kok 2013; Tyler & Moench 2012; Schelfaut et al. 2011; Norris et al. 2008) **Capacity to act according to plan** Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action for flooding events (e.g. guidance for preparation and appropriate response) (Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004a; Gupta et al. 2010; Raadgever et al. 2015) Hazard awareness, (water) safety education programs and response trainings to neighborhood and community organizations (Godschalk 2003; Schelfaut et al. 2011; Pahl-Wostl 2007b) Affected population is provided guidance on flood-resilient construction and how to prepare their homes for flooding (Schelfaut et al. 2011)

High Flux

The principle of High Flux is rooted in the concept of perceiving urban processes to happen in "systems of cities", consisting of social and ecological networks with dynamic interlinkages (panarchies). High Flux represents a fast rate of movement of resources through the system that ensures a fast mobilization of these resources to quickly respond to threats and changes. This mechanism addresses rapidity by seeking ways and implementing conditions to maximize promptness in response. The underlying idea is that the faster the rate of movement of resources, the more resources are available at a given point in time to deal with disturbance.

Availability of and access to resources	**GENERAL** Pre-event arrangements for governmental reimbursement, such as national continency funds or damage compensation payments out of national, regional or municipal funds (Bruneau et al. 2003; da Silva & Morera 2014; van den Brink et al. 2013) Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems (Godschalk 2003) Reduction of irreversible commitment of resources (Wardekker et al. 2010) Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock (Arup 2014b; de Bruijn 2004a; Bruneau et al. 2003) Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs) (Godschalk 2003)
Social & institutional networks	**GENERAL** Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs (Davoudi et al. 2013; Folke et al. 2005; Huntjens et al. 2010) Prevalence of platforms of exchange among actors such as workshops, congresses, city labs (van den Brink et al. 2013; Moench 2014) Level of social cohesion and inter-group contacts among population groups (de Bruijn 2004)
Having options for flexibility in response	**GENERAL** Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required (Schipper & Langston 2015; Tyler & Moench 2012) Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it (Moench 2014; Tyler & Moench 2012; Rockefeller Foundation 2015) Financial mechanisms for fostering (local) business development and innovation (Rockefeller Foundation & ARUP 2015) Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes (Martin & Sunley 2014) Communities' livelihood strategies are not confined to a single economic resource (Norris et al. 2008; Schipper & Langston 2015)
Managing connectivity of critical sectors, infrastructure, natural habitats	**GENERAL** Identification of critical linkages between different spatial layers, critical physical and spatial links between transport networks, ICT networks and vital infrastructure that might be affected by a disaster (Davoudi et al. 2013; Zevenbergen et al. 2008) Investigating into factors that contribute to failure of water, sewerage, transport and food system infrastructure that causes major disruptions, and locating where system failure have major impacts (Moench 2014) Connecting webs of green and ribbons of blue (Sheltair Group 2003) Preserving and implementing well-connected habitat patches (Biggs et al. 2012) Improve spatial heterogeneity in landscapes by implementing spatially alternating land use (Biggs et al. 2012)

ADAPT			
Learning & Reflectivity Under conditions of uncertainty and unexpected changes, learning becomes pivotal for affecting actual change. It is the most important driver for strategic adjustments in part of the system and new strategies to cope with change. It depends on the capacity and willigness of organizations and individuals to apply new knowledge, adopt novel, alternatives strategies in response to changing circumstances and change set goals if a new context requires it.	**Institutional learning capacity & reflectivity**	**GENERAL** Institutions are monitoring their activities and performance (Cutter et al. 2013; Gupta et al. 2010; Huntjens et al. 2010) Iterative revision and updating of plans, strategies and standards based on emerging information and research (Tyler & Moench 2012; Lonsdale et al. 2010; Moench 2014) Participatory co-learning approaches by providing spaces for joint learning, such as information netowkrs, workshops, webinars (Lonsdale et al. 2010) Institutions adopt new routines, patterns of interaction, collaboration or management decisions (Linkov et al. 2013b; Gunderson 2009; Schmitt et al. 2013; Nelson et al. 2007; Gupta et al. 2010) Learning outputs (i.e. changing insights and circumstances) inform policy changes and amendments (Nelson et al. 2007; Liao 2012; Gunderson 2009)
	Experimentation & innovation	**GENERAL** Creation of testing grounds and support for 'informal space' to experiment and innovate (Lonsdale et al. 2010) Small- and large scale experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts which are financially supported (Resilience Alliance 2010; Folke et al. 2005; Biggs et al. 2012; Huntjens et al. 2010; Zevenbergen et al. 2013)
Flexibility Uncertainty requires flexible planning, spontaneous responses and adopting flexible elements that are apt for several scenarios to come. From an institutional perspective, flexibility in structure and processes is crucial to be operational under fast-changing conditions. Flexibility in spatial means refers to creating anticipatory physical "structural elbowroom" for future adjustments, extensions or retrofitting. Flexibility can also be perceived as a design principle for adaptation measures according to reversibility, and avoiding limitations on the range of possible future mesaures.	**Institutional flexibility**	**GENERAL** Institutions offer room for changing the procedures and cooperation arrangements if required (Buuren et al. 2015) Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon and goals of strategies and activities (Buuren et al. 2015) Decision-making processes allow for a change in speed and actor composition if required (Buuren et al. 2015)
	Flexibility in spatial planning	**GENERAL** Development of multi-use spaces or convertible structures that allow for short-term and long-term shifts in the use of space, parcels, buildings (Sheltair Group 2003; Wardekker et al. 2010; Zevenbergen et al. 2008) Spatial design allows for additions or deletions to the quantity of space and land dedicated to particular uses (Sheltair Group 2003) Employing modular elements in buildings (Wardekker et al. 2010) Leaving spaces without development so that they can be used for other purposes (Wardekker et al. 2010; van den Brink et al. 2013; Raadgever et al. 2015; Tyler & Moench 2012) Reducing life-cycles of buildings and infrastructure (Wardekker et al. 2010;)
	Flexibility in measures	**GENERAL** Employing no-regret measures in climate adaptation apt for a broad range of possible future scenarios (de Bruin et al. 2009; Raadgever et al. 2015; Stead & Tasan-Kok 2013; Wardekker et al. 2010) Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: designing measures for reversibility (Huntjens et al. 2010) No one-fits all solution but consideration of alternatives which include small- and large-scale structural and non-strutural measures (Huntjens et al. 2010) Reducing irreversible commitment of financial resources by broadening measures (Wardekker et al. 2010) Urban planning, disaster risk management, climate adaptation strategies and respective policy development account for a long-term planning horizon (Zevenbergen et al. 2008; Lu & Stead 2013; S. Cutter et al. 2013; Godschalk 2003)

Fig. 3.17: Urban Climate Resilience Framework

4 Testing the framework: Methodology

The qualitative research underlying this paper can be structured in two major phases.

The first phase consisted of the development of the diagnostic tool for policy-makers to 1) evaluate resilience baseline conditions and/or 2) check if adaptation plans fulfill resilience criteria (chapter 2 and 3).
The second phase involves testing the framework on the two illustrative case studies Rotterdam and London. This is salient since theoretically based models are frequently confronted with the problem of limited practicality. Since the aim of this research is to develop a diagnostic tool for policy-makers, it still needs to be established to what extent this framework and its indicators are functional and how they can be improved for future use. The findings of the two illustrative case studies Rotterdam and London help answer this question. The following chapter will delve more deeply into the second phase of the research, describing its major methodological approaches.

4.1 Desk research

The first part of the research was mainly based on desk research. It informed the development of the diagnostic tool by selecting the most relevant strands of literature to be used and investigating them for prominent resilience principles (see chapter 3).
Online desk research was further employed to get a full picture of the conditions related to climate adaptation and flooding in the two cities investigated. It yielded climate change projections, trends and challenges with regards to future flooding events, city-wide impacts and the state of climate adaptation and activities. In addition, relevant policy documents regarding current climate adaptation, water safety strategies and management were identified for subsequent analysis.

4.2 Case study research

To find out about its practical value, the diagnostic tool is tested on two illustrative case studies with regards to flood risk management. The testing serves three purposes:

(1) Assess whether the principles and indicators are applied by practitioners, and other alternative ways to adopt the principle;

(2) Identify problematic principles, subprinciples and indicators based on their absence or their limited integration and investigate reasons for their absence; and

(3) Find ways to improve functionality of such indicators.

Against this backdrop the empirical research is required to produce in-depth information for tracking the integration of these principles into current practice and policy development, identifying potential problems of their practicality and exploring relevant indicators to add to the framework.
Since case studies allow for such a thorough investigation of respective local contexts and processes and thereby produce rich, context-dependent data, they are suited for this research (Verschuren et al. 2010; Flyvbjerg 2006).

More specifically, illustrative case studies applied in this paper fall within the category of plausibility probes which aim at "*refining the operationalization or measurement of key variables*" (Levy 2008, p.6).

There are several reasons for selecting Rotterdam and London as cases. First, both cities have a long history of urban floods and therefore exhibit sophisticated flood prevention and water management techniques. Thus, several plans were expected to be in place for strategic urban flood risk management along with established water governing bodies. Second, each city has developed its own comprehensive municipal climate adaptation strategy superseding the national adaptation strategy which exhibits their strong endeavor for the issue area. Third, London and Rotterdam are both members of the 100 Resilient Cities Network which obliges them to develop a city-wide resilience strategy. Besides the benefit of using the therein outlined resilience-building activities to supplement the results, prior exposure to and knowledge of the concept and its underpinnings were expected.

Certainly, choosing the small-scale approach of a case study also has its trade-offs with regards to the generalization of the results and external validity. Yet, the deliberate use of general resilience principles and the suitability of the tool for a broad set of slow-onset, long-term trends and sudden shocks reflects its appropriateness for further testing on different resilience topics. As such, generalization can be enhanced by its subsequent application to other cities, policy domains and disturbances while strengthening the robustness of the framework. Further it is assumed that flood-related impacts and challenges faced by the selected cities are expected to be similar in other European cities. Thus, the investigation of response mechanisms create knowledge that is equally beneficial for other cities.

4.2.1 Semi-structured and structured interviews

The case study approach was complemented by semi-structured and structured interviews with key stakeholders. These involved local practitioners and political authorities in urban planning and water management, emergency responders, private sector and network organizations representatives.

Prior to the field research, interviews with four experts were conducted to gain an overview of the key issues in climate adaptation and water management and underlying governance systems in the two cities (list of interviewees in Appendix 5). Interviewees involved one experienced PBL employee in the field of water safety and management, a representative of the municipality of Rotterdam of the Public Works and Water department, a researcher in the field of flooding and climate adaptation from the University of Applied Sciences in Amsterdam and a researcher at the UK Environment Agency. Through these interviews an understanding of the water sector, responsibilities across institutions and departments from the local to the national level was generated and relevant legal and policy documents were identified. Additionally, they helped in the selection of suitable interview partners most of which were identified via the snowball method.

Moreover, 27 (semi-)structured interviews were held with practitioners, 15 in Rotterdam ranging from 1.5 to 2 hours, 12 in London lasting up to an hour. Responders were employees in the water sector (local to national level), emergency services, different government levels (borough, GLA, municipality), the private sector and network organizations. An overview of interviewees and their functions can be found in Appendix 5, the interview guide is provided in Appendix 6. In addition, presentations attended at the Adaptation Futures Congress 2016 in Rotterdam were used as information sources (R13, R15, parts of L2, L3).

Since the time allocated to interviews varied, the researcher shifted between structured and semi-structured interviews. The Rotterdam interviews ranged from 1.5 to 2 hours or beyond while respondents from London allocated an hour maximum. As a consequence, semi-structured interviews were conducted in Rotterdam and mostly structured ones in London.

Due to the limited time frame, an overview document of the framework with a short description of the phases and principles was sent out prior to the interview (i.e. short descriptions of the principles used in the previous chapter). In addition, a simplified document was created consisting only of the policy directions / phases for the semi-structured interviews which was used to steer questions in which section the institution's activities were to be placed (see Fig. 4.1).

The evaluation questions strictly oriented on the principles were geared towards driving responses with regards to matching internal structures, measures, policies or program orientations of organizations. From these responses or their absence, management and understanding gaps can be detected which will be interpreted in chapter 5 and 6.

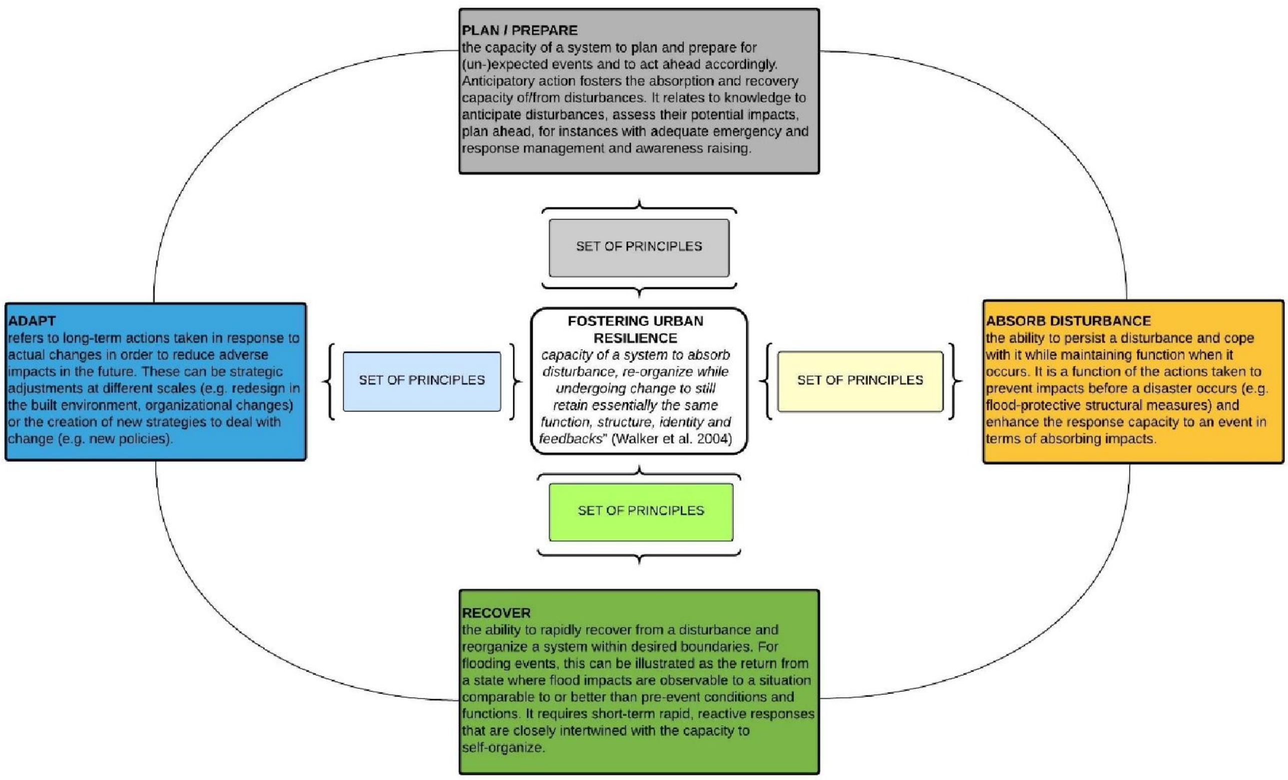

Fig. 4.1: Information handed out to interviewees

4.3 Analysis and presentation of results

Due to the amount of empirical data and the extensiveness of the principles, the use of NVivo software to organize, group and analyze information was deemed useful. A broad pool of data can be fed into the system and differentiated by categories and topics which allows for coding of the different types of documents. For this research, these data contained relevant policy documents, all kinds of supportive material gathered during the research and interview transcripts. A mixture of a deductive and inductive approach was applied. Deductive in a way that the coding was performed along the principles, intermediate principles and indicators of the tool which were defined as nodes. Inductive in terms of capturing replacement or new indicators emerging in the interviews.

For the illustration of the results, it was decided to condense the findings in a simple matrix structure. A valuation system of 0/+/++ was used to measure the amount of information found in documents and interviews for intermediate principles and indicators to be applied by policy-makers. A description for each of the valuation categories used is provided below. A practical illustration of how this matrix system is applied is provided for one principle in Appendix 4. For further information on data supporting the results, the researcher can be contacted in person.

0	No information that the principle is currently being checked / applied
0/+	Scarce information (up to two interviewees, documents etc.) for intermediate principle / indicator to be checked / applied
+	Some sources (more than two interviewees / policy document etc.) report the intermediate principle / indicator to be checked / applied
++	Many sources (interviewees, plans, programs) support the intermediate principle / indicator

It is worth mentioning that this type of valuation deliberately does not attempt a scoring of the cities with regards to their progress on these principles. Although the findings to a certain extent evaluate the state of resilience of the particular cities, the researcher decided against the application of a numerical scoring.
This goes in line with a general criticism towards evaluating qualitative research on quantitative terms provided that they do not fully account for the complexity of social phenomena (Corbin & Strauss 1990). The researcher primarily opted against scoring for the novelty of the resilience concept in the policy arena and its current lack of institutionalization. Despite its prominence in policy discourse, resilience is not yet a fully understood concept without clear, concise recommendations for policy action. Practitioners are not (yet) fully aware of all the principles, let alone able to employ them in policies. The relevant question is therefore a more fundamental one, i.e.: "Do they know what to do?" rather than "How well are they doing it?". Against this backdrop an attempt to score cities on their state of resilience-building seems neither fair nor appropriate. Apart from running danger of bias, results would not adequately reflect on the true capacity of a city for resilience-building.
Therefore, for a principle to be checked / applied includes the range from being aware of it, considering its integration, already making provisions for its integration to having it already implemented.

The matrix structure was deemed a suitable starting point for answering the third research question: *What indicators can enhance the applicability of the framework in policy-making?*
Enhancement in this context is to be understood particularly with regards to what can be done to make the indicators more practical and to make them better understood in terms of required actions in a policy context. Enhancing their practicality entails for instance providing different options for achieving a particular principle for which the case studies offer insights or substituting an allegedly abstract indicator with simpler ones based on identified practice and level of understanding.
Allocating the valuation of 0/+/++ to each of the principles determines which indicators might require amendment in the first place. It differentiates between absent indicators, those that are considered or applied to a limited extent and those that are already adopted (and therefore out of the scope of consideration).

Specific consideration is given to the following two categories:

(1) Indicators with no information cannot be understood, applied in practice or for other reasons not applied. In this case the nature of the problem needs to be identified on the basis of the reasons provided in the interviews. Drawing on the personal experience in interviews and on existing scientific literature on barriers to

climate adaptation by Runhaar et al. (2012), Biesbrock et al. (2009) and Uittenbroek (2015) three explanatory categories are identified (see Fig. 4.2 for a schematic representation of the analytical process):
(1) Lack of understanding or awareness (Biesbroek et al. 2009; Runhaar et al. 2012)
(2) Lack of practical functionality of theoretical indicators
(3) Political, institutional and/or resources-related barriers which are described to include but are not limited to: a short-term political time horizon, missing motives and willingness, absence of shared values and norms, absence of enforcing policies or regulations, influence of existing institutional arrangements and routines (i.e. existing ways of doing things), lack of flexible budgetary or human resources and unclear (financial) responsibilities (Runhaar et al. 2012; Biesbroek et al. 2009; Uittenbroek 2015).

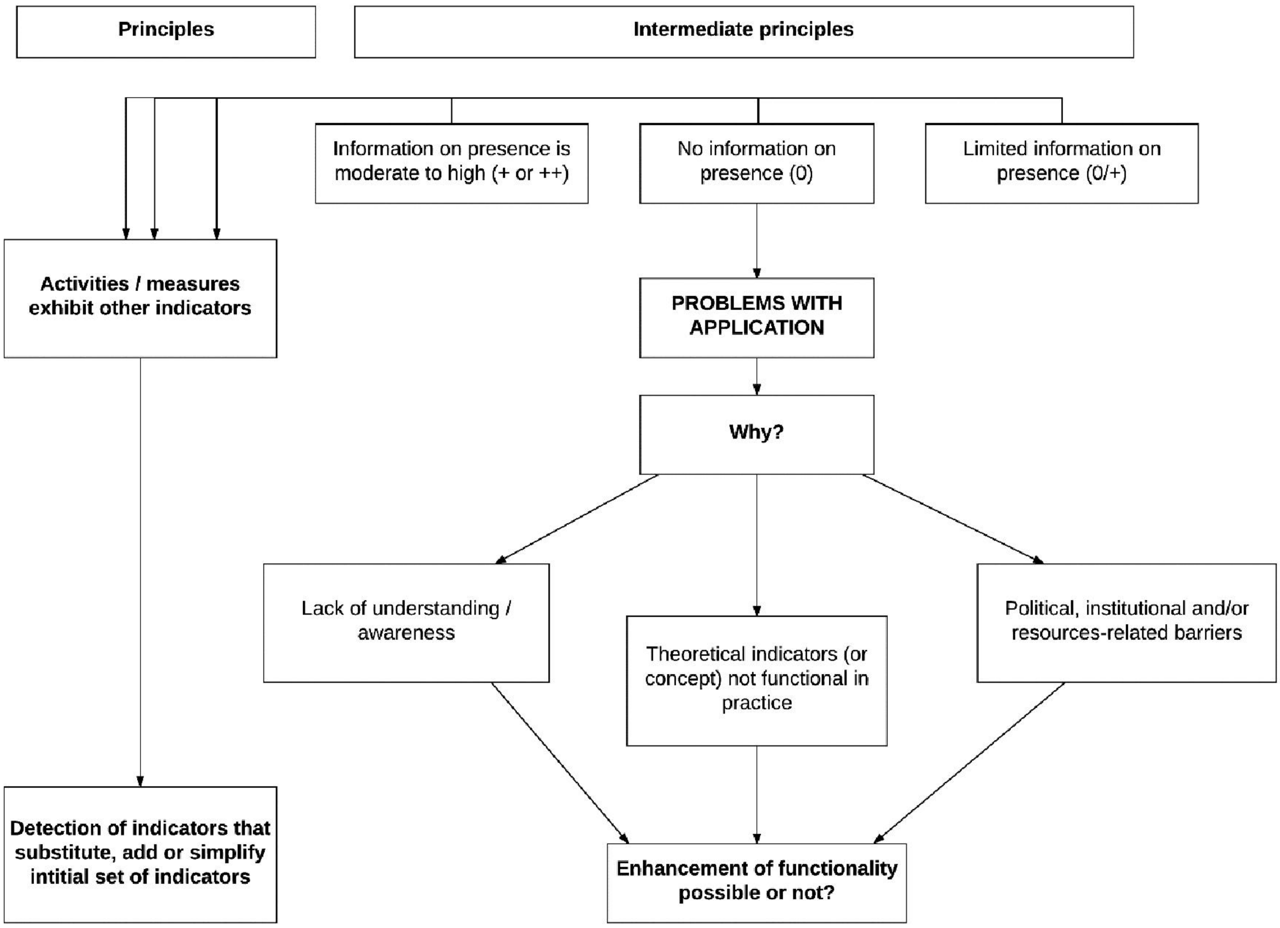

Fig. 4.2: Schematic description of analytical process for determining enhancement potential of indicators

It is important to mention that these categories serve as a means to structure underlying problems for fulfilling principles. It is not the goal of this research to provide a full list of clearly outlined problems.
Depending on the underlying nature of the problem, it is established whether the indicators (or the whole principle) should be excluded from the framework or amended to improve its application in policy-making. Options for amendments are (1) adding information that makes them less abstract or simplifies them, (2) adding instructive indicators for guiding action (3) addressing the removal of reported barriers in additional indicators.

(2) Intermediate principles which yield different indicators than the ones previously established in the theoretical chapter, for instance due to a different practice. These cast doubt on the practicality of the existing set of indicators or outline alternative ways of implementing the principle not yet considered by the existing set, which can replace or add to existing indicators (see Fig. 4.2). New indicators detected for Rotterdam are subsequently included in the London case as a first instance for testing their wider applicability to other cases.

For depicting the results in the Matrix scheme, the following color code will be used:
Green – added indicator based on findings in the case studies
Orange – no indication of consideration or application in the respective case

The researcher's aim is to provide a tool that is as comprehensive as possible and covers all relevant issue areas detected in literature. However, the wide range of indicators makes it impossible to look at all of them in detail within the scope of this thesis due to time and resource constraints.
Therefore, it was decided to leave the intermediate principle inclusiveness & equity standards (Homeostasis) out of the empirical research. One reason for that is that some of its indicators reappear in other principles, such as Flatness (Broad participation, stakeholder engagement & inclusiveness) and High Flux (availability of and access to resources). Another reason for leaving out particularly this category is a practical one. The remaining indicators not covered in the research refer to transparency and accountability. They would require this thesis to delve into law (legally enshrined equal rights and entitlements) and transparency of financial expenditures of institutions. These issue areas did not tie in well with the existing set of questions and were considered too detached from the domain of flood risk management.
In addition, the following general indicators were left out of the research scope due to their irrelevance for flood risk management or for their vague links to this field: indicators relating to food provision, crop diversification and heterogeneous population covering different occupations and expertise (functional diversity and spatial diversity of critical functions).

5 Results: Case study Rotterdam

5.1 Presentation of results per principle in matrix

5.1.1 Anticipation & Foresight

Intermediate Principle: Building knowledge		
Indicators	AoI[5]	Sources
Existence of (regional and city-wide) climate change-related projections, forecasts and scenarios	++	Interview R16, R20, R7, R10 OECD 2014; Royal Netherlands Meteorological Institute 2015
Identification and assessment of climate-related hazards, probability of occurrence, system's exposure, city-wide impacts and associated risks	++	Interview R2, R3, R5, R7, R11, R12, R18; RAS; RWP 2 (Municipality of Rotterdam et al. 2007); Knowledge for Climate Program (Wageningen UR et al. 2014); Kennisportaal Ruimtelijke Adaptatie (2015a)

[5] Meaning amount of information

Mapping of economic assets, critical functions (hospitals, police stations etc.), commercial and manufacturing establishments in flood-prone areas	+	Interview R7, R10, R17, R18

Intermediate Principle: Monitoring of slow variables		
Indicators	AoI	Sources
Flood risk monitoring systems are in place	++	Interview R7, R10, R11, R20; Veiligheidsregio Rotterdam-Rijnmond 2009; Rijkswatertaat 2012
Monitoring of dikes and flood-protective infrastructure meeting the safety standards	++	Interview R6, R9, R10, R17, R20; Rijskwaterstaat 2015
Periodic analysis and inspection of crucial infrastructure (transport, electricity networks, telephone lines, water supply, drainage systems)	++	Interview R7, R10, R15; TNO et al. 2013; Luijf & Ruijven 2016; Buren et al. 2012
Water storage capacity and volume of the sewer system / water system	++	Interview R1, R2, R5, R8, R9, R17; RWP 2
Amount of permeable, impermeable, semi-permeable surfaces in city	+	Interview R2, R13, R17
Population density and growth	0/+	RAS
Soil type and subsidence	+	Interview R8, R12, R17; RAS
Coastal erosion	0/+	Interview R18; Rijkswatertaat 2012
Sea level rise	+	Interview R7, 10, R18

Intermediate Principle: Information management & sharing		
Indicators	AoI	Sources
Access of governance units and organizations to global (scientific) data such as climate scenarios, models etc.[6]	+	Interview R7, R10, R11, R17
Tools and mechanisms for information storage and sharing (i.e. data archives, open access, policy documents) accessible for all employees over time, across institutional borders and between public and private entities[7]	++	Interview R2, R5, R11, R12, R16, R17, R20; RRS; RAS (City of Rotterdam 2013), RCP (Rotterdam Climate Initiative 2013), RRS (Municipality of Rotterdam et al. 2016), RWP 2, Magazine Delta Rotterdam (Municipality of Rotterdam 2016), Connecting Delta Cities Publications (Molenaar et al. 2013), DP Publications, PBL and TNO reports; Rotterdam Centre for Resilient Delta Cities (RDC) (2015)
Presence of platforms of exchange among actors across institutional boundaries (policy officials, municipality representatives, project coordinators)	++	Interview R3, R7, R10, R11, R19, R20

Intermediate Principle: Learning from past hazard experience		
Indicators	AoI	Sources
Presence of accessible long-term track records of previous flooding events and disturbances	+	Interview R1, R8, R9, R20
Lessons learnt from previous flooding events are formulated into tangible, accessible, evaluative reports	+	Interview R9, R10, R11, R18

[6] Also part of the principle Flatness / intermediate principle: Room for autonomous change

[7] Also part of the principle Flatness / intermediate principle: Room for autonomous change

Lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms	++	Interview R1, R5, R6, R9, R11, R18, R20

5.1.2 *Preparedness & Planning ahead*

Intermediate Principle: Public awareness, risk communication, education & training[8]		
Indicators	AoI	Sources
Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations	+	Interview R6, R7, R8, R9, R10, R18; Overstroom ik? Website (Rijkswaterstaat n.d.); NWP (Ministry of Infrastructure and the Environment 2016)
Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action for flooding events (e.g. guidance for preparation and appropriate response)	0/+	
Hazard awareness, safety education programs and response training to neighborhood and community organizations	0	Interview R5, R11

Intermediate Principle: Response & Emergency Management		
Indicators	AoI	Sources
Presence of a flood forecasting and early flood warning system	++	Interview R4, R5, R7, R8, R10, R20; Veiligheidsregio Rotterdam-Rijnmond 2009; Rijkswaterstaat 2011a; Rijkswatertaat; 2012
Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies	+	Interview R10, R11, R20 Luijf & Ruijven 2016
Prevalence of flood management plans, hazard mitigation plans, emergency response plans and contingency protocols	++	Interview R11, R19, R20; Regionaal Crisis Plan Rotterdam-Rijnmond (Veiligheidsregio Rotterdam-Rijnmond 2014b); Regionaal Coördinatieplan Overstromingen (RCO); Gecoördineerde Regionale Incidentenbestrijdingsprocedure Rotterdam-Rijnmond (Veiligheidsregio Rotterdam-Rijnmond 2014a); Luijf & Ruijven 2016
Presence of evacuation plans, designation of evacuation routes and shelter capacity	+	Interview R7, R10, R15, R19; RRS (Municipality of Rotterdam et al. 2016)
Training and capacity building on risk communication for responsible authorities	0	

Intermediate Principle: Preparedness of businesses for adverse events		
Indicators	AoI	Sources
Governing authorities provide companies with (online) tools (i.e. climate scenarios, flood maps), (water-related) knowledge and workshops for climate adaptation, flood risk mitigation and preparation	0/+	Interview R7, R10, R11, R15

[8] All indicators are also part of principle Flatness / Room for autonomous change (chapter 5.1.7)

Presence of issue-specific formal or informal networks for exchange of best practice and knowledge generation	0/+	Interview R12, R15
Companies factor the impacts of climate change into their business practice (for instance by having business continuity and contingency plans in place)	+	Interview R7, R12, R15
Businesses have an understanding of potential climate change related threats, associated risks and vulnerabilities in the business operation as well as opportunities	+	Interview R7, R14, R15

5.1.3 Homeostasis

Intermediate Principle: Preservation and restoration of regulating ecosystem services		
Indicators	AoI	Sources
Policies and plans for natural areas and ecosystem restoration	+	Interview R2, R13, R18, R20
Increasing / creating urban green spaces on public and private property and (re)implementing urban floodplain wetlands	++	Interview R2, R13, R16, R18, R20; RAS, RCP; DP Rhine-Meuse Delta (Ministry of Infrastructure and the Environment et al. 2012)

Intermediate Principle: Integrated planning, coordination & collaboration		
Indicators	AoI	Sources
Creating institutional and organizational structures that promote integrated knowledge sharing between departments, management authorities and across different scales	0	Interview R2, R7, R12, R13
Provide for flexible budget investment mechanisms in organizations and municipal departments	0	Interview R1, R9, R12; RRS
Promote cross-sector collaboration and arrangements for sharing of (confidential) knowledge and information between sectors	0/+	Interview R2, R13; RRS: Infrastructure ready for the 21st century
Presence of leadership driving cross-departmental collaboration and projects forward	0/+	Interview R2, R7
Integration of climate adaptation and water safety into other sectorial policies via anchoring in standards or (national) laws or by harmonizing regulations / policies across sectors and policy areas or creating control mechanisms for spatial planning along the lines of flood protection	0/+	Interview R4, R7, R8, R9, R12, R13, R18
Creating co-benefits to connect agendas of different policy domains	++	Interview R2, R7, R12, R13, R14; RAS, RCP, RWP 2
Presence of a formalized, common vision underlying planning and implementation of projects	+	Interview R2, R16, R20; RAS
Linking urban (re-) development, planning processes, maintenance programs and other ongoing projects	+	Interview R1, R5, R9, R12, R13, R15; RRS

Intermediate Principle: Inclusiveness & equity standards
It was decided to leave out this category in Homeostasis for this research since it will be taken up at a later stage with Flatness (broad participation, stakeholder engagement & inclusiveness) and High Flux (availability of and access to resources)

Intermediate Principle: Clearly defined responsibilities of actors and institutions		
Indicators	AoI	Sources
Responsibilities are clearly defined and allocated for causing and solving water-problems, sewage systems	+	Interview R7, R18, R20; RWP 2; Runhaar et al. 2014
Cross-institutional division of labor and tasks for performing emergency response activities	++	Interview R4, R9, R10, R11, R19, R11; Regionaal Coördinatiplan; Overstromingen, Coordinatieplan Dijkringen 14, 15 en 44; Beleidsplan, Gecoöridneerde Regionale Incidentbestrijdings-procedure (Veiligheidsregio Rotterdam-Rijnmond 2009; Veiligheidsregio Rotterdam-Rijnmond 2012; Veiligheidsregio Rotterdam-Rijnmond 2014a)
Statutory responsibility for flood prevention and protection is defined and determined in policy documents	++	Interview R1, R6, R8, R9, R18; Rijkswatertaat 2012; Rijkswaterstaat 2011b Starflood Country Report NL (Kaufmann et al. 2016)
Legal responsibilities for property damage caused by flooding events are clearly defined	+	Interview R7, R8, R15; RWP 2;
Insurability of private property against flood loss	0/+	Interview R8, R7
Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery	0	Interview R6, R7, R13, R15; NWP

Intermediate Principle: Quick notification of disturbances and shocks		
Indicators	AoI	Sources
Presence of a flood and weather forecasting, early warning system to generate timely information and facilitate anticipation and forecasting	++	Interview R4, R5, R7, R8, R10, R20; Veiligheidsregio Rotterdam-Rijnmond 2009; Rijkswaterstaat 2011a; Rijkswatertaat 2012
Use of centering and remote sensing techniques in dikes to observe system behavior	0/+	Interview R20
Variety of broadcast technologies (internet, mobile phone, telephone, newspaper, TV, radio, public broadcasts in the street) used for communicating flood warnings	0/+	Interview R20; Luijf & Ruijven 2016

5.1.4 Robustness & Buffering

Intermediate Principle: Robustness through infrastructure		
Indicators	AoI	Sources
Presence of flood-protective structural measures and installations	+	Interview R1, R6, R7, R8, R9
Presence of formalized water safety / dike standards that are regularly monitored	+	Interview R1, R4, R9, R10; Rijkswatertaat 2012
Periodic assessment, optimization and improvement of flood-protective infrastructure	++	Interview R1, R6, R9, R10, R18; DP Rhine – Meuse Delta (Ministry of Infrastructure and the Environment et al. 2012); RWP 2
Impacts of flooding events on critical infrastructure and urban public utility networks are assessed (i.e. water system, flood defenses, drinking water, transport systems,	++	Interview R6, R7, R9, R10, R15, R20; Quick-scan studie resilience of the water system (Luijf & Ruijven 2016); Investigation of the blue

gas, ICT, port), vulnerabilities and system failure factors identified and pre-emptive measures and response strategies for maintaining functions developed		spots in the Netherlands National Highway Network (Buren et al. 2012); RAS; Rotterdamse Adaptatiestrategie Themarapport (Buijs & Streng 2013); RRS: Infrastructure ready for the 21st Century; TNO et al. 2013; Rijskwaterstaat 2015

Intermediate Principle: Creating buffer capacities		
Indicators	AoI	Sources
Implementation of additional levees, canals and water arms	+	Interview R8, R16; RAS
Improving (natural) water infiltration and storage capacity, for instance by increasing above and under-ground (rain)water storage and capture mechanisms, (re)creating urban floodplain wetlands and green spaces or using permeable paving	++	Interview R2, R5, R8, R9, R10, R13, R16, R18, R20; RRP; RWP 2; RAS; RRS
Increasing the percentage of floodable areas, for instance by widening river and polder beds, deepening basins, installing emergency basins or temporarily inundating agricultural and nature areas	+	Interview R9, R10, R18, R20; RRP
Increasing the drainage capacity of the urban water system, for instance by enlarging sewerage pipes, installing larger pumping stations or higher capacity pumping stations in the water system, enlarging precipitation channels or implementing design standards for shorter return periods of storm water events	+	Interview R4, R5, R20

Intermediate Principle: Impact- and risk-reducing planning & planning practice		
Indicators	AoI	Sources
Limiting development rights in flood plains and areas at risk from flooding (flood zoning); Prohibiting (property) development in flood-prone areas; Introduction of permits in flood-prone areas; Relocating property from flood-prone areas and inhibiting new development	0	Interview R6, R12
Flood-proofing and flood-resilient design and construction standards for buildings, public facilities and assets	0	Interview R7, R9, R12, R18
Elevation of ground level in urban flood-prone areas and roads (according to a determined minimum level)	++	Interview R5, R7, R8, R10, R16, R17; RAS
Flood-risk conscious interior design and appropriate planning	0/+	Interview R6, R7, R15
Lowering water levels in the water system by pumping water out of the system ahead of an anticipated cloudburst or precipitation event	+	Interview R5, R7, R8, R20

5.1.5 Diversity

Intermediate Principle: Functional & response diversity		
Indicators	AoI	Sources

Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people)	0	
Variety in energy systems using different energy sources which can be generated at different scales (local, regional, global)	0	RRS: diversifying energy sources in the Rotterdam Port area
The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated	?	Could not be answered during this research
Parallel existence of different land-use types in cities	?	Could not be answered during this research
A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization	0/+	Interview R6, R9, R10, R18
Diversity in types of flood protection interventions (preventive alongside adaptive measures) and water absorption mechanisms (i.e. sewer, water storage, permeable paving, public and private green spaces)	0/+	Interview R2, R7

Intermediate Principle: Spatial diversity of critical functions		
Indicators	AoI	Sources
Financial institutions, economic activities, hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city	0	Interview R7, R11
Decentralized flood protection infrastructure	+	Interview R1, R6, R9

Intermediate Principle: Actor & stakeholder diversity		
Indicators	AoI	Sources
Variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process Different government and non-governmental stakeholders are involved in setting the TOR and/or consulted	+	Interview R1, R3, R8, R10, R12, R14, R15, R18; RAS; DP Spatial Adaptation (Focus: Critical infrastructure); RRP; Water Plaza
Actors and stakeholders involved in decision- and policy-making have differing professional and knowledge backgrounds	+	Interview R1, R2, R6, R16
Different problem frames and policy solutions for urban flooding	+	Interview R3, R4, R7, R12, R20

Intermediate Principle: Institutional diversity, multi-level governance systems & linkages		
Indicators	AoI	Sources
Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)	+	Interview R1, R6, R9, R12, R18
Distributed flood-response capacity across levels (households, communities, municipalities)	0	
Governing authorities involved in flood risk management differ in size, culture, internal structure	0/+	Interview R10, R12, R18, R20

Presence of formal and informal partnerships between governing authorities, academia, firms and NGO Presence of platforms of exchange among (governmental and non-governmental) actors operating at different levels	+	Interview R3, R7, R10, R11, R19, R20

5.1.6 Redundancy

Intermediate Principle: Overlapping functions & roles		
Indicators	AoI	Sources
Shared responsibilities, rights and management authorities among responsible institutions across scales	+	Interview R7, R9, R11, R18, R20
Decentralized water and flood risk management with governing authorities distributed across scales (local, regional, national level)	+	Interview R1, R6, R9, R12, R18
Constant group of people participating in projects and the creation of policy documents; Working groups / project groups integrate multiple actors (shared knowledge)	+	Interview R2, R7, R11, R16
Flood risk mitigation measures are taken by public and private organizations and actors	+	Interview R2, R4, R18, R20

Intermediate Principle: Functional redundancy in important functions & services		
Indicators	AoI	Sources
Several transmission towers to sustain communication, multiple counterparts for vital functions, multiple routes of supply, electricity and sewage removal, multiple access and evacuation routes	0	Interview R7, R10, R15
Provision of redundancy mechanisms in critical infrastructure (i.e. water system, electricity, ICT sector, transport networks)	++	Interview R4, R7, R9, R10, R16, R20; Luijf & Ruijven 2016; Runhaar et al. 2014

Intermediate Principle: Spare capacities & back-up resources		
Indicators	AoI	Sources
Alternative power supplies and energy back-up generators for all key businesses, critical infrastructure and services	+	Interview R10, R11, R20; Luijf & Ruijven 2016
Maintaining stocks and provision mechanisms for food, medicine, water supplies in case of disruption	0	Interview R11, R15, R19

Intermediate Principle: Compartmentalization & modularity		
Indicators	AoI	Sources
Presence of polycentric, multi-level governance systems	+	Interview R1, R6, R9, R12, R18
Communication, transport networks, infrastructure grids and other vital functions and services in cities are based on a modular network structure	0/+	Interview R15
Presence of compartmentalization dikes, dike rings, compartmentalized polders, temporary dams or flood defences that prevent floodings from spreading to other regions or locally retain substances	+	Interview R7, R9, R18, R20; RAS

5.1.7 *Flatness*

Intermediate Principle: Decentralization & Autonomy		
Indicators	AoI	Sources
Governing authorities involved in water and flood risk management are distributed across scales	+	Interview R1, R6, R9, R12, R18
Municipal authorities have the autonomy to authorize plans and legislate policy; Autonomous management capacity and ability to autonomously develop own strategic goals, tailor-made policies and measures	+	Interview R4, R9, R12,R18, R20; National Spatial Strategy (Ministry of Infrastructure and the Environment 2011)
Financial independence of governing bodies	+	Interview R9, R12, R18
Shared responsibilities, functions and management authorities among responsible institutions for water governance	+	Interview R9, R11, R18, R20

Intermediate Principle: Broad participation, stakeholder engagement & inclusiveness		
Indicators	AoI	Sources
Presence of open, deliberative forums or platforms of exchange between actors (policy officials, municipality representative, project coordinators, local population)	++	Interview R1, R3, R8, R10, R12; RRP; DP Spatial Adaptation; RAS, RRS; Zoho District Climate-Proof (De Urbanisten 2015); de STRAADkrant (Bosch Slabbers Landschapsarchitecten et al. 2016)
Non-governmental stakeholders are involved at an early stage in the planning & design process contribute to developing solutions, for instance by means of co-creation spaces or public contests that facilitate individual inputs of ideas or the presence of small-scale adaptive measures in public space which offer room for broad participation[9]	++	Interview R2, R3, R16, R17, R20; de STRAADkrant, Zoho Climate Proof Initiative; RAS, RRS: National Innovation Challenges
Designing varied local and context-specific mitigation approaches based on neighborhoods consultation and collaboration and needs assessment	+	Interview R2, R3, R16, R20; de STRAADkrant
Legal provisions concerning access to information, participation in decision- making (e.g. consultation requirements before decision-making) and access to courts	0/+	General Administrative Law Act, Access to Information Act (Kaufmann et al. 2016)

Intermediate Principle: Room for autonomous change		
Indicators	AoI	Sources
Including indicators from chapter 5.1.1 (Information management & sharing) and chapter 5.1.2 (Public awareness, risk communication, education & training) – see footnotes		

[9] It needs to be mentioned that the participation of citizens in the early stages of projects is mostly confined to creating additional water storage, for instance through the water square or greening of private properties. However, these are mostly pilot projects. With regards to coastal or riverine flooding, involvement was only indicated to occur when it comes to dike reinforcement projects which involve private property. Consequently deliberative forums or platforms of exchange are usually limited to policy officials and do not systematically include the local population.

Public awareness, education programs, and hands-on showcases concerning water management approaches with respect to climate change impacts	+	Interview R3, R18, R20
Providing solutions, tools and guidance for small-scale (storm-water-related) measures on private property (i.e. urban wetland, storage facilities for rainwater)	+	Interview R2, R4, R12
Affected communities / population are provided guidance on flood-resilient construction	0	Interview R5, R7, R19
Procedures that enable groups to form legal voluntary organizations, raise funds or subsidies for residents' or community-led initiatives and autonomous small-scale projects and provide required venues and space for developing them	++	Interview R2, R3, R8, R12, R13, R16, R18, R20; RRS: Rotterdam Network City

5.1.8 High Flux

Intermediate Principle: Availability of and access to resources		
Indicators	AoI	Sources
Pre-event arrangements for governmental reimbursement, such as national contînency funds or damage compensation payments	0/+	Interview R4, R7, R9, R11, R19;
Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock	0	
Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems; Reduction of irreversible commitment of resources	0	
Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs)	0	Interview R7, R6, R8
Quick mobilization of human resources for disaster response (due to standby mode and rapid operational readiness)	+	Interview R4, R11, R18, R20
Presence of fixed protocols (in calamity, continuation, recovery plans) with clearly defined tasks in the chain of emergency responders	+	Interview R9, R10, R11, R18, R20
Tools for swift visualization of flooding scenario and impacts and accessible knowledge base about the affected area, the water system and its reaction to hazards	+	Interview R7, R9, R11, R15; TNO et al. 2013; Mandaag & Verhoek 2016

Intermediate Principle: Social & institutional networks		
Indicators	AoI	Sources
Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs	+	Interview R3, R7, R10, R11, R19, R20
Prevalence of platforms of exchange among actors such as workshops, congresses, city labs	+	Interview R10, R12, R20;

		Rotterdam Climate Initiative; Resilient Delta Cities (RDC); 100 RC Network; C40; URBACT network: Resilient Europe; RRS: Rotterdam Network City
Presence of local, community-level projects that improve social cohesion and maintain connections between different groups of people	+	Interview R2, R3, R18; RRS: Program We-Society ; Zoho Climate Proof
Governing authorities connect, strengthen existing networks, community-led initiatives and contribute to the emergence of new ones	0/+	RAS; RRS: Program We-Society
Partnering with community leaders with broad social networks and existing initiatives to improve stakeholder engagement	+	Interview R2, R3, R12; Rotterdam Exchange Initiative / Resilient Delta Cities (Municipality of Rotterdam et al. 2015)

Intermediate Principle: Having options for flexibility in response		
Indicators	AoI	Sources
Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required; Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it	0	
Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes; Communities' livelihood strategies are not confined to a single economic resource	?	Could not be answered during this research
Financial mechanisms for fostering (local) business development and innovation	0/+	Interview R18
Developing education, leadership, entrepreneurship programs and curricula aiming at skills development in rapidly changing contexts	0/+	RRS: Education program 21st century skills & Roadmap to the next economy; Nationaal Programma Rotterdam Zuid (Programmabureau NPRZ 2015)
Authorities involved in flood-risk management and response have mobile resources for flood mitigation at their disposal (i.e. pumps, removable flood walls, slide-in wooden tiles to be inserted into the structure)	+	Interview R6, R19, R20

Intermediate Principle: Managing connectivity of critical sectors, infrastructure and natural habitats		
Indicators	AoI	Sources
Critical points for accessibility to critical infrastructure during adverse events are identified and pre-emptive measures and response strategies for maintaining functions are developed	++	Interview R6, R7, R9, R10, R15; RAS; Buijs & Streng 2013; Buren et al. 2012; Luijf & Ruijven 2016; TNO et al. 2013; Rijskwaterstaat 2015
Spatial intersections of networks with other infrastructure systems and potential cascading effects to other systems are identified and response mechanisms developed	++	Interview R7, R10, R11, R12, R15; RAS; RRS; Buijs & Streng 2013
Connecting habitat patches and creating blue corridors (i.e. new water networks from existing and new canals)	+	Interview R16; RCP; DP: Rhine-Meuse Delta, RWP 2

5.1.9 Learning & Reflectivity

Intermediate Principle: Institutional learning capacity & reflectivity		
Indicators	AoI	Sources
Institutions are monitoring their activities and performance and critically evaluate implemented polices	++	Interview R6, R9, R10, R12, R13, R16, R17
Institutions adopt new routines, patterns of collaboration and engage new stakeholders in projects	++	Interview R2, R3, R4, R7, R8, R20
Iterative revision and updating of plans, strategies and standards based on emerging information and research (i.e. climate scenarios)	++	Interview R4, R7, R9, R17, R18, R20; RAS
Participatory co-learning approaches by providing spaces for learning, through exchange of perspectives in workshops, practice sessions, discussions	+	Interview R2, R7, R11, R12, R20
Learning outputs inform policy changes and amendments	+	Interview R6, R9, R16, R20; DP, RRP, NWP, RCP

Intermediate Principle: Experimentation & Innovation		
Indicators	AoI	Sources
Small- and large scale experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts which are financially supported	++	Interview R2, R3, R4, R13, R15, R16, R18, R20; RAS; RCP
Creation of testing grounds and support for ‘informal space’ to experiment and innovate (i.e. living labs, research laboratories)	+	Interview R20; Aquadock Heijplaat (Municipality of Rotterdam 2016); Concept House Village at RDM campus (RAS)

5.1.10 Flexibility

Intermediate Principle: Institutional flexibility		
Indicators	AoI	Sources
Institutions offer room for changing the procedures and cooperation arrangements if required	+	Interview R3, R7, R8, R20
Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon and goals of strategies and activities	+	Interview R2, R3, R4, R12
Decision-making processes allow for a change in speed and actor composition	?	Could not be answered during this research

Intermediate Principle: Flexibility in spatial planning		
Indicators	AoI	Sources
Development of multi-use spaces or convertible structures that allow for short-term and long-term shifts in the use of space, parcels, buildings	+	Interview R1, R6, R16, R18; RAS
Spatial design allows for additions or deletions to the quantity of space and land dedicated to particular uses	+	Interview R4, R8, R18

Leaving spaces without development so that they can be used for other purposes	0	
Employing modular elements in buildings	0	
Reducing life-cycles of buildings and infrastructure	0	

Intermediate Principle: Flexibility in measures		
Indicators	AoI	Sources
Employing no-regret measures in climate adaptation apt for a broad range of possible future scenarios	+	Interview R12, R13, R18; RAS
Urban planning, disaster risk management, climate adaptation strategies and respective policy development account for a long-term planning horizon (i.e. looking at spatial function, life-cycle of utilities and renewal period)	++	Interview R7, R8, R9, R10, R12, R13, R18; DP; RAS
Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: designing measures for reversibility	0/+	Interview R12, R13, R18
Reducing irreversible commitment of financial resources by broadening measures	0	
Implementing policies that allow for a strategy change and amendments in agreements rather than legislative acts	0/+	Interview R12, R18
No one-fits all solution but consideration of alternatives which include small- and large-scale structural and non-structural measures (i.e. combination grey with green measures) based on local context	++	Interview R2, R3, R4, R5, R10, R13, R18; RAS, RRS

Table 5.1: Matrix of results per principle for Rotterdam

5.2 Problem indicators (orange)

5.2.1 Preparedness & Planning ahead

5.2.1.1 Public awareness, risk communication, education & training and response & emergency management

Hazard awareness, safety education programs and response training to neighborhood and community organizations; Training and capacity building on risk communication for responsible authorities

In Rotterdam, flood risk education for the wider public does not go beyond providing flood risk information. There are several reasons why hazard awareness and response trainings are absent.
First, the odds of the occurrence of flooding events in the inner-dike areas of Rotterdam is rather low and major events have not occurred since 1953 so that social memory and learning is limited (Interview R5, R8, R9, R10 and R18). "*So these type of incidents are really really rare it is like once in 10,000 to once in 100,000 years. That's actually why people are totally not aware of flood risk in this region. That's a good thing, also a bad thing*." (Interview R7).
Second, this tendency is a product of the technocratic water management regime anchored in institutional structures. Since flood risk management is traditionally located within the public domain, citizens expect the

national government to take care of flood risk mitigation. Therefore, limited response of people to such measures is expected which has justified political passivity in this regard (Interview R5, R7 and R9).

A wake-up call came with an OECD report on the water and flood risk management system which attested public flood risk awareness to be poor in the Netherlands. "*The OECD made a study of our water management system in 2014 and they said you are quite fit for the future, however you should be aware of the lack of public awareness, people take it all for granted, and are not prepared and resilient in a way that they can know what you expect them to do, they don't know. Somewhat less for the people that live outside the primary defense, they know if high water comes, they have to take actions but people behind the primary defense, even cloudbursts, they don't know what to expect, what to do, how to make their own arrangements. So that is one thing the NL has to do.*" (Interview R9)
The national government has responded to this deficit by declaring improving public flood risk awareness and preparedness a focal priority for this political period and integrating in into the most recent NWP a major objective (Ministry of Infrastructure and the Environment 2016). One interviewee points out the change that is required in the mindset of Dutch citizens for crisis management to be effective. "*The people themselves don't want to leave their homes, especially when the dikes are still intact they say well there is threat but why should I leave. So you have to prepare the mindset of the people that they are capable of evacuating anyway*." (Interview R18)

Given these recent developments and the awareness of the majority of interviewees of the need to improve public flood risk awareness, the development of respective instruments can be expected and no improvement of indicators is required.

5.2.2 Homeostasis

5.2.2.1 Clearly defined responsibilities of actors & institutions

Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery

The absence of this indicator from the Rotterdam case can be explained with the reasoning above (see chapter 5.2.1.1):

5.2.3 Robustness & Buffering

5.2.3.1 Impact- and risk-reducing planning & planning practice

Limiting development rights in flood plains and areas at risk from flooding (flood zoning)
Prohibiting (property) development in flood-prone areas
Introduction of permits in flood-prone areas
Relocating property from flood-prone areas and inhibiting new development

The discussion of the absence of above mentioned indicators needs to be located in the broader context of spatial planning governance and perceptions of hard versus soft law.

Spatial planning is decentralized in the Netherlands and the implementation of planning decisions mostly relies on municipalities and the province which are equipped with a considerable level of autonomy. The tendency is to make use of soft law instead of top-down regulation (Government of the Netherlands 2014; Ministry of Infrastructure and the Environment 2011). In addition, it is argued that a current "*strong tendency for less regulation*" counteracts ambitions to "*propose extra standards or regulation*" (Interview R12).
As a consequence, there are no permits or other regulations to limit development in flood-prone areas. Restrictions are not considered feasible since they are believed to be overruled by property developers and the real estate sector. "*In the NL where houses are going to be built or not there are all kind of factors which are important for this decision but they are not coming from the water sector except for situations where it is very clear that you should not build there. But even then, there are all kinds of places in the NL where parts of cities should not have been built on these spots but they have*." (Interview R12)

Flood-proofing construction codes and standards for buildings and public facilities

Since climate adaptation is mostly the domain of spatial adaptation, there are no legal instruments to influence decisions of landowners or property developers with respect to climate adaptation and mitigating flood risk (Kaufmann et al. 2016; Interview R8). "*We are still in the phase to convince all these parties to think about adaptation. It is a practice which should develop so before there is any legislation needed […] There are all kinds of acts and by-laws so we have to see if there is any change needed in the upcoming years because of climate change but we cannot say that yet.*" (Interview R12)
It is worth mentioning that flood-proofing measures, such as raising ground elevation, using watertight building materials or building compartment dikes around critical units by some interviewees are not considered necessary in areas protected by the primary dike system. *"From a flood management perspective there is almost no urgency to invest into spatial adaptation because I am not going to adapt buildings to make them more safe, or hospitals, because we already have this very strong dike system and I already told you this protects us for situations 1 in 10,000 years* […] *but you still have to look into this redundancy principle you just mentioned, we also have to look into our hospitals, not to adjust them or make them flood-proof but more like if things go wrong and we have a flood incident what are we going to do with our crisis management then."* (Interview R7)
More general, there is a divide between the water, the spatial planning sector and the municipal departments and even within those entities when it comes to enshrining water safety and flood-proofing measures into law. Several interviewees believe that legal standards and norms can fasten the process of climate-proofing along with mainstreaming climate adaptation, specifically with regards to construction and spatial planning activities (Interview R7 and R8). Officials in the water sector for instance are in favor of hard law, which is represented in the tendency to legally enshrine water standards.
Similarly, the integration of building permits and standards in national legislative acts are stated to be required by municipal officials since city governments are not allowed to add additional requirements to national regulations and therefore current "*legislation or building policies [cannot] handle these local types of measures*" (Interview R7 and R13).

It turns out that the above mentioned indicators are subject to discussion, though not yet being applied in Rotterdam. Therefore, they are deemed valid and do not need improvement.

5.2.4 Diversity

5.2.4.1 Functional & response diversity

Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people);
Variety in energy systems using different energy sources which can be generated at different scales (local, regional, global)

Although Rotterdam generally provides for a diversity of transport options with bus, train networks and waterways, there is no strategic planning for diversification with regards to particular modes of transport compensating for others in the face of a flooding event. This is mostly because of an identified lack of awareness of this principle although preparatory measures are identified.
TNO, the Rotterdam Climate Initiative and RWS made investigations into failure mechanisms of different means of transport (highways, roads, waterways, air transport etc.) (TNO et al. 2013; Buijs & Streng 2013; Buren et al. 2012). Therefore, there is knowledge about which stretches of roads and highways are flood-prone, and about flooding impacts on the operation of water, land, air transport and the port of Rotterdam. However, these efforts revolve around vulnerabilities and therefore rather reflect the principle of robustness (as will be outlined in more detail in chapter 5.3.4.1). However, current information is not advanced enough to determine which transport means could stay operational and therefore compensate for failure of others. *"How bad will be the effects and can other areas or other parts of the system just take it over or not? We still don't know the answer, it takes a few years."* (Interview R10)
With regards to diversification of food supply, self-sufficiency via local, urban farming is an issue area touched on with urban greening initiatives under the umbrella of other concepts. Thus, diversification might be a beneficial by-product but not at a stage where food supply is considered to be able to compensate for the outfall of external food supplies (Interview R2, R8; Bosch Slabbers Landschapsarchitecten et al. 2016).
In the Rotterdam Resilience Strategy (following RRS), there is mentioning of diversifying energy sources by developing an energy mix in the Rotterdam port and the city in order to make the urban energy infrastructure more flexible (Municipality of Rotterdam et al. 2016). However, the underlying aim is sustainability, the use of alternative, sustainable energy to reduce carbon emissions rather than providing substitutes in case of outfalls.

Going beyond the general indicators and specifically looking at flood risk management, diversity in measures is not a priority[10]: "*The NL is built on prevention and the WA has a saying that we also have multi-layer-safety, first layer is prevention, second is prevention and third layer is also prevention. So variety I don't usually think about that so much"* (Interview R9)
In addition to its allegedly limited adoption, associations of respondents with functional diversity exhibit a lack of understanding of the concept itself. With regards to water management, several interviewees pointed out the variety and versatility of context- and local-specific measures for flood protection which tends towards flexibility of measures (in the adaptation phase) instead of representing functional diversity for absorbing disturbances (Interview R4, R5 and R16). Diversity was also associated with water-related spatial planning according to differing physical features of the urban landscape (Interview R5 and R16) and different types of

[10] See indicator: A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization in chapter 5.1.5.

dikes that provide water safety[11] (Interview R4 and R18), neither of which qualifies as functional diversity. Moreover, diversity was also referred to as the strategic framing of flood-protective interventions to provide several co-benefits (other functions: social, economic etc.). "*If we had only said that green roofs were made to solve water issues they would not be subsidized by the city of Rotterdam and WB. The politics became interested because the green roofs both added green, are good for isolation and are something owners of houses can do for themselves*." (Interview R16).
Associations with functional diversity reflect an ad-hoc tailoring of diversity to current practice instead of an intentional application of the principle in its original sense.

5.2.4.2 Spatial diversity in critical functions

Financial institutions, economic activities, hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city

This indicator is among the ones absent from current planning practice in Rotterdam. According to several respondents, adopting spatial diversity in critical functions into practice is problematic. Especially for densely built cities which have grown organically without considering the strategic location of vital infrastructure, required post-interventions into these structures are unlikely and costly (Interview R7 and R11). "*I have been in work groups to train people how to act in emergency situations. It was very interesting and I remember one of those trainings, where we divided certain groups for areas that are part of the problem. And one of the group was looking for emergency areas, so now we have to evacuate a part of the country. How do we get those people into the evacuation area? Is there a building or facilities available and also are there roads available to get there? It was eye-opening, we never planned for that. Most of the cities grow organically, with the buildings and places to live. That kind of understanding, you hardly see that*." (Interview R8)
However, data unravel that the functionality of this indicator is not required since there is a compensatory practice in place which will be further outlined in chapter 5.3.5.2. These findings provide ground for removing this indicators from the framework in case it also proves non-functional for the London case.

5.2.4.3 Institutional diversity, multi-level governance systems & linkages

Distributed flood-response capacity across levels (households, communities, municipalities)

The absence of this indicator can be traced back to the reasoning provided in chapter 5.2.1.1.

Governing authorities involved in flood risk management differ in size, culture, internal structure

In the Netherlands the water governance system combines functional democracies with central, provincial and local authorities (OECD 2014). There are several governance authorities on different levels: RWS (national), the IenM (national), the Province (regional) and WBs (local, same level as municipality). When it comes to flood risk management, the municipality and the safety region Rotterdam-Rijnmond also play a role. These governing

[11] Different types of dikes that have different ways of absorbing disturbances, such as unbreachable Delta Dikes that can only be overtopped by water as opposed to conventional dikes, which are higher and have known failure mechanisms, do represent functional diversity but in a very restricted way, since the approach (i.e. prevention) is the same.

bodies do differ in size, culture and internal structure to a certain extent. However, with the current indicator it is unclear to what extent institutions need to differ in order to qualify for institutional diversity and are therefore able to contribute to resilience. This is an issue discussed and currently unresolved in the scientific resilience literature (Biggs et al. 2012; Biggs et al. 2014). At this point, the researcher cannot propose any solution to this shortcoming.
The indicator along with the concept of institutional diversity might be of use to determine a city' baseline conditions but is deemed unsuitable for policy-making and as an assessment criterion for adaptation plans in the case of Rotterdam. Specifically with regards to water management, governing authorities evolved over centuries, so that their structures are unlikely to change. It is also unlikely that new governing authorities will join their domain. Therefore, it seems very hard to steer development for attaining this indicator.

5.2.5 Redundancy

5.2.5.1 Functional redundancy in important functions & services

Several transmission towers to sustain communication, multiple counterparts for vital functions, multiple routes of supply, electricity and sewage removal, multiple access and evacuation routes

The analysis of results showed that the duplication of vital functions and services is not common practice in Rotterdam. This strategy is not pursued for reasons of cost-effectiveness since interviewees implied that a large investment in infrastructure which has a very low chance of being used (due to very high dike safety standards) is not justifiable.
With regards to multiple access and evacuation routes, several factors determine the absence of this approach. Since the road network has limited capacity in the Netherlands and there is not much room for expanding, creating additional evacuation routes is not a welcome option, especially against the backdrop of contested use of space (Interview R18). Furthermore, due to the anticipated short time frame for making decisions in case of a flooding event in Rotterdam, vertical evacuation (people seeking higher elevation points in their own flats or in shelters) is the prioritized option.
The duplication of transmission towers is reported to be unnecessary since in case of a crash of the communication network, emergency services can make use of back-up resources and quickly set up additional transmitting stations (Interview R11).

Taking into account local constraints, other small-scale approaches are employed which have a compensatory function for the initial indicator. They will be outlined in chapter 5.3.6.2.

5.2.5.2 Spare-capacity & back-up resources

Maintaining stocks and provision mechanisms for food, medicine, water supplies in case of disruption

The only issue currently considered in Rotterdam is drinking water supply. Within the focus area vital functions, drinking water companies start investigating into the amount of potable water required for citizens in case of vertical and horizontal evacuation. This is especially salient for vertical evacuation, in which citizens will be asked to seek higher elevation points or stay in their own homes and won't be able to leave these locations.

Strategy development therefore revolves around provision mechanisms of drinking water during emergencies, such as drinking water points across the city or advising citizens to prepare themselves and maintain stocks of essential goods in their homes (Interview R11, R10, R15 and R19). Differing answers illustrate that this is an issue area considered but there is no concrete, coherent policy developed yet.

5.2.6 Flatness

5.2.6.1 Room for autonomous change

Affected communities / population are provided guidance on flood-resilient construction

As outlined in chapter 5.2.1.1, flooding is not a frequently occurring event in Rotterdam except for the residents of Noordereiland, an island in the middle of the river Maas which gets flooded every other year. However, measures taken to prepare them for these events do not include guidance on flood-resilient construction but are rather confined to advice for flood-conscious interior design, such as keeping valuable items away from the ground floor. Furthermore, guidance on flood-resilient construction only makes sense when residents own the property because otherwise they are often not authorized to make such interventions (Interview R7).

5.2.7 High Flux

5.2.7.1 Availability of & access to resources

Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems; Reduction of irreversible commitment of resources

Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock

The WBs can quickly mobilize compensation payments following cloudburst events since they have easy and swift access to loans from banks, including the European bank (Interview R9). Therefore, withholding financial resources for emergency expenditures is reported not to be required. No answers could be generated with regards to the speed in the provision of financial support which can be explained by the absence of major flooding events since 1953. “*A cloudburst in our system comes every 5 to 10 years, then it is nice to have a recovery plan. A flood I never have lived so long, it is since 1953, so it is hard to have a recovery plan you probably never use. That’s the main difference between them*.“ (Interview R9).
In addition, there are no insurance providers willing to cover coastal or riverine flooding events. “*Most companies are not very willing to cover that. Most policies exclude it. Risk is not that high but if it’s happening, insurance companies are going bankrupt*.” (Interview R8)

Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas

This indicator turned out to be non-functional for Rotterdam.
First, in contrast to non-European countries where vulnerable groups are often forced to reside in high-risk areas, there is no such distinction to be made for the Rotterdam population since it is mixed and high risk areas are not exclusively populated by vulnerable groups (Interview R6).

Second, if a severe coastal flooding event is to happen, mostly associated with a malfunction of the Maeslantkering during a storm surge on the North Sea or a dike breach in the primary defense system, everybody is reported to carry the same burden regardless of social class or wealth. "*If we have an incident like this is does not matter if people are poor or rich because everyone will have the same problem. Because there are a lot of mortgages of course with the houses, people will not have enough money to recover and then you have a national problem, a national disaster of course and the only possibility that remains then is that the national government will say we will pay for the damage*." (Interview R7)

5.2.7.2 Having options for flexibility in response

Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required;

Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it

From the absence of responses for these indicators, the researcher derives their non-functionality for Rotterdam. Three explanations can be offered:
First, due to the high safety standards of flood-protective infrastructure, the absence of major flooding events and with flood protection assigned a domain of highly specialized water authorities, autonomous public action for recovery does not constitute a priority issue area. This is closely intertwined with perception of recovery as an undesired state itself, as outlined by one of the interviewees: "*We are especially [located] in prevention, planning, preparing before disaster and adapt it to long-term circumstances, changing circumstances. So this is our cycle. I we have a disturbance like a flooding, then we think we haven't done our job correctly, so we don't want to talk about a real flooding and therefore we don't have to recover.* […] *Although we know that there is no absolute safety against disturbances."* (Interview R9)
Second, the problem might lie with the indicators themselves. They are outcome-oriented (i.e. describe a state) and not process-related (describing processes to achieve the outcome) and therefore do not explain required policy action to anchor them in society (this point is further discussed in chapter 5.3.8.3). For this reason the translation to concrete examples in the Rotterdam case is difficult for respondents.
Third, since options of response are frequently associated with social class and wealth of individuals (in terms of the ability to accrue savings), they require measures in the societal and economic realm that are somewhat removed from the domain of flood risk management and mindsets. "*In the Delta Program the focus is really on hard infrastructure. Also the Delta Decision Spatial Adaptation is thinking about how to protect vital infrastructure when there is a flooding […] but it all involves infrastructure but it does not involve the social aspect and that is really missing from the Delta Program.*" (Interview R18)
Respondents might be unaware of what is happening in other policy domains, or might not have been able to make this ad-hoc connection in the interview.

Either way, the two indicators prove non-functional in conditions of high water safety standards and barriers for adopting them therefore seem to be anchored in institutional contexts and value propositions.

5.2.8 Flexibility

5.2.8.2 Flexibility in spatial planning

Leaving spaces without development so that they can be used for other purposes

In a densely populated country like the Netherlands where space is very limited, multi-functional use of space seems to be the preferred option to leaving plots empty for alternative uses. The combination of spatial functions, such as natural preservation areas with recreation and temporary water storage, or a parking garage to be used as a water storage facility and green space on top, is a well-established practice in urban planning in the Netherlands. It allows for modest flexibility in the modification of spatial use within the context of scarce surface space. Not unknown but neither common is the temporary designation of plots falling vacant for greening or agricultural activities suggested as a design tool for sustainable, resilient and climate proof cities (Atelier GROENBLAUW n.d.). One example of urban agriculture at Mullerpier in Rotterdam was reported to fall in this category (Interview R16).

Employing modular elements in buildings

Reducing life-cycles of buildings and infrastructure

The first indicator did not come up in association with flexibility in spatial planning in any of the interviews and is therefore not considered salient. It needs to be mentioned that responses could have differed if the researcher spoke to architects or property developers. Yet, this is an indication that the indicator might be too sector-specific in order to be of value for the framework and is therefore proposed to be removed in case of a similar result in the London.

With regards to flood protective infrastructure, one interviewee pointed out the priority of keeping pieces of infrastructure robust throughout their design life. Therefore, reducing life-cycles does not seem to be a feasible option considering the amount of investment for those assets.

5.3.8.3 Flexibility in measures

Reducing irreversible commitment of financial resources by broadening measures

The fact that the doctrine of Dutch water safety management is prevention has important implications for the applicability of "reduction of irreversible commitment of financial resources by broadening measures."

The range and nature of flood protection measures is increasingly broadened following the multi-layer safety approach (layer two: spatial adaptation and layer three: crisis management), but the first layer of prevention is still the strongest. "*The best thing to do because we have done it for thousand years is just protection. It is always possible to make dikes higher, bigger, that's the most cost-effective way. Because in an area where you build a new part of a city, elevated, only that part is adapted and the rest is not. That's of course expensive and you can make calculations what should be the probability of failure to make that cost-effective.*" (Interview R10)

In comparison with major investments being made for dike reinforcement, the budget for climate adaptation is minimal, depending mainly on EU funds and budgets dedicated to pilot projects (Interview R5 and R7). Due to long-term investments in flood-protective infrastructure, the Netherlands are also bound to path dependency which hinders the reduction of irreversible commitment of financial resources. "*Once you have started with the* *infrastructural changes, then flexibility is really low because there is huge economic interest and there are a lot of stakeholders involved.*" (Interview R18)

5.3 Indicators that enhance functionality (green)

5.3.1 Anticipation & Foresight

5.3.1.1 Monitoring of slow variables

The researcher detected additional indicators to specify the initial general indicator: Monitoring of factors that affect sea level, river, canal and polder water levels.

Monitoring of water storage capacity and volume of the surface water system

Among other things, groundwater levels in cities depend on the construction and water storage capacity of the sewer system. Rotterdam has a combined sewer system, which means that the wastewater and rainwater are collected in one joint system, which during cloudbursts can cause sewer overflows (called surface water flooding) (Interview R1; City of Rotterdam 2013). For the Waterplan 2 an analysis of the existing water system was conducted with regards to its water storage capacity which yielded a shortage of 600,000m³ for 2015 which extends to 800,000m³ up to 2050 (Municipality of Rotterdam et al. 2007). Also the polder system is regularly assessed for its capacity to store cloudburst events (Interview R5 and R9).

Monitoring of amount of permeable, impermeable and semi-permeable surfaces

Most of Rotterdam has densely paved surfaces that prevent water absorption (Interview R2). Enhancing the permeability of city surfaces to improve its water sponge capacity is an explicit goal of the RAS and the RRS (City of Rotterdam 2013; Municipality of Rotterdam et al. 2016). The municipality of Rotterdam therefore uses the indicator of "sealed soil ratio" for monitoring its progress on climate adaptation (Interview R17).

Monitoring of population density and growth

The population of Rotterdam in inner- and outer-dike regions has grown considerably along with economic activities over recent decades. This has implications for the probability of casualties, property damage and economic losses (City of Rotterdam 2013). Population growth also enhances the amount of impermeable surfaces due to housing requirements.

Monitoring of soil type and subsidence

Soil type and subsidence are interconnected factors that increase the likelihood of flooding. For instance, sand allows for quick infiltration of the water into the soil, peat has the tendency to oxidize and cause land subsidence of up to 1 centimeter per year which is sped up when combined with low water levels; clay prevents water from being absorbed into the ground (Interview R8, R12, and R16). While parts of Rotterdam are built on low-lying peat and therefore constantly subsiding, other parts have a clay ground. These are aspects that need to be factored into water management and spatial planning (City of Rotterdam 2013). The municipality of Rotterdam assessed subsiding areas via flood risk maps per catchment area up until 2100 (Interview R17).

Monitoring of coastal erosion

Dune and coastal erosion caused by water levels and waves affect the capacity of the coast to absorb current and future sea level rise. Wave action and changes in dune landscapes are monitored in the Netherlands by RWS and a pilot project set-up at the coastal area of Schreveningen called sand motor (Interview R18, Rijkswaterstaat 2011a; Rijkswatertaat 2012)

Monitoring of sea level rise

By influencing river levels, sea level rise has an impact on flooding and flood risk management and is monitored by the Water Management Center of RWS in Lelystad (Rijkswatertaat 2012). "*The probability of a flood of course increases with sea level rise but normally you have maybe a situation once every 1,000 years but because of sea level rise it becomes every 200 years, so the event is still rare but the probability is increasing because of sea level rise or decreased soil. So, sea level rise influences flood risk management*…" (Interview R10)

Yet, sea level rise due to subsequent salt water intrusion is considered more influential for agricultural practice and freshwater provision than water safety because the coastal area is deemed safe until 2050 according to current safety standards (Interview R18).

5.3.2 Preparedness & Planning ahead

5.3.2.1 Preparedness of businesses for adverse events

With the exception of the EU Seveso Directive III which requires businesses dealing with hazardous substances to perform risk assessment for all types of disturbances (flooding, earthquakes etc.) and develop respective contingency plans, there are no legal obligations for companies to factor climate adaptation into their business practice in the Netherlands (Interview R11 and R15). The creation of business continuity plans or proactive asset management therefore mostly depend on the level of climate risk awareness in a company (Runhaar et al. 2014; Interview R7 and R15). Therefore, the necessity of guidance mechanisms to go beyond mere information provision, as outlined by the initial indicator, was recognized by officials (Interview R7 and R15).

Several means are provided to help businesses embark on climate adaptation like online tools, guidelines (which are to be found on the website ruimtelijke adaptatie) or working sessions. "*One of the things we do is organize meetings for our network for all people that want to work on adaptation, be it public or private. We just had one two weeks ago, about finance, all kinds of aspects, how do I organize in complex projects that adaptation is taken into account. These meetings are a way for us to share knowledge and make people find each other, we put them together*." (Interview R12)

Furthermore, companies are provided with flood maps, water-related knowledge and scenarios from the databases for risk assessments from RWS. This helps them to visualize different incidents and subsequent disruptions and conduct a joint problem analysis (Interview R7 and R15). According to these insights, the indicator is proposed to be slightly modified as follows:

Governing authorities provide companies with (online) tools (climate scenarios, flood maps), (water-related) knowledge, and workshops for climate adaptation, flood risk mitigation and preparation

5.3.3 Homeostasis

5.3.3.1 Integrated planning, coordination & collaboration

Integrated, coordinated, collaborative processes of multiple parties lie at the heart of streamlined procedures, foster acceptance of decisions and thereby enhance compliant practice. Its importance cuts across emergency planning, integrated flood risk and water management, as well as the integration of climate adaptation / water safety into other policy domains, such as spatial planning and development, land use or drainage.
However, regarding the latter, according to municipal and water authority officials no systematic integration of the climate adaptation into working processes and operations has been achieved in Rotterdam so far. Mainstreaming occurs to a limited extent between the water sector and spatial planning, the two major pillars of climate adaptation in Rotterdam.
There are efforts to mainstream water and climate issues into municipal activities, and climate adaptation into the water sector. An example is the water test (in Dutch *Water Toets)*, which obliges municipalities to evaluate new spatial planning decisions, such as the location of facilities and functions, according to their consequences on water safety and other water-related problems (Interview R4, R8, R9). Another example is combining water issues with the social agenda and programs of the municipality which is the aim of the WB Delfland (Interview R20). Also, since last year climate adaptation was the subject of 19 show cases over the whole area of the WB Delfland: "*those are our main points where we want to really make steps.*" (Interview R3). To drive progress in combining urban redevelopment with adaptation measures, the municipality of Rotterdam currently collaborates with different municipal departments and infrastructure providers to identify plans (street by street) to replace sewerage, utilities, roads, electricity, and transportation in order to spot common projects (Interview R13).

Several interviewees pointed out factors underlying institutional structures and cultures that hinder effective integration and required collaboration. These provide clues for potential hurdles others cities might also encounter. Turned into enabling factors for integrated planning and adaptation mainstreaming, they enhance the practical implementation of this principle and are therefore added to the existing set of indicators.

First, the existence of departmental silos was pointed out several times. In addition, institutional processes in general were reported to leave no space for integrated knowledge exchange (Interview R2, R7, R12 and R13). According to the RRS this problem also extends to cross-sector collaboration, for instance of infrastructure providers where hesitation to share confidential information can be observed to obstruct coordinated, integrated planning. On these grounds, the following two indicators are established:

Creating institutional and organizational structures that promote integrated knowledge sharing between departments, management authorities and across different scales

Promote cross-sector collaboration and arrangements for sharing of (confidential) knowledge and information between sectors

Second, interviewees indicated that unclear responsibilities in joint projects, especially with regards to funding are a barrier to smooth collaboration. The budget of municipal departments is reported to be bound to be spent on specific issue areas which counteracts the practice of *Meekoppelen* and joint efforts (Interview R1, R9 and R12). Therefore, the following enabling indicator is added:

Provide for flexible budget investment mechanisms in organizations and municipal departments

The initial set of indicators included "the presence of bridging mechanisms (e.g. actors, policies, laws, tools and instruments) that link and align strategies". The Rotterdam case provides specification of the different dimensions mentioned, both on a strategic and operational level and will therefore be investigated more closely.

For instance, the presence of leadership is referred to as a bridging mechanism on the actor dimension since it is reported to drive cross-departmental collaboration and strategy alignment. Progress is often owed to proactive individuals that go beyond their required tasks and unite different stakeholders (Interview R2, R3, R7 and R12): "*There is a tendency that every organization is only doing what they are meant to do and what we are doing is try to approach the things more integral and try to collaborate and that's actually why we are now ahead of everyone because we are clever enough to use every part of information from every organization. We collaborate with the good people who are also quite proactive in thinking and handling. I have to say we really have to push people in organizations*." (Interview R7)

Presence of leadership driving cross-departmental collaboration and projects forward

When it comes to policy integration and alignment, the Rotterdam case sheds light on the different ways to administer the integration of climate adaptation and water safety into other sectorial policies on a strategic level.
One way proposed by policy officials to drive climate-proofing and reduce flood risk across the city is via anchoring climate adaptation measures in sectorial standards, either by building codes, creating a standard design for public areas (Rotterdamse Stijl) or national law. "*What we are trying to do now is that we have certain standards and are implementing them into our spatial development plans so we will then come across every new spatial development and they have to increase the safety themselves*." (Interview R7).
Whereas spatial planners mostly believe in the application of soft law (Interview R12 and R18), municipal officials reported the integration of building permits and standards in national legislative acts to be required. City governments are not allowed to add additional requirements to national regulations and therefore current legislation does not account for local requirements (Interview R7 and R13). A similar stance is adopted by water officials along with the tendency of the water sector to legally enshrine water standards. "*My advice will be, if water is an important thing in the country, ensure that some mechanisms are in the law that can't change that fast. Of course all the details can be worked out later, but the major part has to be in law. We do that for all kind of things…"* (Interview R8)
Another instrument reported to stimulate integrated planning and collaboration is harmonizing or streamlining so far fragmented policies or regulations across sectors and policy areas. This is for instance pursued by the forthcoming Environmental Planning Act (in Dutch *Omgevingswet*) which integrates water issues, spatial planning and nature conservation by uniting 26 so far separate acts on water, waste, soil protection and environmental protection in one act on environmental and physical issues (Interview R12).
To account for these different alternatives outlined above, the initial indicator is modified as follows:

Integration of climate adaptation and water safety into other sectorial policies via anchoring in standards or (national) laws, by harmonizing regulations / policies across sectors and policy areas or creating control mechanisms for spatial planning along the lines of flood protection

Finally, another bridging mechanism for linking agendas is the creation of co-benefits. It was frequently mentioned with regards to linking urban redevelopment with water safety measures but is also applicable to a wider climate adaptation policy context (Interview R2, R7, R12, R13, and R14). This relates to the strategic framing of projects to offer wider benefits in other policy domains in order to win investments or project

proponents. "*That's actually the thing that made us famous internationally because people always invest in flood management but it only has a function as a flood protection but be try to combine things and to do it integral and to have more benefits of it.*" (Interview R7).
"*You look at how you can make adaptation part of the different processes which is already going on which have budget. It is a way to hop over the urgency question because if the mayor for instance already has committed himself to a green project, the only thing the civil servant has to do is to tell him: do you know that this green project may as well have a function to prevent a heat island effect or water problems*?" (Interview R12)
Therefore, the following indicator is proposed to be added to the current set:

Creating co-benefits to connect agendas of different policy domains

5.3.3.2 Quick notification of disturbances & shocks

The WB Delft pointed out the use of centering techniques implemented in dike systems to observe and achieve a better understanding of system behavior. Based on that it will be possible to predict failure behavior of dikes, such as moist behavior since peaty dikes can dry out and breach, and react quicker to disturbances. "*We are looking for centering techniques, which we can use for predicting things but also for observing system behavior but that is also still in the phase, we call it children phase. We are experimenting and looking for ways to explore it more to better respond to system behavior. […] We are now also engaged in a project for remote sensing development where we can just observe system behavior.*" (Interview R20)
Consequently, the following respective indicator can be added to the framework:

Use of centering and remote sensing techniques in dikes to observe system behavior

5.3.4 Robustness & Buffering

5.3.4.1 Robustness through and of infrastructure

The following passage of the RAS illustrates the importance of preserving and improving robustness of the current flood protection infrastructure as an integrative part of adaptation (see Fig. 5.1): *"When it comes to adapting the city to cope with the effects of climate change, Rotterdam can continue to rely on the current robust system, which consists of storm surge barriers and dikes, of canals and lakes, outlets, sewers and pumping stations. We will continue to keep this system in good shape, to maintain it and to improve it where necessary. This system forms the basis for a climate proof Rotterdam."* (City of Rotterdam 2013, p.24)

Apart from the dike safety standards, robustness is associated with the probability of failure of flood defense structures. A broad range of research and reports were generated on safety and failure mechanisms by knowledge institutions supporting WBs and the province (Deltares, STOWA, and Rijkswaterstaat). For instance, the "Achterlandstudie Maeslantkering" performed by Rijkswaterstaat in 2006 which identified its failure risk, traced back to its software, to not comply with safety standards (Municipality of Rotterdam et al. 2007). STOWA, the research organization of the WBs investigated the failure mechanisms of dikes. The results are used for dike failure models which are important sources of information for determining the new dike safety standards (Interview R18).

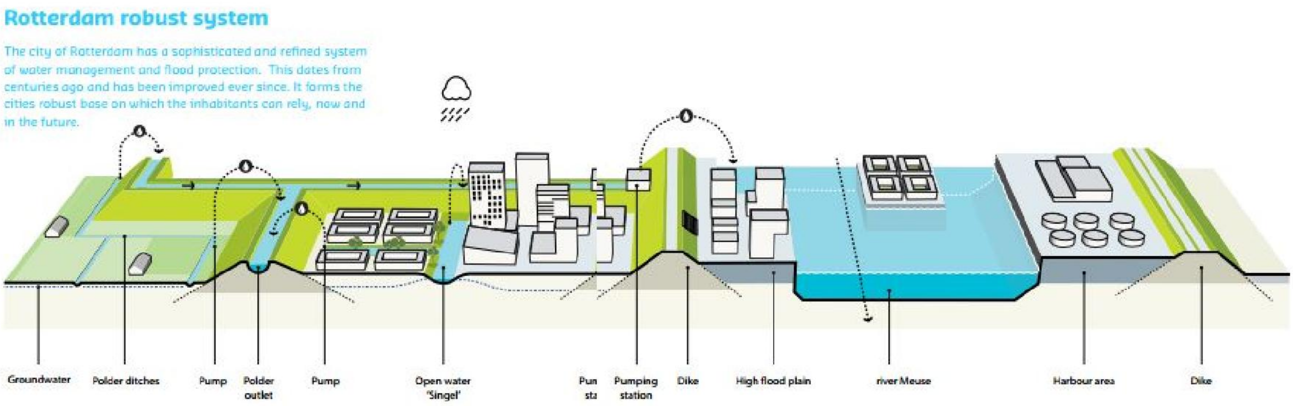

Fig. 5.1: Robust water management system and flood protection in Rotterdam (City of Rotterdam 2013)

Yet, in the course of the interviews it became clear that the term robustness is not only confined to the flood-protection infrastructure but also expands to critical infrastructure such as the wider water system, transport, gas networks, ICT, the port of Rotterdam and to the design life of assets in general (Interview R6, R7, R18 and R20). These notions are outlined by the following interview portions:
"*The Delta Decision Spatial Adaptation is thinking about how to protect vital infrastructure when there is a flooding, so in your model it is more robustness via infrastructure and creating buffer capacity, but it all involves infrastructure*." (Interview R18)
"What we try to do is looking at the life span of an activity to see if it can be robust during its lifespan. We are evaluating it during the operational period, we see if additional measures are needed." (Interview R20)
Thus, the current set of indicators requires expansion.

Robustness of critical infrastructure during adverse events is an issue area covered by several programs, such as the DP Spatial Adaptation (focus vital infrastructure), the RAS which has issued a special report on critical infrastructure, or the RRS by its focus on "Infrastructure Ready for the 21st Century" (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs 2014; Buijs & Streng 2013; City of Rotterdam 2013; Rotterdam Climate Initiative 2013; Municipality of Rotterdam et al. 2016).
Progress differs between different businesses, some sectors are far ahead in risk identification and inventarisation when it comes to all kinds of risks (also flooding) since they underlie strict regulation, while others such as highway departments are lagging behind (Interview R12). Rotterdam is currently at the stage of problem and impact analysis. "…*first what will happen, so impact analysis, and we should make policy, do we want to do anything about it and what and in the coming years work on that to make it happen*." (Interview R10)
Outputs are for instance water safety risk maps such as the one shown in Fig. 5.2.
Special reports were issued for instance by the Rotterdam Climate Initiative about the impacts of different climate threats (extreme precipitation, high water levels, heat, drought) on critical infrastructure with subsequent adaptation suggestions. The consultancy TNO recently performed a quick scan study on the performance of the urban wastewater and surface water system under long-term power outage and ICT failure (Luijf & Ruijven 2016). Also RWS commissioned an investigation of flood-prone roads and routes in their highway network (Buren et al. 2012).

Based on these findings, the researcher proposes to add the following indicator:
Impacts of flooding events on critical infrastructure and urban public utility networks are assessed (i.e. water system, flood defenses, drinking water, transport systems, gas, ICT, port), vulnerabilities and system failure factors identified and pre-emptive measures and response strategies for maintaining functions developed.

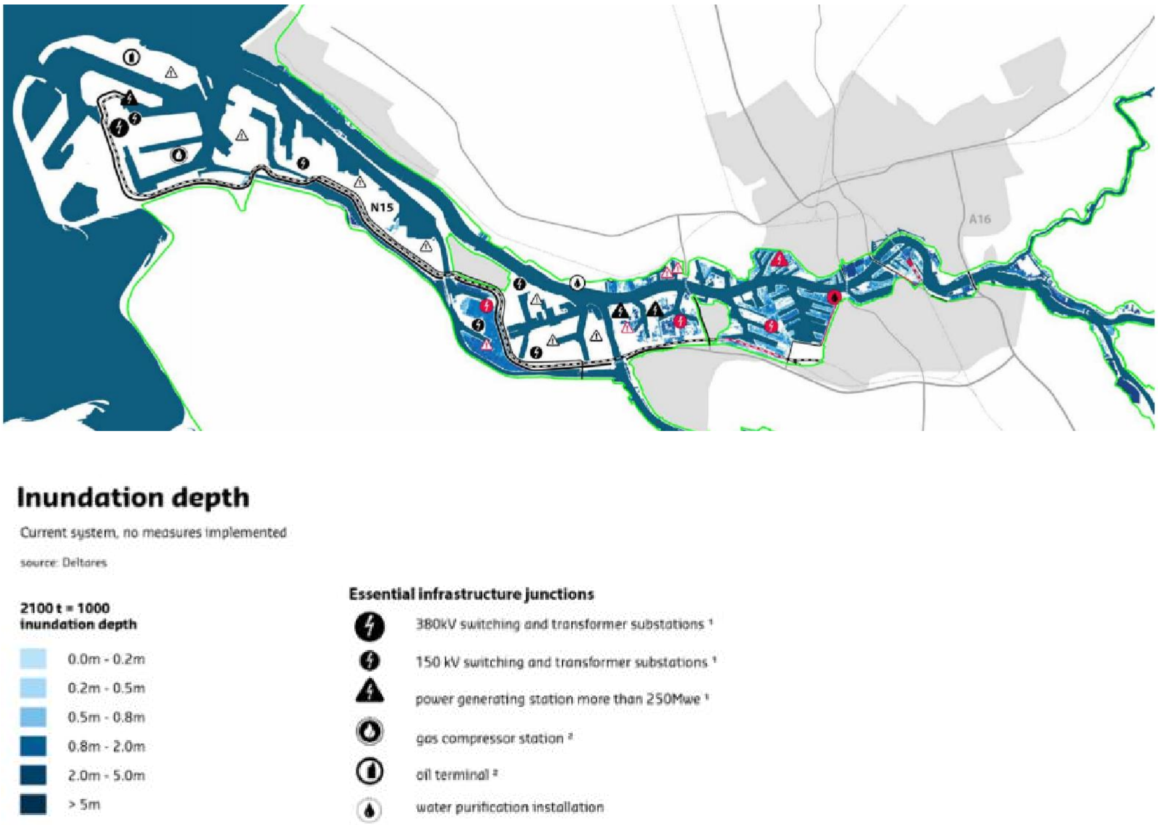

Fig. 5.2: Outerdike water safety risk map – 2100 (City of Rotterdam 2013)

5.3.4.2 Creating buffer capacities

No new indicators were found in this category. Nevertheless, the researcher proposes some amendments since illustrating different options in the respective categories is believed to enhance the functionality of the indicators for cities not that advanced as Rotterdam:

Improving (natural) water infiltration and storage capacity, for instance by increasing above and under-ground (rain)water storage and capture mechanisms, (re)creating urban floodplain wetlands and green spaces or using permeable paving.

Increasing the percentage of floodable areas, for instance by widening river and polder beds, deepening basins, installing emergency basins or temporarily inundating agricultural and nature areas.

Increasing the drainage capacity of the urban water system, for instance by enlarging sewerage pipes, installing larger pumping stations or higher capacity pumping stations in the water system, enlarging precipitation channels or implementing design standards for shorter return periods of storm water events.

5.3.4.3 Impact- and risk-reducing planning & planning practice

A planning practice mentioned by several interviewees salient for proactive flood risk management is the lowering of water levels in the water system up to several days ahead of a predicted cloudburst. This can the increase water storage capacity in the polders or canals (Interview R7 and R8). WBs have precipitation protocols where the first step of action is pre-pumping water out of the system (Interview R20). This practice is also suggested to greenhouse owners to prevent flooding of the irrigation channels (Interview R18) and is reflected in the following indicator:

Lowering water levels in the water system by pumping water out of the system ahead of an anticipated cloudburst or precipitation event

5.3.5 Diversity

5.3.5.1 Functional & response diversity

The interviews unraveled that practitioners mostly cannot translate the principle correctly to the flood risk management and water management domain, although it is partly being practiced. A reason for that might be that the indicators provided were too unspecific. To improve the practicality of this principle the researcher proposes to add a replacement indicator tailored specifically to flood risk management.
Functional diversity in flood risk management can imply the co-existence of different approaches, like the ones exhibited by the multi-layer safety approach. For storm water events, this implies the co-existence of different water absorption approaches, which are partly already addressed and taken into account: sewer system, rainwater retention basins, natural water absorption in public and private spaces or permeable paving in streets. "*The multi-layer safety approach could be used for all urban functions, so urban water management is the same: first layer is the sewer system, second layer is adaptation and outer space*…" (Interview R2).
For riverine or coastal flooding, it entails spatial adaptation measures level also in areas protected by the dikes, such as flood-proofing buildings or elevating their ground, so that when a dike breach happens, properties are still safe. The following indicator includes these approaches:

Diversity in types of flood protection interventions (preventive alongside adaptive measures) and water absorption mechanisms (i.e. sewer, water storage, permeable paving, public and private green spaces)

Yet in practice, considerations of cost-effectiveness seem to act against functional diversity endeavors. *"From a flood management perspective there is almost no urgency to invest into spatial adaptation because I am not going to adapt buildings to make them more safe, or hospitals, because we already have this very strong dike system and this protects us for situations 1 in 10,000 years so you can imagine it is not a very good investment to do an extra investment into your houses or hospitals*." (Interview R7).

5.3.5.2 Spatial diversity in critical functions

An alternative practice was identified to compensate for this principle which is located under the principle of connectivity (see chapter 5.3.8.4 where it will be explained in more detail):
Critical points for accessibility to critical infrastructure during adverse events are identified and pre-emptive measures and response strategies for maintaining functions are developed.

The current focus is on looking at physical infrastructure in terms of reachability during flooding events in case of a dike breach rather than their strategic spatial distribution across Rotterdam (Interview R7 and R15). In fact the physical distribution of vital infrastructure is deemed irrelevant unless being checked for accessibility under adverse circumstances.

The latter is an exercise currently being performed by the pilot project crisis management improvement where various parties, such as WBs, the municipality of Rotterdam and the safety regions are involved. Since spatial diversity of critical functions except for its manifestation in decentralized flood protection infrastructure, turns out to have no practicality in use it should be excluded from the diagnostic tool.

5.3.6 Redundancy

5.3.6.1 Overlapping functions & roles

It was mentioned in the theoretical chapter that overlapping functions and roles of actors and actor groups lack operationalization in the scientific literature. In the case of Rotterdam several ways to implement this type of redundancy were found that serve as worthwhile illustrations of integrating this principle into operations without duplicating official functions. In fact, the latter is opted against for reasons of cost-effectiveness and efficiency gains.

Specifically with regards to flood risk management and climate adaptation, ways to create redundancy of knowledge in institutional memory consist of engaging a constant group of people in projects and the design of policy documents (RWP 2, RAS, RCP and RRS). Redundancy is also achieved by repetitive working group meetings that include a variety of constant actors (Interview R2, R7, R11 and R16):

Constant group of people participating in projects and the creation of policy documents;
Working groups / project groups integrate multiple actors (shared knowledge)

Specifically with regards to flood risk management, shared responsibilities and roles can increasingly be observed along the tendency to outsource public functions to private domains due to municipal budget cuts (Interview R14).
In water safety (i.e. riverine, tidal and coastal flooding), an exclusive domain of the water authorities, officials are hesitant to transfer responsibilities, which they also don't see to be welcomed by the public: "*Because you said that people are getting a voice, I think that there is a tendency that they are more glad and happy to leave things to the government instead that they are responsible for themselves."* (Interview R7)
Contrastingly, the issue area of storm water buffering and respective action space is increasingly being shared by public and private actors with urban greening neighborhood projects or measures taken on private property. "*It really depends on the type of threat, when there is a threat from the sea and river you can hardly do anything autonomously apart from preparing and knowing what to do when the threat really comes. In case of excessive rain you can do a lot of small things, for instance don't pave your whole terrain but keep open space*." (Interview R4)

Tailored to flood risk management, the following indicator should therefore be added to the set:

Flood risk mitigation measures are taken by public and private organizations and actors

5.3.6.2 Functional redundancy in important functions & services

The Dutch approach taken towards functional redundancy in critical functions and services aims at adjusting existing structures with small-scale measures instead of duplicating functions.

For instance the shoulders of major arteries and highways designated as evacuation routes are broadened to reduce potential bottlenecks in case of an incident. Such measures are easy to administer since they can be coupled with road maintenance projects (Interview R15).
The focus is also on building internal redundancy mechanisms into the networks of critical infrastructure, such as electricity networks or the water system, based on identified failure mechanisms. Redundancy provisions for the latter are for instance the number of pumps exceeding the requirements for normal operation, the use of on-call mobile pumps or the option to switch to manual operation of pumps in case of an outfall of the telemetric system which measures water levels in the surface water system (Interview R4, R7, R9, R10, R16 and R20; Luijf & Ruijven 2016; Runhaar et al. 2014).
This alternative approach is a more realistic way for adopting functional redundancy in urban infrastructure and is therefore added to the existing set of indicators:

Provision of redundancy mechanisms in critical infrastructure (i.e. water system, electricity, ICT sector, transport networks)

5.3.7 Flatness

5.3.7.1 Broad participation, stakeholder engagement & inclusiveness

According to the findings, there are limits when it comes to the involvement of non-governmental stakeholders in policy processes and the design of solutions, which should be acknowledged in the indicator.
The room for the river project is often outlined as a role model project when it comes to collaboration with citizens. In some cases municipalities were even mentioned to have taken the lead (Interview R1 and R6). Respondents also indicate examples of active public involvement in designing solutions in dike reinforcement projects, including discussions at the “kitchen table”, village and district meeting where plans are openly deliberated (Interview R4 and R8). However, since water and flood risk management requires specialized knowledge and technical solutions, the involvement of public stakeholders in all stages of the policy process is not always practical nor desired (Interview R7). Apart from the above mentioned examples, broad stakeholder engagement so far only prove successful in small-scale pilot projects (Rotterdam water square), but has not been systemically integrated on a broader scale. Apart from the required specialized knowledge, general absence of interest on behalf of the population are indicated to hinder public integration in all program phases (Interview R3, R7 and R16).

Against this backdrop, the initial indicator seems too ambitious and should therefore be adjusted to a more realistic dimension: “Non-governmental stakeholders contribute to agenda setting, analyzing problems, developing solutions (‘‘coproduction’’)”. Instead the following replacement is proposed:

Non-governmental stakeholders are involved at an early stage in the planning & design process and contribute to developing solutions, for instance by means of co-creation spaces or public contests that facilitate individual inputs of ideas or the presence of small-scale adaptive measures in public space which offer room for broad participation.

5.3.7.2 Room for autonomous change

Awareness creation and incentives to act are described as key drivers for autonomous public action.

This is especially salient in the Dutch context where citizens are used to rely on the government for water safety since they pay taxes to the WBs to keep them safe. This pre-arranged system does not require them to take action on their behalf. Whereas there is no need to change this deeply entrenched behavior with regards to riverine or coastal flooding, where high levels of protection hardly offer room for citizen intervention, a behavioral change is required for surface and storm water management.
The reason for that is that urban greening in public spaces can only cover 30% of the city, whereas the rest is private property (Interview R2). To create enough buffer capacity for future precipitation events, public authorities will increasingly depend on citizens to implement green infrastructure or storm water retention systems in their own gardens to delay water flow to the already pressured combined sewer system. Thus, thoughts revolve around how to stimulate private parties to do so, provide them with incentives to act on their behalf.
For the future, one big issue is can we provide them with some incentive to act themselves, for instance not that they get a discount or subsidy to take measures, but rather that they pay less taxes, then they feel it right away in their wallet, and then they are more willing to take action I think." (Interview R20)
Launching initiatives that teach citizens urban gardening, or measures how to hold on to water for dry periods form a crucial part of this approach and should therefore be recognized in the framework (Interview R2, R3, R4 and R12).

Providing solutions, tools and guidance for small-scale (storm-water-related) measures on private property (i.e. urban wetland, storage facilities for rainwater)

5.3.8 High Flux

5.3.8.1 Availability of & access to resources

The case of Rotterdam gives clues for additional indicators with regards to the swiftness in emergency response and the quick mobilization of information.
Emergency responders along with the WBs exhibit rapid operational readiness since they are set on a stand-by mode and are required to be available on call:

Human resources for disaster response are on standby mode and have rapid operational readiness

Another important factor for facilitating quick response in the chain of emergency responders are clear procedures and responsibilities for each different threat during and after emergencies, laid down in calamity, organizational continuation and recovery plans.
Emergencies require a close collaboration between different parties, such as RWS, WBs, municipalities and the safety regions which play a major coordinating role. There is a broad evaluation of potential risks, calamity and action plans for all types of hazards performed by the safety regions and WBs. With regards to flooding events, the most important emergency response plan is the "*Coordinatieplan Dijkringen 14, 15 and 44*". Three scenarios are elaborated in this plan: coastal flooding, river flooding and a combination scenario for storm surge on the North Sea and high river levels (worst case scenario). This plan also entails a clear allocation of responsibilities by determining lead parties for each of the scenarios. A distinction is made between an overall calamity plan describing responsibilities, required action, a list of contacts and detailed plans for distinctive hazards, such as a cloudbursts, pipe or dike breaches (Interview R9). The latter describe operational measures, required coordination with other partners like RWS and the safety region, communication with authorities and they

provide guidance for the restoration of the water system after a disturbance (Luijf & Ruijven 2016). Several interviewees pointed out the importance of these protocols for shortening reaction and response time of emergency responders and fastening information transfer since they structure and determine which action is required, when to upscale and which channel to choose for decision-making (Interview R4, R9, R10 and R20; TNO 2013). This explains the importance of the following indicator:

Presence of fixed protocols (in calamity, continuation, recovery plans) with clearly defined tasks in the chain of emergency responders

Also a knowledge base to quickly draw from in times of need was reported to advance decision-making about appropriate measures and facilitates informed decision-making on behalf of responsible politicians. In this regard, broad internalized and quickly accessible knowledge about the affected area, the regional water system and its reaction to disturbances were deemed crucial. "*You have some knowledge about the water system, its specifics, specific situations where the cloudburst or flood occurs, the system will always react at something given the possibilities of that area. So you have to have knowledge about how the system will react, what are the possible measures, what will be the best measures, what will be the quickest measures, who has to decide? It can be very quick, but you have to be, well, in the proper channels*." (Interview R9)
In addition, modelling techniques that allow for an immediate visualization of flood scenarios and impacts and regionally varying water depths were mentioned to support decision-making (for instance for evacuation) during emergencies on the spot. Consequently, the following indicator is argued to be added to the framework:

Tools for swift visualization of flooding scenario and impacts and accessible knowledge base about the affected area, the water system and its reaction to hazards

5.3.8.2 Collaboration, social & institutional networks

While institutional networks and collaboration across institutional boundaries are well established in Rotterdam and their value generally recognized, aspects of social cohesion and intergroup-contacts among population groups are not.
"*I am working in the unit of the city with development areas, so we don't look that much at social impact, maybe it is coming, but it is going step by step. Every city must have its own vision for what is handy in each city […] maybe it is the time, the trend, but…like social networks, we don't look at that now, maybe when we know what is best working we keep searching for these things but not now. Maybe can you influence the size of the social networks, yes, then when we think it is a good thing to do in Rotterdam.*" (Interview R17)
This is a clear call for more guidance on how to influence factors like the level of social cohesion on behalf of policy makers. Moreover, according to interviewees, the initial theoretical indicator "level of social cohesion and inter-group contacts" turned out to be non-functional due to the difficulty in measuring it. "*How you make an indicator of that, then you have to say you are going into the neighborhood and see how many people are active, and do it next year again, I don't think so.[…].*" (Interview R17). Therefore the researcher proposes to replace the latter with two indicators that reflect more concretely on particular actions to influence social cohesion in society. These are drawn from already prevalent approaches pursued in urban greening neighborhoods and school projects. It is expected that such initiatives will gain more salience as a consequence of the RRS and its declared objectives of a "balanced society" and turning Rotterdam into a "network city" (Municipality of Rotterdam et al. 2016).

Presence of local, community-level projects that improve social cohesion and maintain connections between different groups of people.

Governing authorities connect, strengthen existing networks, community-led initiatives and contribute to the emergence of new ones.

With regards to social networks, another factor so far not represented in the framework is the importance of community leaders for driving local action. Their value is especially acknowledged in areas where inclusiveness of groups based on differing ethnic backgrounds is difficult to achieve otherwise. Partnering with community leaders is outlined as a strategy to drive stakeholder engagement for instance in small-scale water retention projects. Relying on local leaders which have broad social networks and are well-anchored in the community, and linking in with their project agenda was described as a powerful facilitator that compensates for limited time and human resource of organizations. "*Those ladies had a lot of connections in this part of the city and in the end we asked them to make a plan for this area to make people more conscious of water, so what they can do. [..] And they know other community leaders from other parts of the city, so it's quite a network which you can't build on you own with your own, non-involved organization, well we are involved but on a high, not reachable level.*" (Interview R3)

Partnering with community leaders with broad social networks and existing initiatives to improve stakeholder engagement

5.3.8.3 Having options for flexibility in response

Noteworthy, flexibility in response only generated responses relating to actions and resources within the confines of the own organization, not in relation to citizens. WB officials for instance could easily relate the principle to their flexible response strategies to flooding events which led to the discovery of an additional indicator (Interview R6, R19 and R20):

Authorities involved in flood-risk management and response have mobile resources for flood mitigation at their disposal (i.e. pumps, removable flood walls, slide-in wooden tiles to be inserted into the structure)

Despite WBs not being aware of respective measures with regards to the wider public, there is recognition of these aspects in the RRS and the Nationaal Programma Rotterdam Zuid which points to the basic understanding of the mechanism (Municipality of Rotterdam et al. 2016; Programmabureau NPRZ 2015).
Albeit not in explicit relation with enhancing flexible response to flooding events, attempts to diversify livelihood options for Rotterdam citizens are represented in creating curricula and education programs to develop skills for rapidly changing contexts. In support of the overall goal to create a more balanced society "*flexibility, creativity and individual learning empower people to take responsibility for their own future and to play a part in their local community.*" (Municipality of Rotterdam et al. 2016, p.53).
Indirectly, this can be seen as a pathway to increase the financial means of citizens and their ability to accrue savings, in order to be able to shift livelihoods, modify property structures or change physical location if required after a flooding strikes. The development of skills for rapidly changing contexts, as mentioned in the RRS, might also contribute to the development of entrepreneurial skills in support of the ability to repurpose resources and means when changing contexts require it. To enhance functionality, the researcher proposes the following replacement indicator that outlines a possible pathway to attaining this principle, rather than an end state:

Developing education, leadership, entrepreneurship programs and curricula aiming at skills development in rapidly changing contexts

5.3.8.4 Managing connectivity of critical sectors, infrastructure and natural habitats

Due to its economic importance for the city, accessibility of the port of Rotterdam is a number one priority. Thus, connectivity of critical sectors and infrastructure are issue areas dealt with in the RAS and RRS. Focal questions are the accessibility to roads and highways in and out of city, the functionality of bus, train, water and air transport (as important supplier routes for the port) as well as the deliverability of electricity, drinking water or communication services under adverse circumstances. Accessibility to infrastructure networks (ICT, gas, electricity, transport ways on land, water and in the air, drinking water) under different types of adverse events are mostly studied together with vulnerability assessments and failure mechanisms (see chapter 5.3.4.1). Some of them also propose potential pre-emptive measures and solutions to outfall problems (see Table 5.2).

Noteworthy it is still work in progress. "*I have followed it longer but the partners just start with this process, such as drinking water companies. They ask themselves what happens with our stocks in the ground, does it affect it or not? We don't know that but we will find out. How do we deal with pumping stations, should we bring the water to them? These are the questions they ask, which started half a year ago.*" (Interview R10)
Since the aspect of accessibility did not feature in the initial set of indicators, the researcher proposes the following to be added:

Critical points for accessibility to critical infrastructure during adverse events are identified and pre-emptive measures and response strategies for maintaining functions are developed.

Netwerk	Hoge waterstanden
Wegennetwerk	- Aanleg infrastructuur zonder tunnels - Verzwaren van tunnels - Pompcapaciteit tunnels vergroten - Infrastructuur verhoogd aanleggen - Aanleg verhoogde routes naar belangrijke locaties - Toepassing drijvende infrastructuur - Verhogen dijken
Railnetwerk	- Infrastructuur verhoogd aanleggen - Aanleg ondergrondse waterveilige infrastructuur - Verhogen dijken
Luchtnetwerk	- Verhoogde aanleg landingsbanen - Vergroten waterafschot landingsbanen - Verhogen dijken
Vaarwegennetwerk	- Verhoogde aanleg overslaglocaties - Schepen met lage doorvaarthoogte inzetten
Gasnetwerk	- Tijdelijke afsluiting van gas bij overstroming - Gebruik noodaggregaten bij uitval elektriciteit
Elektriciteitsnetwerk	- Tijdelijke afsluiting van elektriciteit bij overstroming - Kwetsbare onderdelen zoals regelkasten niet op maaiveldniveau
Drink- en industriewaternetwerk	- Toepassen verdringingsreeks bij uitval
ICT-netwerk	- Kwetsbare onderdelen niet op maaiveldniveau
Warmtenet	- Tijdelijke afsluiting van warmte
Buisleidingen-straat havengebied	- Tijdelijke afsluiting van getransporteerde gassen
Riolering	- Overstorten

Table 5.2: Measures to reduce adverse impacts of high water levels on (infrastructure) networks (Buijs & Streng 2013)

Another pivotal point so far not sufficiently addressed by the indicators is the assessment of cascading effects caused by critical links in spatial layers of different infrastructure networks. According to interviewees, respective activities are just at the onset and not at a stage where response mechanisms are developed. Infrastructure providers are stimulated to go beyond risk assessments of their own systems (previously touched on in chapter 5.3.4.1) towards considering interdependencies between networks (Interview R12). Also joint workshops are being held with infrastructure providers to determine the latter along with cascading effects to other systems. "*Supposed there is electricity outfall, or no more communication possible, what can you do? We think this is one of the topics we have to look more into. We have our own calamity plans but the interdependency with other agencies like the communication and electricity providers, and these cascading effects, we have to look more closely"* (Interview R20). In accordance with the results the indicator is slightly modified:

Spatial intersections of networks with other infrastructure systems and potential cascading effects to other systems are identified and response mechanisms developed

5.3.9 Flexibility

5.3.9.1 Flexibility in measures

An important factor described to enhance the flexibility in measures came up during research. Since it was not considered in the indicator set, it is added to the framework. Employing strategies and policies rather than law enforcement is outlined as an approach taken by spatial planning, as opposed to top-down water safety standards. "*When it is a policy you always have the flexibility to change strategy and make new appointments or agreements which strategy to follow. […] since it cannot be legally enforced, it gives us the flexibility to decide are we going to intensify certain measures or are we going to postpone them. So if you have for instance if the rainfall will be more intense than predicted, you can always increase the efforts that we are doing on spatial adaptation*." (Interview R18)

Implementing policies that allow for a strategy change and amendments in agreements rather than legislative acts

5.4 Reflection on the Rotterdam case and the practicality of the indicator set

The aim of the reflection is to bring together the results of the previous chapters. In the first chapter the attainment of principles is recaptured in the light of current flood management traditions, respective value propositions and strategic framing of policy objectives. Based on these, links to preferences for particular policy directions and principles are drawn. The aim is to show the limits of practicality improvement of the indicators, since such tendencies are often deeply entrenched in societal and political structures and therefore unlikely to change. The second chapter focuses particularly on the problematic and non-functional principles and indicators while scrutinizing their value for the framework.

5.4.1 Preferences for policy directions and principles in Rotterdam

Attainment of principles is inextricably linked to their desirability and importance allocated to them. To draw an overall picture of the Rotterdam case it is therefore worth looking at the preferences for policy directions first.

Rotterdam's activities in flood risk management can be located mainly in the two policy directions of "plan "prepare" and "adapt", and to a limited extent also in "absorb", specifically regarding cloudbursts.
With 60 percent of the population living under sea level and therefore at high risk of coastal and riverine flooding, high safety standards of the existing flood-protective infrastructure and robust critical infrastructure are key, which explain the primary focus in the Netherlands on prevention (Plan & prepare, Absorb - robustness). Due to these high standards and the subsequent absence of a major (coastal) flooding events since 1953 and riverine flooding since 1993/1995, considerations of recovery have been absent in Rotterdam until recently. More precisely, they gave rise to a long-lasting unwillingness to make provisions for catastrophic scenarios such as a primary dike breach or even to think about recovery mechanisms[12].

This has major implications for the fulfillment of several principles and indicators for Rotterdam.
First, little emphasis is put on the preparedness of citizens, most of whom are unaware of the location of their residences in flood-prone areas (Preparedness & Planning ahead).
Second, with recovery being interpreted as "already being too late" which represents its undesirability overall, there is very limited understanding about the necessity of "having options for flexibility in response" or "social networks".
While water authorities easily reported on their own strategies to swiftly respond to and recover from disturbances they were not aware of respective measures with regards to the wider public, which is explained by their absence (chapter 5.2.7.2). Flood risk management by tradition is a technocratic domain which leaves no room for the intervention of citizens. For these reasons, the uptake of these principles can be considered rather difficult since they would require a complete shift in the public mindset from assigning flood safety to the government to taking over responsibility for autonomous response.
Yet, there is indication that this shift is about to happen. Although not in direct relation with flood management, the recently released resilience strategy puts emphasis on aspects of Flatness and Social networks. In the latter, there is mentioning of education programs and skills development aimed at the diversification of livelihood options, showing that measures are being developed on a broader level. The same document outlines valuable strategies for enhancing social cohesion, an issue area neglected in traditional flood risk management and only recently touched on by urban greening projects.
Another indicator of change is the current review of emergency and evacuation management and improved flood risk information and communication. "*First we only had prevention. Now we are moving towards the other two as well. But still I think, the first one is most important. But people are making evacuation plans, and what do we do next, how do we search people staying there. People are thinking about this."* (Interview R5)

Interestingly, more autonomy for citizens' responses is offered by storm water management, which might further support this shift. Noteworthy, the emphasis on principles for cloudbursts also differs from that of riverine and coastal flooding: public awareness, room for autonomous change and social networks gain salience. Small scale, bottom-up initiatives for urban greening of public and private property are particularly aimed at. Their importance originates from increasing inability of the current combined sewer system to drain rainwater from extreme precipitation events, which are expected to become more frequent in the future. Since there are limits to upgrading and expanding the capacity of the current system both from a cost and space perspective, creating a water sensitive Rotterdam by combining small and large water storage with greening initiatives in public and private space is the way to go forward. "*We have to be prepared for the future events to come and*

[12] To illustrate the dimension of such a catastrophic event: depending on its location, a breach in the primary defense system can imply water depths of up to four meters in certain areas (around Amsterdam). Considering the capacity to pump away one centimeter per day, recovery can take several months with most areas devastated and rendered inhabitable (Interview R10).

not by investing in sewer pipes and infrastructure, but by having sponge for a part, awareness for a part, dealing with it for a part and then you talk about resilience" (Interview R2)
Relying to a great extent on measures in private space, these strategies imply a shift to participatory, integrative approaches for water management while requiring new tools and incentives to encourage this transition in governance.

A third implication of the reliance on a strong flood protection system is the absence of inclusiveness. Not with regards to broad stakeholder participation but concerning the provision of supportive recovery services for vulnerable groups. Interviewees reacted with a lack of understanding for its necessity. "*If we have an incident like this is does not matter if people are poor or rich because everyone will have the same problem. Because there are a lot of mortgages of course with the houses, people will not have enough money to recover and then you have a national problem*." (Interview R7) Other interviewees pointed me to the fact that vulnerability to flooding events does not necessarily overlap with socio-economic vulnerability since it is not only low-income groups residing in outer-dike areas.

Framing can also play a major role in enhancing the desirability of certain principles. This is the case for learning and experimentation, two principles given preference in Rotterdam. They need to be embedded in the endeavor to portray Rotterdam as a world-wide role model for water management and climate adaptation practice. Consequently, a strong focus is put on pilot projects and showcases to test alternative approaches and develop new ways to deal with the challenges of a changing climate. However, such pilot projects are confronted with the problem of scaling up and frequently do not translate into city-wide programs.

Finally, the emphasis on prevention and robustness of infrastructure has implications for the adoption of the flexibility principle. Long-term investment in the sophisticated system of flood protection makes Rotterdam prone to path-dependency which limits the scope of flexibility and broadening of measures. Accordingly, some interviewees described robustness and flexibility to be contradictory. Flexibility is further limited in spatial terms by population density and competing interests when it comes to spatial use.
The chosen way to overcome this alleged dichotomy is a long-term planning horizon (as the one adopted in the DP), building in allowances according to climate projections and multi-functional use of space. Therefore, flexibility is a parameter that has to be deliberately planned in advance with respective policies and tools, for instance spatial reservation in order to facilitate dike reinforcement at a later stage or keeping options open for diversified future interventions.

5.4.2 Scope and options for improving the practicality of indicators

The previous chapter showed that the attainment of some principles and their desirability is deeply rooted in contextual factors. Inaction in particular principles is often linked to barriers beyond the control of the researcher, which therefore cannot be addressed by the framework.
Contrastingly, this chapter addresses the improvement potential of the theoretical indicators. Doing so, it:
(1) identifies those that prove non-functional in practice
(2) explains the ones newly found based on alternative compensatory practice
(3) outlines which ones were further specified or clarified based on the case findings
For better readability, the chapter is structured according to these three categories.

1) ***Indicators (or intermediate principles) were found to be non-functional***
2) ***The case indicates another practice than the one exhibited by the initial indicator which might compensate for non-functional indicators***

Functional and response diversity turned out to be a challenging for practitioners due to a lack of awareness of the principle of diversity overall.
Associations with the field of flood risk and water management were based on incorrect interpretations of the principle. Therefore the researcher opted for adding an indicator specifically tailored to this field to clarify the correct implications of the principle (chapter 5.3.4.1 and 5.3.5.1).
Linking up with and expanding existing initiatives that already address functional diversity, though under different concepts such as sustainability or climate mitigation, are a way to promote the adoption of the intermediate principle. For instance, urban farming is promoted with regards to greening the city and could provide a base for local food production and supply. Also energy diversification and decentralization is approached by efforts to increase alternative energy sources, taken up in the RRS. Another example is accessibility to critical infrastructure, which as one of the five focal themes in the RAS is a priority issue area of the Rotterdam Climate Initiative and the RRS, primarily for economic reasons and keeping the port operational and accessible in times of disruption. All these existing initiatives are a fruitful ground for promoting the uptake of functional diversity.

The researcher also identified two major problem dimensions with Institutional diversity (chapter 5.2.4.3).
First, enhancing the diversity of institutions is hardly possible since water governing authorities along with their particular size, culture or structure evolved over centuries, especially in the case of the Netherlands where water boards can be traced back to the middle ages. Therefore, deliberate changes in the latter are neither realistic nor feasible. Second, measurability of this indicator is a challenge since it does not sufficiently address what extent of diversity is required to contribute to resilience which is also subject to discussion in the scientific literature (see Biggs et al. 2012, 2014). However, it does have value for evaluating baseline conditions and should therefore remain in the framework.

Furthermore, introducing spatial diversity in critical functions seems to be problematic. Required cost-intensive post-interventions into existing structures of densely built cities which grew organically are not feasible and therefore unrealistic. Thus, the researcher proposes to exclude it from the framework (chapter 5.2.4.2). In addition, another practice was identified to compensate for this intermediate principle. Investigations and probable future investments to manage connectivity and accessibility seem to outweigh spatial diversity of critical functions. The current focus is on looking at physical infrastructure in terms of their flood vulnerability and reachability during flooding events and designing pre-emptive measures and response strategies for maintaining functions (chapter 5.3.5.2).

Also for functional redundancy in vital functions and services the Dutch approach seems to differ from the original indicator of duplicating functions (chapter 5.2.5.1). In practice, existing structures are adjusted via small-scale measures to create functional redundancy as opposed to the costly duplication of functions. For instance the shoulders of major arteries and highways designated as evacuation routes are broadened to reduce potential bottlenecks (relates to creating buffer capacity) or redundancy mechanisms are implemented in infrastructure networks (chapter 5.3.6.2).

For the intermediate principle of overlapping functions and roles, the initial set of indicators implying the duplication of official functions was deemed too ambitious to be realized. Current municipal budget cuts and increasing efficiency counteract the creation of new redundant posts. Instead, more subtle ways of creating institutional memory are employed by engaging constant actors groups in projects or the creation of policy documents. In addition, from the perspective of flood risk management storm water buffering and respective action space are increasingly shared by public and private actors with urban greening neighborhood projects or measures taken on private property (chapter 5.3.6.1).

With respect to social & institutional networks the initial indicator of "level of social cohesion"was deemed non-functional because it is too unspecific to gear any policy action. Since it has not been a priority issue area in Rotterdam up to the release of the RRS, the need for further guidance became clear. It was followed up by substituting the initial indicator with two, more practice-related ones (chapter 5.3.8.2).

3) ***An established practice sheds light on further specification and clarification of indicators, for instance by illustrating different options or opinions of how to implement them.***

In the category of monitoring of slow variables, indicators could be added that narrow the broad initial indicator down to specific issue areas relevant for cities. Among these are storage capacity of the water system, population density, impermeable surfaces, soil type and subsidence and coastal erosion (chapter 5.3.1.1).
Different options for implementation were also found for creating buffer capacities. Those consist of improving natural water infiltration, increasing the percentage of floodable areas and the drainage capacity of the urban water system (chapter 5.3.4.2).

In the course of the interviews it became clear that the term robustness is not only confined to the flood-protection infrastructure but also expands to critical infrastructure (i.e. the wider water system, transport, gas networks, ICT) and to the design life of assets (such as greenhouses). The current focus is on building knowledge and determining impacts on vital infrastructure during adverse events, for instance via the DP Spatial Adaptation or the RRS. Accordingly, an indicator was added to account for this robustness dimension (chapter 5.3.4.1).

Finally, with regards to availability of & access to resources, the Rotterdam case helped to expand the set of indicators that previously were primarily focused on financial resources, with mechanisms and tools in use to improve the speed in emergency response (human resources), informed political decision-making in disaster situations and quick information transfer (chapter 5.3.8.1).

6 Results: Case study London

6.1 Presentation of results per principle in Matrix

6.1.1 Anticipation & Foresight

Intermediate Principle: Building knowledge		
Indicators	AoI	Sources
Existence of (regional and city-wide) climate change-related projections, forecasts and scenarios	++	Interview L2, L5, L11; Thames Catchment Flood Management Plan (following TCFMP) (Environment Agency 2009b), London Climate Change Adaptation Strategy (following LCCAS) (Greater London Authority 2011), Technical Guidance to the National

		Planning Policy Framework (following NPPF) (Department for Communities and Local Government 2012b), UK Climate Change Risk Assessment (following UKCCRA) (Committee on Climate Change 2016)
Identification and assessment of climate-related hazards, probability of occurrence, system's exposure, city-wide impacts and associated risks	++	Interview L1, L2, L4, L5, L7, L10, L12, L13; London Resilience Partnership Strategy (following LRPS (London Resilience Partnership 2013a), National Risk Register of Civil Emergencies (following NRR) (Cabinet Office 2015), Regional Flood Risk Appraisal (following RFRA) (Environment Agency 2009a), Technical Guidance LCCAS, London Plan (Greater London Authority 2015b), NPPF, UKCCRA, Strategic Flood Risk Assessment (following SFRA) (City Corporation & Halcow Group 2012; London Borough of Southwark 2008; Kissi 2011a), TCFMP
Mapping of economic assets, critical functions (hospitals, police stations etc.), commercial and manufacturing establishments in flood-prone areas	+	Interview L13; TE2100, LCCAS, TCFMP

Intermediate Principle: Monitoring of slow variables		
Indicators	AoI	Sources
Flood risk monitoring systems are in place	+	Interview L5, L6; National Flood Resilience Review (following NFRR) (HM Government 2016), London Strategic Flood Response Framework (following LSFRF) (London Resilience Partnership 2015)
Monitoring of dikes and flood-protective infrastructure meeting the safety standards	++	Interview L1, L10, L11; TE2100, RFRA, TCFMP
Periodic analysis and inspection of crucial infrastructure (transport, electricity networks, ICT, water supply, drainage systems)	++	Interview L1, L7; TE2100, LCCAS, UK CCRA, RFRA, Adaptation Reporting Power (following ARP) (Port of London Authority 2015; Gatwick Airport Limited 2016; Transport for London 2015b; Energy UK 2015; Energy Networks Association 2015; UK Power Networks 2015; Thames Water 2016; Horrocks et al. 2010)
Water storage capacity and volume of the sewer system / water system (Cloudbursts)	++	Interview L2, L5, L8, L12, L13; TCFMP, Pitt Review (Pitt 2008), ARP Thames Water
Amount of permeable, impermeable, semi-permeable surfaces in city	++	Interview L2, L8, L10; TE2100, TCFMP, ARP Thames Water
Population density and growth	++	Interview L2, L10, L12; RFRA, TCFMP, London Plan
Soil type and subsidence	+	Interview L10, L12; TCFMP, LSFRF
Coastal erosion	+	TE2100, UK CCRA, Flood and Coastal Erosion Risk Management appraisal guidance (following FCERM) (Environment Agency 2010)
Sea level rise	+	Interview L10, L11; NPPF, TE2100, UK CCRA

Peak river (fluvial) flood flows	+	Interview L11; TE2100, UK CCRA, NFRR
Public and institutional attitudes to flood risk	+	Interview L2, L11; TE2100

Intermediate Principle: Information management & sharing		
Indicators	AoI	Sources
Access of governance units and organizations to global (scientific) data such as climate scenarios, models etc.[13]	++	Interview L6, L8, L10, L13; ARP: Gatwick, Thames Water, TfL
Tools and mechanisms for information storage and sharing (i.e. data archives, open access, reports, policy documents) accessible for all employees over time, across institutional borders and between public and private entities[14]	++	Interview L5, L6, L7, L8, L10, L12, L13; London Plan, LCCAS, ResilienceDirect (Ordnance Survey 2016), Pitt Review, RFRA; ARP: Port of London
Presence of platforms of exchange among actors across institutional boundaries (e.g. policy officials, municipality representatives, project coordinators)	++	Interview L2, L4, L5, L6, L7, L8, L10, L13

Intermediate Principle: Learning from past hazard experience		
Indicators	AoI	Sources
Presence of accessible long-term track records of previous flooding events and disturbances	++	Interview L5, L6, L10, L13; RFRA, NFRR, TCFMP
Lessons learnt from previous flooding events are formulated into tangible, accessible, evaluative reports	++	Interview L1, L5, L6, L10, L11; Pitt Review, Bye Report (Bye & Horner 1998)
Lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms	+	Interview L5, L6, L10, L11; RFRA

6.1.2 Preparedness & Planning ahead

Intermediate Principle: Public awareness, risk communication, education & training[15]		
Indicators	AoI	Sources
Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations	++	Interview L1, L2, L4, L6, L13; LRPS, LCCAS, NFRR, Pitt Review, Flood Resilience Community Pathfinder (following FRCP) (Department for Environment / Food and Rural Affairs 2015)
Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action for flooding events (e.g. guidance for preparation and appropriate response)	+	Interview L1, L8, L6, L13
Hazard awareness, safety education programs and response training to neighborhood and community organizations	+	Interview L6, L10, L11
Making flood risk comprehensive for the public	+	Interview L1, L2, L4; Public Dialogues on Flood Risk Communication (Environment Agency & DEFRA 2015)

[13] Also part of the principle Flatness / intermediate principle: Room for autonomous change

[14] Also part of the principle Flatness / intermediate principle: Room for autonomous change

[15] All indicators are also part of principle Flatness / Room for autonomous change (chapter 6.1.7)

Intermediate Principle: Response & Emergency Management		
Indicators	AoI	Sources
Presence of a flood forecasting and early flood warning system	++	Interview L1, L6, L8, L11; TCFMP, LSFRF, NFRR
Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies	++	Interview L1, L6, L8, L13; LSFRF, LCCAS, Pitt Review
Prevalence of regional flood management plans, hazard mitigation plans, emergency response plans and contingency protocols	++	Interview L2, L6, L11, L13; LSFRF, LESP Major Incidence Procedure Manual (London Resilience 2015a), Strategic Coordination Protocol (London Resilience 2015b), London Recovery Management Protocol (London Resilience Partnership 2013b), Multi-agency flood plans on borough level, National Emergency Response and Recovery Guidance (HM Government 2013)
Presence of regional evacuation plans, designation of evacuation routes and shelter capacity	++	Interview L1, L2, L6; LSFRF, London Mass Evacuation Framework (London Resilience Partnership 2014a), London Mass Shelter Framework (London Resilience Partnership 2014b)
Training and capacity building on risk communication for responsible authorities	++	Interview L1, L6, L7, L10; LRPS, NFRR, Strategic National Framework on Community Resilience (following SNFCR) (Cabinet Office 2011), Public Dialogues on Flood Risk Communication

Intermediate Principle: Preparedness of businesses for adverse events		
Indicators	AoI	Sources
Governing authorities provide companies with (online) tools (i.e. climate scenarios, flood maps), timely and tailored flood warnings, (water-related) knowledge, workshops for climate adaptation, flood risk mitigation and preparation	++	Interview L2, L4, L6, L8, L9, L11; UK CCRA, LCCAS, Pitt Review
Presence of issue-specific formal or informal networks for exchange of best practice and knowledge generation	++	Interview L1, L4, L6, L9; CIRIA (Construction Industry Research and Information Association 2016), LCCP, Business Continuity Institute (BCI 2016), Business Improvement Districts
Companies factor the impacts of climate change into their business practice (for instance by having business continuity and contingency plans in place)	+	Interview L2, L4, L7; LCCAS, ARP: Gatwick Airport, Port of London, Thames Waters, Energy UK, ICT sector, UK Power Networks, Energy Networks Association
Businesses have an understanding of potential climate change related threats, associated risks and vulnerabilities in the business operation as well as opportunities	+	Interview L4, L7, L11; ARP: Gatwick Airport, Port of London, Thames Waters, Energy UK, ICT sector, UK Power Networks, Energy Networks Association; UK CCRA

6.1.3 Homeostasis

Intermediate Principle: Preservation and restoration of regulating ecosystem services		
Indicators	AoI	Sources
Policies and plans for natural areas and ecosystem restoration	++	Interview L2, L5, L9, L12, L13; Green Infrastructure 12 Point Plan (London Bridge Business Improvement District n.d.), London SUSD Action Plan (Greater London Authority 2015a), TCFMP, FCERM, London Plan, LCCAS, NPPF, SUSD Manual (Woods Ballard et al. 2015), TE2100
Increasing / creating urban green spaces on public and private property and (re)implementing urban floodplain wetlands	++	Interview L2, L5, L7, L9, L12, L13; ARP: Thames Water, UK CCRA, London Plan, RFRA, NPPF

Intermediate Principle: Integrated planning, coordination & collaboration		
Indicators	AoI	Sources
Provide for flexible budget investment mechanisms in organizations and municipal departments	0	Interview L2, L4, L13; UK CCRA
Promote cross-sector collaboration and arrangements for sharing of (confidential) knowledge and information between sectors	++	Interview L2, L6, L7; UK CCRA, NFRR, Pitt Review, ARP: UK Power Networks, Energy UK
Presence of leadership driving cross-departmental collaboration and projects forward	+	Interview L2, L4, L9, L13
Integration of climate adaptation and water safety into other sectorial policies via anchoring in standards or (national) laws or by harmonizing regulations / policies across sectors and policy areas or creating control mechanisms for spatial planning along the lines of flood protection	++	Interview L2, L5, L7, L10, L12, L13 FCERM, SUSD Action Plan, NPPF, RFRA, ARP, Making space for water (DEFRA 2005)
Creating co-benefits to connect agendas of different policy domains	0/+	Interview L2, L12; London Plan
Linking urban (re-) development, planning processes, maintenance programs and other ongoing projects	+	Interview L2, L7, L12, L13
Presence of a formalized, common vision underlying planning and implementation of projects	++	Interview L2, L3, L9, L12; NPPF, LCCAS, SUSD Action Plan

Intermediate Principle: Inclusiveness & equity standards
It was decided to leave out this category in Homeostasis for this research since it will be taken up at a later stage with Flatness (broad participation, stakeholder engagement & inclusiveness) and High Flux (availability of and access to resources)

Intermediate Principle: Clearly defined responsibilities of actors and institutions		
Indicators	AoI	Sources
Responsibilities are clearly defined and allocated for causing and solving water-problems, sewage systems	+	Interview L5, L6, L10, L13 LCCAS
Formal mechanisms of oversight and /or cooperation such as an agreed coordinating responsibility where there are more than one risk owners	++	Interview L2, L6, L7, L11, L13; LSFRF, LESP Major Incidence Procedure Manual, Strategic Coordination Protocol, London Recovery Management Protocol, Multi-agency flood plans

		on borough level, National Emergency Response and Recovery Guidance
Statutorily defined risk owner with clear line of oversight and responsibility	++	Interview L2, L3, L11, L13; Flood and Water Management Act 2010 (Government 2010), Civil Contingencies Act 2004 (HM Government 2004), FCERM
Insurability of private property against flood loss	+	Interview L1, L2, L6, L13
Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery	0/+	Interview L2, L6, L11; Pitt Review, TE2100, Public Dialogues on Flood Risk Communication

Intermediate Principle: Quick notification of disturbances and shocks		
Indicators	AoI	Sources
Presence of a flood and weather forecasting, early warning system to generate timely information and facilitate anticipation and forecasting	+	Interview L1, L8, L10, L11; SFRF; ARP: Port of London, Thames Water
Variety of broadcast technologies (internet, mobile phone, telephone, newspaper, TV, radio) used for communicating flood warnings	+	Interview L1, L6, L11

6.1.4 Robustness & Buffering

Intermediate Principle: Robustness through infrastructure		
Indicators	AoI	Sources
Presence of flood-protective structural measures and installations	++	Interview L2, L5, L7, L10, L11, L13; RFRA, TCFMP, TE2100, ARP: Gatwick Airport, UK Power Networks
Presence of formalized water safety / dike standards that are regularly monitored	0	Interview L1, L10; Coastal Erosion and Risk Management Outcome Measures (Environment Agency 2015)
Periodic assessment, optimization and improvement of flood-protective infrastructure	++	Interview L1, L5, L10, L11; RFRA, TE2100, TCFMP
Impacts of flooding events on critical infrastructure and urban public utility networks are assessed (i.e. water system, flood defenses, drinking water, transport systems, gas, ICT, port), vulnerabilities and system failure factors identified and pre-emptive measures and response strategies for maintaining functions developed	++	Interview L2, L7, L11, L13; RFRA, LCCAS, UK CCRA, ARP: TfL, Thames Water, Port of London, Gatwick Airport, ICT sector, UK power networks, Energy UK, energy network association, Sector Resilience Plans (Cabinet Office 2014)

Intermediate Principle: Creating buffer capacities		
Indicators	AoI	Sources
Improving (natural) water infiltration and storage capacity, for instance by increasing above and under-ground (rain)water storage and capture mechanisms, (re)creating urban floodplain wetlands and green spaces or using permeable paving	++	Interview L1, L2, L5, L7, L9, L10; Green Infrastructure 12 Point Plan, London Plan, TCFMP, LCCAS; ARP: Thames Water, NPPF, RFRA, SUSD Action Plan, UK CCRA
Increasing the percentage of floodable areas, for instance by widening river and polder beds, deepening basins,	++	Interview L1, L5, L10, L13; LCCAS, Pitt Review, RFRA, NPPF; Making space for water

installing emergency basins or temporarily inundating agricultural and nature areas		
Increasing the drainage capacity of the urban water system, for instance by enlarging sewerage pipes, installing larger pumping stations or higher capacity pumping stations in the water system, enlarging precipitation channels or implementing design standards for shorter return periods of storm water events	+	Interview L2; London Plan, ARP Thames Water, RFRA, UK CCRA

Intermediate Principle: Impact- and risk-reducing planning & planning practice		
Indicators	AoI	Sources
Limiting development rights in flood plains and areas at risk from flooding (flood zoning); Introduction of permits in flood-prone areas	++	Interview L11, L12; London Plan, NPPF, Planning and Policy Statement 25 (Development and Flood Risk Practice Guidance) (Department for Communities and Local Government 2009), SFRA
Prohibiting (property) development in flood-prone areas; Relocating property from flood-prone areas and inhibiting new development	0	Interview L11, L12; Pitt Review
Flood-proofing and flood-resilient design and construction standards for buildings, public facilities and assets	++	Interview L1, L2, L5, L7; London Plan, NPPF, Prepare your property for flooding guidance (Environment Agency n.d.); Improving the flood performance of new buildings (Bowker et al. 2007); Design Manual for Roads and Bridges (Highways England 2012), ARP: UK Power Networks
Elevation of ground level in urban flood-prone areas and roads (according to a determined minimum level)	+	Interview L5, L10, L12, L13
Flood-risk conscious interior design and appropriate planning	+	Interview L5, L12, L13; London Plan, NPPF, ARP Gatwick Airport, Best practice property level protection (DEFRA 2014)

6.1.5 Diversity

Intermediate Principle: Functional & response diversity		
Indicators	AoI	Sources
Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people)	+	Interview L9, L12, L13; London Plan, Green infrastructure 12 Point Plan
Enhancing the variety in energy systems by promoting the generation of different energy sources at different scales (local, regional, global), for instance via creating incentives for decentralized heat or energy networks	0/+	Interview L12; ARP: Thames Water, London Plan
A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization	0/+	Interview L6, L11
Diversity in types of flood protection interventions (preventive alongside adaptive measures) and water	++	Interview L1, L6, L11, L13; SUSD Action Plan, TE2100, London Plan, NPPF, Room for water

absorption mechanisms (i.e. sewer, water storage, permeable paving, public and private green spaces)		
The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated	0/+	Interview L9, L12; London Bridge Plan
Parallel existence of different land-use types in cities	+	Interview L9, L12; London Plan, London Bridge Plan
Strengthening mixed use developments by creating incentives for small- and medium-sized enterprises, promoting clusters of research and innovation, supporting changes of office surplus use to other uses and/or identifying opportunities for new workspace development	+	Interview L9, L12; London Plan, London Bridge Plan

Intermediate Principle: Spatial diversity of critical functions		
Indicators	AoI	Sources
Financial institutions, economic activities, hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city	0	Interview L5, L6, L11; NPPF, London Plan
Decentralized flood protection infrastructure	+	Interview L1, L10, L11

Intermediate Principle: Actor & stakeholder diversity		
Indicators	AoI	Sources
Variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process	++	Interview L4, L5, L6, L9, L11; TCFMP, London Plan, London Bridge Plan, Londons SUSD Action Plan, LRPS
Actors and stakeholders involved in decision- and policy-making have differing professional and knowledge backgrounds	+	Interview L2, L4, L5
Different problem frames and policy solutions for urban flooding	+	Interview L1, L6, L11, L13; SUSD Action Plan, TE2100, Room for water

Intermediate Principle: Institutional diversity, multi-level governance systems & linkages		
Indicators	AoI	Sources
Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)	++	Interview L1, L2, L4, L6, L9, L11
Distributed flood-response capacity across levels (households, communities, municipalities)	+	Interview L6, L10, L11, L13; SNFCR, Flood Action Groups
Governing authorities involved in flood risk management differ in size, culture, internal structure	+	Interview L1, L2, L4, L10
Presence of formal and informal partnerships between governing authorities, academia, firms and NGO; Presence of platforms of exchange among (governmental and non-governmental) actors operating at different levels	++	Interview L1, L2, L4, L5, L6, L7, L8, L10, L9, L13; LCCP, London Drain Forum, London Resilience Partnership, BID, Infrastructure Operation Adaptation Forum

6.1.6 Redundancy

Intermediate Principle: Overlapping functions & roles		
Indicators	AoI	Sources
Shared responsibilities, rights and management authorities among responsible institutions across scales	+	Interview L6, L9, L10, L13
Decentralized water and flood risk management with governing authorities distributed across scales (local, regional, national level)	++	Interview L1, L2, L8, L9, L11, L12, L13; Flood Action Groups (National Flood Forum 2016), Flood and Water Management Act, London Plan
Working groups / project groups integrate multiple actors (shared knowledge)	+	Interview L6, L8, L9, L10; London Plan, London Bridge Plan (Team London Bridge Business Improvement District n.d.)
Flood risk mitigation measures are taken by public and private organizations and actors	+	Interview L5, L10, L11, L13; ARP: Gatwick Airport, UK Power Networks

Intermediate Principle: Functional redundancy in important functions & services		
Indicators	AoI	Sources
Several transmission towers to sustain communication, multiple counterparts for vital functions, multiple routes of supply, electricity and sewage removal, multiple access and evacuation routes	0	
Provision of redundancy mechanisms in critical infrastructure (i.e. water system, electricity, ICT sector, transport networks)	++	Interview L5, L6, L7, L9, L13; RFRA, London Plan, ARP: Gatwick Airport, TfL, Thames Water, Sector Resilience Plans

Intermediate Principle: Spare capacities & back-up resources		
Indicators	AoI	Sources
Alternative power supplies and energy back-up generators for all key businesses, critical infrastructure and services	+	Interview L5, L7, L11, L13; ARP: Gatwick Airport, UK Power Networks, TfL, Sector Resilience Plans
Maintaining stocks and provision mechanisms for food, medicine, water supplies in case of disruption	0	Interview L9; Pitt Review

Intermediate Principle: Compartmentalization & modularity		
Indicators	AoI	Sources
Presence of polycentric, multi-level governance systems	++	Interview L1, L2, L5, L8, L9, L11, L12, L13; Flood Action Groups, Flood and Water Management Act, London Plan
Communication, transport networks, infrastructure grids and other vital functions and services in cities are based on a modular network structure	0/+	ARP: Gatwick Airport, TfL
Presence of compartmentalization dikes, dike rings, compartmentalized polders, temporary dams or flood defences that prevent floodings from spreading to other regions or locally retain substances	+	Interview L10, L11, L12, L13; NFRR

6.1.7 Flatness

Intermediate Principle: Decentralization & Autonomy		
Indicators	AoI	Sources
Governing authorities involved in water and flood risk management are distributed across scales	++	Interview L1, L2, L5, L8, L9, L11, L12, L13; Flood Action Groups, Flood and Water Management Act, London Plan
Municipal authorities have the autonomy to authorize plans and legislate policy; Autonomous management capacity and ability to autonomously develop own strategic goals, tailor-made policies and measures	++	Interview L2, L5, L8, L9, L12, L13; SFRA (London Borough of Southwark 2008), Surface Water Management Plans on borough level (Kissi 2011b), Local Development Frameworks (Greater London Authority 2015b) London Bridge Plan
Financial independence of lower governing bodies	0	Interview L4, L10, L12, L13
Shared responsibilities, functions and management authorities among responsible institutions for water governance	+	Interview L1, L2, L9, L10

Intermediate Principle: Broad participation, stakeholder engagement & inclusiveness		
Indicators	AoI	Sources
Presence of open, deliberative forums or platforms of exchange between actors (policy officials, municipality representative, project coordinators, local population)	+	Interview L4, L9, L13; Making space for water, London Plan, London Bridge Plan
Non-governmental stakeholders are involved at an early stage in the planning & design process and contribute to developing solutions	0/+	Interview L5, L6, L10; London Plan, NPPF
Designing varied local and context-specific mitigation approaches based on neighborhoods consultation and collaboration and needs assessment	+	Interview L4, L10, L11, L13; Neighborhood Plans, Flood Forum, Flood groups
Legal provisions concerning access to information, participation in decision- making (e.g. consultation requirements before decision-making) and access to courts	+	Flood and Water Management Act 2010, Localism Act 2011 (Neighborhood Plan, Neighborhood Development Order, Community Right to Build Order) (HM Government 2011), Catchment Management Plans, Shoreline Management Plans, Making space for water

Intermediate Principle: Room for autonomous change		
Indicators	AoI	Sources
Including indicators from chapter 6.1.1 (Information management & sharing) and chapter 6.1.2 (Public awareness, risk communication, education & training)		
Public awareness, education programs, and hands-on showcases concerning water management approaches with respect to climate change impacts	+	Interview L2, L4, L10, L11, L13; London SUSD Action Plan, LCCAS
Providing solutions, tools and guidance for small-scale (storm-water-related) measures on private property (i.e. urban wetland, storage facilities for rainwater)	0/+	Interview L2; London SUSD Action Plan
Providing funding and guidance on flood-resistance measures, flood-resilient construction and property retrofitting	++	Interview L1, L5, L6, L11, L13; Making space for water, LCCAS, FRCP, Prepare your property for flooding, Improving the flood

		performance of new buildings, Best practice property level protection systems (DEFRA 2014),
Procedures that enable groups to form legal voluntary organizations, raise funds or subsidies for residents' or community-led initiatives and autonomous small-scale projects and provide required venues and space for developing them	++	Interview L2, L6, L10, L11; FRCP, Neighborhood Plans, Flood Forums, Flood Risk Action Groups (National Flood Forum 2016), London Plan, NPPF, SNFCR

6.1.8 High Flux

Intermediate Principle: Availability of and access to resources		
Indicators	AoI	Sources
Pre-event arrangements for governmental reimbursement, such as national continency funds, damage compensation payments	0	Interview L6, L8, L13; Flood support schemes. Guidance note (Department for Communities and Local Government 2014)
Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock	0	Interview L6, L13; Pitt Review
Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems; Reduction of irreversible commitment of resources	0	
Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs)	0/+	Interview L6, L8, L13; Flood Re (Flood Re n.d.), FRCP, Pitt Review
Quick mobilization of human resources for disaster response	0/+	Interview L5, L10
Presence of fixed protocols (in calamity, continuation, recovery plans) with clearly defined tasks in the chain of emergency responders including for citizens on local levels (i.e. through community flood plans which are regularly enacted)	++	Interview L2, L6, L10, L13; LSFRF, LESP Major Incidence Procedure Manual, Strategic Coordination Protocol, London Recovery Management Protocol, Multi-agency flood plans on borough level, National Emergency Response and Recovery Guidance, ARP: Gatwick Airport, TfL, Joint operating principles for the emergency services (JESIP 2016)
Tools for swift visualization of flooding scenario and impacts and accessible knowledge base about the affected area, the water system and its reaction to hazards	+	Interview L6, L10; LSFRF, NFRR, RFRA, Pitt Review, ResilienceDirect, ARP: UK Power Networks

Intermediate Principle: Social & institutional networks		
Indicators	AoI	Sources
Formal and informal partnerships and networks between emergency responders and citizens that advance the speed of recovery (i.e. flood groups, flood forums, mutual aid agreements, church groups)	+	Interview L2, L10; SNFCR, Volunteers' contribution to flood resilience (Brien et al. 2014)
Integrative, participatory measures, physical and virtual places that link citizens	0/+	Interview L9; London Bridge Plan

Governing authorities connect, strengthen existing networks, community-led initiatives and contribute to the emergence of new ones	0/+	Interview L4, L9; FRCP, London Bridge Plan, London Plan, Pitt Review, SNFCR

Intermediate Principle: Having options for flexibility in response		
Indicators	AoI	Sources
Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required; Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it	0	
Vulnerable groups in areas exposed to flooding (i.e. low-income occupations, unemployment, pensioner households, social renters) have access to funding mechanisms to reduce flood risk to physical structures (property protection), to flood insurance for compensation payments in case of flood damage and loss, and other support services required for their safety and resuming livelihoods after a flooding event	0/+	Interview L6, L13; Flood Re (Flood Re n.d.), FRCP, Pitt Review
Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes	+	Interview L9, L12; London Plan, London Bridge Plan
Developing education, leadership, entrepreneurship programs and curricula aiming at skills development in rapidly changing contexts	0/+	London Plan
Authorities involved in flood-risk management and response have mobile resources for flood mitigation at their disposal (i.e. pumps, removable secondary defenses)	+	Interview L10, L11; NFRR

Intermediate Principle: Managing connectivity of critical sectors, infrastructure and natural habitats		
Indicators	AoI	Sources
Measures to calculate and improve accessibility to urban areas and connectivity of (public) transport options	+	Interview L7; TE2100, London Plan, London Bridge Plan, Assessing transport connectivity in London (Transport for London 2015a)
Critical points for accessibility to critical infrastructure during adverse events are identified and pre-emptive measures and response strategies for maintaining functions are developed	++	Interview L7, L10, L11; ARP: Gatwick Airport, Port of London, Thames Waters, Energy UK, ICT sector, UK Power Networks, Energy Networks Association, TfL; LCCAS, RFRA, UK CCRA, Sector Resilience Plans
Spatial intersections of networks with other infrastructure systems and potential cascading effects to other systems are identified and response mechanisms developed or in development	++	Interview L2, L3, L6, L7, L10; Sector Resilience Plans, London Plan, LCCAS, UK CCRA, ARP: Gatwick Airport, Thames Water, TfL
Connecting habitat patches (i.e. green grid) and creating blue corridors (i.e. new water networks from existing and new canals)	++	Interview L2, L9; All London Green Grid Planning Guidance (Mayor of London 2012), LCCAS, Green Infrastructure 12 Point Plan, London Plan, London Bridge Plan, London SUSD Action Plan

6.1.9 Learning & Reflectivity

Intermediate Principle: Institutional learning capacity & reflectivity		
Indicators	AoI	Sources
Institutions are monitoring their activities and performance and critically evaluate implemented polices	++	Interview L1, L2, L4, L5, L6, L8, L9, L12; London Plan Monitoring (Greater London Authority 2016), TE2100
Institutions adopt new routines, patterns of collaboration and engage new stakeholders in projects	+	Interview L2, L4, L10, L13
Integration of long-term resilience thinking into processes and procedures and recognizing when changes to standard practice are required	0	Interview L2, L5, L4, L7
Iterative revision and updating of plans, strategies and standards based on emerging information and research (i.e. climate scenarios)	++	Interview L1, L2, L5, L6; TCFMP, London Plan, NPPF, NFRR, TE2100
Learning outputs inform policy changes and amendments	++	Interview L1, L2, L7, L11, L13; TCFMP, NPPF
Participatory co-learning approaches by providing spaces for learning, through exchange of perspectives in workshops, practice sessions, discussions	+	Interview L6, L8, L9, L12, L13

Intermediate Principle: Experimentation & Innovation		
Indicators	AoI	Sources
Small- and large scale experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts which are financially supported	+	Interview L1, L2, L4, L6, L9, L11, L13; London SUSD Action Plan, NFRR
Creation of testing grounds and support for 'informal space' to experiment and innovate (i.e. living labs, research laboratories)	0/+	Interview L9, L12

6.1.10 Flexibility

Intermediate Principle: Institutional flexibility		
Indicators	AoI	Sources
Institutions offer room for changing the procedures and cooperation arrangements if required	0/+	Interview L4, L6, L7, L9, L11
Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon and goals of strategies and activities	+	Interview L2, L6, L7, L8, L9, L11, L13
Decision-making processes allow for a change in speed and actor composition if required[16]	0/+	Interview L2, L5, L8, L9, L13

[16] Since flexibility in procedures, strategy and activities reportedly vary even within organizations, depending on the department and seem to depend on several external factors, such as size of the organization, internal hierarchy levels, funding mechanisms, the existing set of indicators requires a thorough investigation of organizations and institutions to deliver rigorous results. Due to time constraints such an investigation could not be delivered, therefore findings need to be read with this caveat in mind.

Intermediate Principle: Flexibility in spatial planning		
Indicators	AoI	Sources
Development of multi-use spaces or convertible structures that allow for short-term and long-term shifts in the use of space, parcels, buildings	+	Interview L7, L9, L12; London Plan, London Bridge Plan
Respective policies and provisions are in place that safeguard additions or deletions to the quantity of space dedicated to particular uses at a later stage or interventions into land-use if required	+	Interview L1, L10, L11, L12, L13; RFRA, TE2100
Leaving spaces without development so that they can be used for other purposes	0	Interview L11, L12, Pitt Review
Employing modular elements in buildings	0	
Reducing life-cycles of buildings and infrastructure	0	Interview L7

Intermediate Principle: Flexibility in measures		
Indicators	AoI	Sources
Employing no-regret measures in climate adaptation apt for a broad range of possible future scenarios	++	Interview L2, L5, L7, L11, L13; Making space for water, Reeder & Ranger 2010
Building in allowances according to future climate projections	+	Interview L1, L7, L10, L13; NPPF
Urban planning, disaster risk management, climate adaptation strategies and respective policy development account for a long-term planning horizon (i.e. looking at spatial function, life-cycle of utilities and renewal period)	++	Interview L1, L2, L4, L7, L11, L12, L13; TCFMP, TE2100
Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: options are designing measures for reversibility or sequencing of planning decisions and required sets of interventions according to key thresholds in the current flood risk management system	++	Interview L1, L2, L6, L7, L11, L13; RFRA, TE2100, Making space for water, Reeder & Ranger 2010
Reducing irreversible commitment of financial resources by broadening measures	0/+	Interview L1, L2, L11
Implementing policies that allow for a strategy change and amendments in agreements rather than legislative acts	0/+	Interview L2, L12
No one-fits all solution but consideration of alternatives which include small- and large-scale structural and non-structural measures (i.e. combination grey with green measures) based on local context	+	Interview L2, L5, L11

Table 6.1: Matrix of results per principle for London

6.2 Problem indicators (orange)

6.2.1 Homeostasis

6.2.1.1 Integrated planning, coordination & collaboration

Provide for flexible budget investment mechanisms in organizations and municipal departments

Whereas the integration of flood risk considerations with planning policy is well developed with the guidance of the NPPF, linking climate adaptation measures such as sustainable drainage with urban (re-)development and maintenance programs is not mature in the UK. "*I mean it's fairly new, UK hasn't been doing this as other parts of Europe, so it is a question of wait and see really*." (Interview L13)

This might be the reason why flexible budgetary arrangements for governance authorities to facilitate joint projects are not a concern yet. Instead interviewees report the underlying problem to lie in the overall absence of financial resources, in particular for local authorities to link flood risk measures with projects of other policy domains and on a broader scale for climate adaptation activities in general.

In the attempt to mainstream climate adaptation in the UK, the government ceased any funding for climate change adaptation in England as of April 2016 which decisively impacts the capacities of institutions, such as the LCCP, to inform policy development with local knowledge. Developing an understanding of how to find other funding sources was described as a major challenge for climate adaptation projects (Interview L4).

Budgetary constraints are also reported to affect mainstreaming activities on borough level, especially with regards to maintenance of green infrastructure schemes and permeable paving in and around highways. *"I share the constraints in the maintenance, in the cost of maintenance. […] If I get money for implementing a scheme, I don't get money to maintain it, the Council will have to maintain it and if funding is an issue, they are not going to want to put something in which will not be adequately maintained."* (Interview L13)

Similarly, TfL states capacity constraints to hinder mainstreaming on a larger scale. "*That's our goal but I think we are I'd say we are still in the early days to have some really good stories to tell about that one.* […] *Generally speaking road asset engineers, all their time and budget they spend working to mend what they have already got, we have a huge existing drainage system already what we own, and this is very old and in disrepair, so the priorities to make sure that what we own already is mended and working well and that isn't gonna be the work of some months.*" (Interview L7)

This standpoint is echoed in the UK CCRA which links the lack of alignment between policy goals such as flood risk management with housing and planning policies to capacity gaps caused by funding and resources constraints, particularly at the local level (Committee on Climate Change 2016).

The researcher cannot propose anything to enhance functionality of the indicator at this point since barriers are rooted in current socio-economic, institutional and political conditions.

6.2.2 Robustness & Buffering

6.2.2.1 Robustness through and of infrastructure

Presence of formalized water safety / dike standards that are regularly monitored

In contrast to the Netherlands, there are no formal British standards for coastal and riverine flood defense. Reportedly standards of protection vary from site to site based on economic and environmental feasibility (DEFRA 2005). "*So you might have a scheme which only provides a 1 in 25 years standard of protection, whereas something like the Thames barrier is more like 1 in a 1,000 years protection depending on the value of the properties at risk and the level of investment required to provide that level of protection*." (Interview L1)

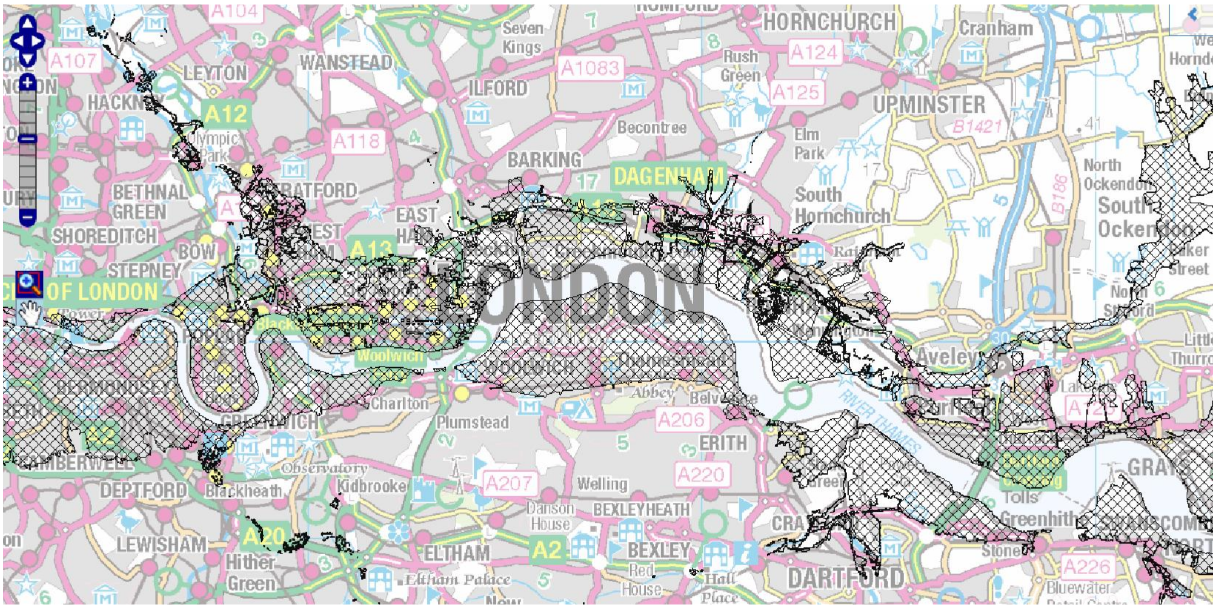

Fig. 6.1: Areas benefiting from flood defenses (Source: http://www.climatejust.org.uk/map)

Yet, there is other legislation that covers flood defenses and the quality of assets, such as the Reservoir Act. In many cases a defined body of qualified engineers is licensed to continuously do inspections of some of the more critical reservoirs in order to keep the public safe and prevent flood defenses to fall into deterioration. Alternatively to formalized standards, there is a defined position by the Environment Agency (following EA) towards the acceptable safety level of their flood defenses (indicated in condition grades) enshrined in their corporate strategy. A way towards more formalized defense standards taken by the UK is the adoption of the ISO 55000 asset management by the EA. This standard allows them to grow up to the objective set by the national government for demonstrating their knowledge about the condition of each flood defenses, what is to be done in case of a flooding event and in case of a damage and what are the measures to quickly resume to previous function and condition (Interview L10).

One of the reasons for this approach is that the UK exhibits a flood risk management scheme which is largely adaptive and does not rely on a steady supply of taxes to fund dike reinforcement investments (Interview L10, R9). "*The UK model looks at what is affordable as opposed to having a standard of protection that everybody is gonna pay into*." (Interview L10).

In addition, flood risk is confined to a much smaller amount of the population where only five percent of England's population are potentially at risk from flooding from rivers, the sea or estuaries. Finally, in some parts the geography of the UK does not allow for a high standard of protection. "*We have got some very steep catchments with very flashy, very rough hydrological rises where we can never provide, in so many instances you can never provide a high standard of protection because the communities are on the very floor of what are very steep-sided valleys."* (Interview L1)

Notably, this strategy does have implications for the degree of public self-sufficiency and the promotion of autonomous flood response capacity on behalf of citizens (see chapter 6.1.7 and 6.1.8)

6.2.2.2 Impact- and risk-reducing planning & planning practice

Prohibiting (property) development in flood-prone areas

Relocating property from flood-prone areas and inhibiting new development

Similar to Rotterdam, complete prohibition of development in flood-prone areas, which would especially pertain to areas next to the Thames, is neither practiced nor realistic in the densely populated urban context of London. "*Generally speaking, we are trying to keep away development from the flood plains but we see that that doesn't apply to London where you have a massive amount of them and well-defended flood plains*." (Interview L11) "*Especially in an area like London, if you took a harder line, it just wouldn't work you know. The vast majority of central London is in a higher risk flood zone but actually arguably at the current time all the developments in that zone are quite well protected."* (Interview L12)

Yet, with the Planning and Policy Statement 25 (Development and Flood Risk Practice Guidance) and the NPPF an alternative system is in place that regulates and diverts larger property development (for business or commercial purposes) away from flood-prone areas (Department for Communities and Local Government 2012a; Department for Communities and Local Government 2009).
The NPPF discerns different flood risk areas according to their probability of being flooded (set out by the SFRA of the local planning authority) and obliges new planning developments over one hectare in size in risk areas to perform a Sequential Test. The latter safeguards that new developments are not permitted to be located in flood-prone areas if there are reasonably available sites in areas with lower flooding probability for the proposed development (Department for Communities and Local Government 2012b; Department for Communities and Local Government 2012a).
If, following the Sequential Test, it is not possible for the asset to be located in low risk flood zones, in a second step, planning interventions are rejected or permitted depending on the combination of their degree of vulnerability and flood probability in the particular area (see Fig. 6.2). The two relevant zones with restrictions for planning applications are the high probability flood zone (1 in 100 or greater annual probability of river flooding (>1%), or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year) and the functional floodplain which comprises land required for flood storage and free water flow.

Flood risk vulnerability classification (see table 2)		Essential infrastructure	Water compatible	Highly vulnerable	More vulnerable	Less vulnerable
Flood zone (see table 1)	Zone 1	✓	✓	✓	✓	✓
	Zone 2	✓	✓	Exception Test required	✓	✓
	Zone 3a	Exception Test required	✓	×	Exception Test required	✓
	Zone 3b functional floodplain	Exception Test required	✓	×	×	×

Key: ✓ Development is appropriate.
× Development should not be permitted.

Fig. 6.2: Flood risk vulnerability and flood zone "compatibility"

(Department for Communities and Local Government 2012b)

In these two flood zones only water-compatible infrastructure (without restrictions) and essential infrastructure is allowed (when passing the exception test), whereas highly vulnerable developments are not permitted[17].
The Exception Test requires property developers to demonstrate (1) that the planning application has wider sustainability benefits for the community that outweigh the respective flood risk and (2) that the planning application along with its users remains safe throughout the lifetime via arrangements to reduce flood risk (Department for Communities and Local Government 2012a). The latter can entail flood-resistant or flood-resilient construction, safe escape routes and emergency planning (Interview L12).

6.2.3 Diversity

6.2.3.1 Spatial diversity of critical functions

Financial institutions, economic activities, hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city

According to several interviewees, spatial diversity of critical functions is not being particularly targeted.
"*No, not really most of the time they tend to be where they tend to be*." (Interview L5)
"*It's being thought about but in some cases it's just oh dear that's a problem*." (Interview L11)
"*I think again sort of early stages of that. The reservoir work is particularly difficult but yeah, we are certainly aware of that*." (Interview L6)
Due to required high investment costs, the relocation of critical infrastructure, such as power stations or water treatment works away from their water supplies is neither a point for consideration (Pitt 2008).

Instead of spatially distributing critical assets, new planning applications and their planned location are evaluated from a flood risk and impacts perspective, following the provisions of the NPPF and additional guidance (for further information see chapter 6.2.2.2). "T*here is information in the NPPF's Technica Guidance in terms of the categorization of different types of infrastructure, and depending on the judgement about their criticality to society, there are requirements to locate those in more or less higher risk zones. So I guess to an extent that is influencing that sort of strategic planning of where that infrastructure is although in a central London context that can be quite challenging*." (Interview L12)
The researcher concludes that risk- and impact-reducing planning and planning practice (such as flood-resistant or flood-resilient design and construction) along with other mechanisms to absorb disturbance (such as building redundancy mechanisms) have a higher salience, are more functional than and therefore supposed to compensate for the spatial distribution of critical infrastructure. Based on the findings about alternative practices that outweigh this intermediate principle in both cases, its exclusion is proposed.

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[17] Water-compatible infrastructure includes amongst others flood control infrastructure, pumping stations, water transmission, sewage transmission infrastructure or open natural space. Essential infrastructure is described as transport infrastructure required for evacuation purposes or essential utility infrastructure that needs to be placed in that area for operational reasons. Further, police, fire, ambulance stations, telecommunication installations qualify as highly vulnerable developments (Department for Communities and Local Government 2012b).

6.2.4 Redundancy

6.2.4.1 Functional redundancy in important functions & services

Several transmission towers to sustain communication, multiple counterparts for vital functions, multiple routes of supply, electricity and sewage removal, multiple access and evacuation routes

Similar to Rotterdam, there is no indication that the duplication of critical functions is common practice in London or the wider UK. Instead, building in redundancy mechanisms into infrastructure networks and assets (see chapter 6.1.6) along with flood-resistant and flood-resilient measures by design (see chapter 6.1.4) seem to be an alternative, more cost-effective pathway. Since this goes in line with the findings in the Rotterdam case, the researcher recommends to exclude above mentioned indicator from the framework.

6.2.4.2 Spare capacities & back-up resources

Maintaining stocks and provision mechanisms for food, medicine, water supplies in case of disruption

No information could be gathered in the interviews as to whether stocks and respective provision mechanisms for critical supplies are being taken care of. "*My hopefully informed guess would be it is pretty minimal given that the real estate and land values are so ridiculously expensive around here, so storage space is certainly kept to a minimum. One of the major problems we have in the area is traffic congestion, because of in-time deliveries, so restaurants are getting food.* (Interview L9)
At the national level, the Cabinet Office issued Sector Resilience Plans based on investigating the resilience of a variety of sectors to different disruptions. Among them the food industry including supply chains and the water sector. From this document, it becomes apparent that research into the food sector and its vulnerability to disruptions is just at the onset. "*In the coming year, the sector will build on recent Government sponsored research looking at the resilience of the food supply chain to port disruption and "pinch points" created by potential fuel disruption. Further research projects will provide an evidence base to strengthen the food industry's ability to respond to and recover from a major coastal flooding event, and build resilience in the supply chain to extreme weather events."* (Cabinet Office 2014, p.11). The researcher therefore assumes that provision mechanisms represented in the indicator are not yet formulated into concrete policies.
In contrast, water companies are stated to be required by law to provide water by alternative means in case the main supply fails (Cabinet Office 2014). In order to generate decisive results in this category, this topic needs further research.

6.2.5 Flatness

6.2.5.1 Decentralization & Autonomy

Financial independence of lower governing bodies

Several interviewees stated financial independence of lower governance levels (boroughs) to constitute a problem in the UK which is rooted in prevalent system of fund allocation and distribution among political authorities.

Financial resources are provided and channeled by the national level. The major funding is provided by the Department for Environment, Food and Rural Affairs (following DEFRA) via the Flood Defense Grant in Aid scheme which consists of about half a billion pounds. Yet, governing authorities across scales reportedly are all "*fishing in the same funding pool*" (Interview L10). Whereas local authorities can apply for funding by handing in a business case, most of this funding is allocated to the EA and the implementation of flood alleviation schemes since they have access to resources and skills that the local authorities don't have (Interview L10 and L13). While major responsibilities for flood risk management and planning were devolved to lower governance levels by the Flood and Water Management Act 2010, they are subject to public sector budget cuts which constrains their capacities to implement respective schemes (Department for Environment / Food and Rural Affairs 2015). "*If I get money for implementing a scheme, I don't get money to maintain it, the Council will have to maintain it and if funding is an issue, they are not going to want to put something in which will not be adequately maintained.*" (Interview L13).

Together with the Localism Act 2011 which provides local authorities with more financial freedom in terms of funding arrangements of local flood alleviation schemes, the recently introduced partnership funding approach is geared towards leveraging contributions and resources from partners (primarily the EA). "*Something called partnership funding, the government has set for LLFA and the EA in the flood defense in aid, 16% must be funded from other parties through the partnership funding idea, and it can come from the Regional Flood Coastal Committee, they can tax people on a local levee to support their own flood defenses in their own communities"* (Interview L10)

6.2.6 High Flux

6.2.6.1 Availability of and access to resources

Pre-event arrangements for governmental reimbursement, such as national continency funds, damage compensation payments

According to the findings, there is no indication that national compensation or reimbursement funds are particularly set-up before emergencies nor institutionalized. The reason for that might be that these are considered a domain of the private insurance sector. *"There are some, it is not, I don't think that there is any sort of particular well-developed for that at the moment but I know that occasionally funding is available for all sorts of community projects, we have also spoken to colleagues particularly in Cornwall after they had some flooding events about how they used some of their money to instigate and initiate some planning work at the very local level."* (Interview L6)

Current compensation approaches are rather reactive apart from previously mentioned repair and renew grants targeted at improving the ability of a property to withstand future flooding. Reportedly the decision to implement a grant and the size of the funding occurs after the event and depends on the size of the event (Interview L8).

Support to fasten recovery in the UK is delivered after an event, in different ways and adjusted to local needs. For instance, there is a business rate relief for flooded business premises where local authorities provide owners three months tax relief. Another service provided to private house owners with flooded properties is the council tax discount which can range from a reduction to complete exemption from taxes for a period of three months. In other cases a fund was stated to be set up by the council to support people in sorting out insurance issues and receipt of respective damage payments (Department for Communities and Local Government 2014; Interiew L13).

Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock

Provision of swift payouts by insurance companies was reported to be a challenge. *"It doesn't work that quickly as we would want them to work, you know if somebody is flooded they have to send somebody to check everything out, then do a report […] insurance is quite a slow process."* (Interview L13). To tackle this issue in some instances support services were set up by local authorities to assist people in handling insurance claims and also guidance is provided about the management of insurance issues (Interview L13; National Flood Forum 2014). In addition, a scheme called Flood RE was initiated to improve the situation: "*it is a way of making sure that the insurance industry is able to pay out should they get a lot of claims, it is relatively new."* (Interview L6) Yet, to that point no unified procedure has been implemented to fasten this process. For that reason the researcher cannot recommend any improvement of functionality.

Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems; Reduction of irreversible commitment of resources

Since this indicator showed to be non-functional for the UK as well it should to be excluded. The responsibility for highways is divided between the three bodies of Highways UK, TfL and local authorities, for the drainage and sewage system it involves Thames Water, TfL and 33 Local Lead Flood Authorities (one in each London Borough). Neither of the interviewees mentioned that financial resources for damages caused by flooding events are withheld. Instead, it is assumed that these expenditures are accounted for within the overall budget for repair and maintenance (Interview L7).

6.2.6.2 Collaboration, social & institutional networks

Governing authorities connect, strengthen existing networks, community-led initiatives and contribute to the emergence of new ones

Though there are fragmented attempts to link up with existing initiatives, primarily by the LCCP, strengthening existing networks and encouraging the emergence of new ones is not (yet) a strategic approach taken up by policy-makers or practitioners in London. There is acknowledgement of the importance of social networks as a driver for communities to pull together in times of emergencies but at the same time a lack of understanding how to strategically gear on that from a policy perspective.*"We are aware that community capacity is a major issue, we had several academics trying to measure and understand it, but we haven't produced anything collaboratively that we think has enough rigor to base anything upon. So we recognize it, list it as identified quality, but we don't do anything on it. That's partly because the GLA is the strategic authority for the whole of London, you know we have the local authorities underneath, they are much closer to their communities and much better in understanding the communities relate better to them than they relate to the mayor."* (Interview L2)
A possible reason for that might be that there is limited understanding about what motivates citizens to engage in community activities and how their interests can be sustained, which is also echoed in the SNFCR (Cabinet Office 2011). Flood Risk Action Groups (FLAGs), Flood Wardens or volunteering groups are reported to pop up where flooding events are experienced more frequently but overall it is described as difficult to strategically plan for them to emerge (Interview L10 and L11). *"It think that it is something that is growing particularly in sort of learning from recent flood events where it has been community groups or volunteers that helped with recovery work. I think that is very difficult to plan in advance in any sort of detailed way. We are never sure where this pockets are gonna happen. So I think it is about the flexibility of identify some of those things early and make the approaches and say if there is anything that we can do to support your local initiatives that would particularly happen at the local government level."* (Interview L6)

With a rising number of case studies and research on the emergence and active encouragement of community resilience across the UK, for instance by the EA, there is a chance that underlying mechanisms will be better identified to inform future policy-making (Brodie et al. 2011; Department for Environment / Food and Rural Affairs 2015; Brien et al. 2014).

6.2.6.3 Having options for flexibility in response

Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required;
Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it

The absence of responses of interviewees that could be associated with these indicators points to their non-functionality for policy-making in the case of London. Representing an output of measures or a best case scenario, it is assumed that they are too complex to be understood by policy-makers and therefore need to be broken down into more concrete, process-related actions to be taken to achieve this end state. A more appropriate indicator will be explained in chapter 6.3.6.2.

6.2.7 Flexibility

6.2.7.1 Flexibility in spatial planning

Leaving spaces without development so that they can be used for other purposes

See reasoning chapter 6.2.2.2

Employing modular elements in buildings

In none of the interviews this came up as a particular activity with regards to flexibility in spatial planning, which does however not exclude the possibility of its presence. This indicator is too much tailored to interior design and architecture as to provide a useful indicator for policy-makers. It requires knowledge about interior planning by architects and clearly goes beyond the insight of spatial planners. For this reason the researcher opts for removing this indicator from the framework.

Reducing life-cycles of buildings and infrastructure

Based on the absence of responses for this indicator, the researcher assumes this is not an approach taken to improve flexibility in spatial planning. One interviewee specifically referred to it counteracting sustainability efforts and pursued long-term robust design for the lifetime of an asset, building development or infrastructure piece. "*I am not sure whether this is sustainability, we tend to frown upon them if buildings are taken down and replaced frequently. We try and say can't you design for a long term and adapt it, rather than, well it does seem a quite wasteful approach to materials*." (Interview L7)

6.3 *Indicators that enhance functionality (green)*

6.3.1 Anticipation & Foresight

6.3.1.1 Monitoring of slow variables

An important variable so far not integrated into this framework, but captured by several policy documents as a decisive factor for combined tidal and riverine flood risk, are river flows. They are also outlined to be critical for potential damage to vital infrastructure such as bridges or pipelines (Committee on Climate Change 2016; Environment Agency 2012). Due to projected increases in rainfall, peak river flows are expected to increase by 10 percent up to 2055, and from 2055 onwards by 20 percent (Department for Communities and Local Government 2012b). Therefore, the recent UK CCRA proclaimed implications of projected changes in river flows on future risk a priority research area (Committee on Climate Change 2016). The relationship between river flows and precipitation is complex and non-linear, influenced by factors such as catchment size, land use, steepness, roughness and catchment saturation. High resolution rainfall scenarios of the Met Office and hydrological models of the EA, fed with rainfall, catchment and ground surface information help to determine the extent, depth and velocity of flooding resulting from a river flow (HM Government 2016). Thus, the following indicator is proposed to be added:

Modeling of peak river (fluvial) flood flows

The researcher also suggests an additional indicator decisive in the London case. The acceptable level of risk on behalf of the wider public (also called risk appetite) and the preparedness of institutions to manage and respond to emergencies was reported to be a pivotal factor since it determines the quantum of adaptation that needs to be delivered to stay within the band of acceptable risk (Interview L2). A city's attitude to flood risk was therefore integrated as one of the indicators for the TE2100 strategy due to its influence on the course and timing of delivery of adaptation measures. Monitoring is mostly based on national surveys (Interview L11; Environment Agency 2012).

Public and institutional attitudes to flood risk

6.3.2 Preparedness & Planning ahead

6.3.2.1 Public awareness, risk communication, education & training

With 15 percent of London's surface area being at risk of tidal or fluvial flooding and the whole population potentially at risk from surface water flooding through cloudbursts and longer periods of precipitation, public risk awareness and response capacity is high up the political agenda in the UK (Greater London Authority 2015b). Yet, interviewees deem the current level of risk awareness to be low except among the population with previous flooding experience (Interview L6 and L10). "*How well the actual community is aware of this is another issue, we have the flood warning system, but we have quite of a Holland syndrome in the middle of London since it's quite well protected against tidal flooding, so it's probably not at the forefront of the people's minds, I am sure it isn't as much as it should be.*" (Interview L11)

Information about how to prepare for flooding is provided through various channels and agencies but they experience difficulties with making people act upon the information provided. A point brought up by several respondents and reports is the way by which messages are conveyed to the public as well as the translation into useful knowledge that can be integrated into the practice of employees (Interview L4 and L6; HM Government 2016; Pitt 2008). "..*So it is about telling people how they are at risk and what to do. So we have done a lot of research into how to get the message across better, use language that people understand. They don't understand the language of return periods so a 1 in a 100 years flood is a meaningless concept to most people. We have done work on […] looking at how people absorb information from maps, communicate that and how much should be best produced to allow people visualize the information that is key for them."* (Interview L1)

"I think people understand the impacts of floods because they see it on the news but trying to get them to understand some of the likelihood factors is quite difficult, preventing a one in hundred years flood probably does not make so much sense to them." (Interview L6)

Being a crucial clue for improving public flood risk awareness which appears to be a barrier in both cases, this recommendation is added in the form of an additional indicator:

Making flood risk comprehensive for the public

6.3.2.2 Preparedness of businesses for adverse events

A smaller adjustment is made in preparedness of businesses for adverse events by adding a particular tool, namely "timely and tailored flood warnings", used in London to deliver early and tailored flood notification messages to businesses. "*We got a system called Cross-Sector Security Communication System (CSSC) and that allows London Resilience but also the police and Transport for London to provide timely messages in a sort of authoritative way to businesses, it is not just the public information that is available, we can go beyond that, so it is about the particular issues we want businesses to be aware of."* (Interview L6)

6.3.3 Homeostasis

6.3.3.1 Clearly defined responsibilities of actors and institutions

Two changes are suggested to be made with regards to clearly defined responsibilities.

The first one is a minor adjustment based on the recognized necessity to place responsibilities within a wider context than flood prevention and protection. When it comes to climate-resilience, there are several risks to be taken into account and therefore the idea of broader risk ownership is introduced.

The term and indicator is adopted from the adaptation score card, proposed for the monitoring of the implementation of 33 actions proposed in the LCCAS. "*I came to ask what I can boil adaptation down to on its simplest levels. So what we have done is looking at flood/drought/cold and heat and for each of them ask six questions and for each question we traffic-light, red, yellow, green and then there is a summary column. [One of them is] do we have a defined owner."* (Interview L2)

Statutorily defined risk owner with clear line of oversight and responsibility

Instead of: Statutory responsibility for flood prevention and protection is defined and determined in policy documents

The second change refers to an issue not appropriately addressed in the framework but reported to be crucial by several interviewees. Allegedly, responsibilities and required response are more prone to unclarity when there is more than one problem owner, as illustrated by the following interview sections. *"It can get a little bit confusing, particularly with flooding, is it surface water flooding or is it water of the canals or river channels because technically they are owned by different agencies…"* (Interview L6)
"There are a lot of grey areas and I think that the change is that because of the complexity of the landscape I am not sure whether it makes necessarily a lot of sense to the general public. I think they, responsibilities on surface water vs. river flooding is quite tricky particularly when it comes concurrently. So you get surface water problems when the drains can't discharge to the rivers, you only get it in extreme instances of rainfall" (Interview L1)

For these issue areas (including emergency response) merely outlining responsibilities is not sufficient. Reportedly, a central control and coordinating instance is required, along with more formal mechanisms of oversight and cooperation (Interview L2, L4, L6; HM Government 2016; Port of London Authority 2015). The importance of such an agreed coordinating resource is underlined by its adoption in emergency response with regards to a determined lead agency for each type of flooding event (Interview L5, L6 and L13; Greater London Authority 2015b; City of London 2010; London Resilience Partnership 2015). It is also integrated into the adaptation score card as one of the central indicators for adaptation monitoring: "…*so is there somebody leading or engaging all the other bodies to own risk, is there somebody coordinating it, leading the process?*" (Interview L2)

For this reason, the researcher proposes the following indicator:
Formal mechanisms of oversight and /or cooperation such as an agreed coordinating responsibility
Instead of: Cross-institutional division of labor and tasks for performing emergency response activities

6.3.4 Diversity

6.3.4.1 Functional & response diversity

The transition to decentralized energy production through localized heat networks across the London area is stated as an explicit objective in the Mayor's London Plan and forms part of a wider shift towards a more sustainable economy. Therein, 25 percent of the heat and power used in London is stated to be delivered by decentralized heating and cooling networks and larger scale heat transmission networks by 2025 (see Fig. 6.3) (Greater London Authority 2015b).
Interviewees mentioned this strategy with regards to functional diversity and referred to it as contributing to "*an added resilience to failure of the national grid*" while outlining a clear mandate to make respective policy and planning provisions on the local level. "*I guess in terms of sustainability policy we and the London Mayor more generally have a strong focus on delivering decentralized heat networks, so again you could see delivery of those approaches alongside requirements for more renewable energy and so on…"* (Interview L12)
Accordingly the following amendment of the initial indicator is recommended:

Enhancing the variety in energy systems by promoting the generation of different energy sources at different scales (local, regional, global), for instance via decentralized heat or energy networks

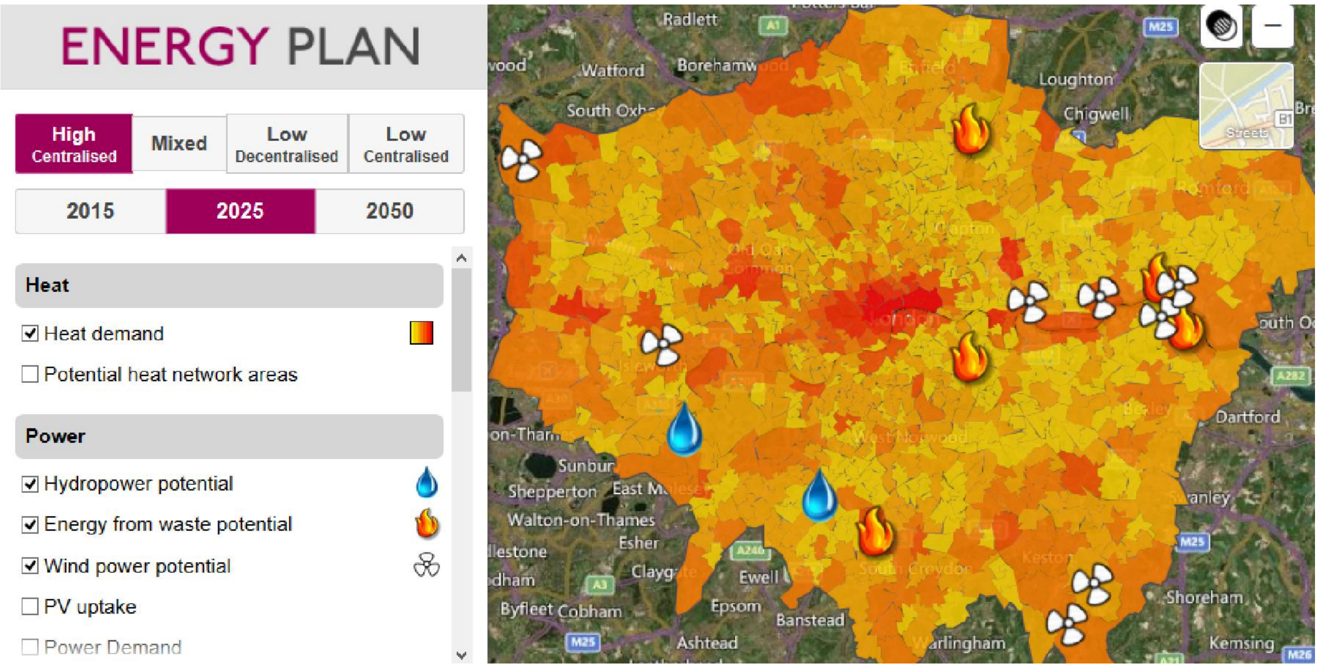

Fig. 6.3: Map of Greater London Boundary with options for decentralized energy generation in 2025
(Source: https://www.london.gov.uk/what-we-do/environment/energy/scenarios-2050-london-energy-plan)

Another aspect touched on by the indicators for functional and response diversity is diversity in land-use.
In cities, different land use types come down to mixed use development exhibiting a variety of different business types and sizes, a tenant mix and diversity in activities going on.
"I would see in terms of land use, we are a very diverse borough, so there is a large residential area, and there is a quite mixed economy, from big office development in the North to an industrial, and kind of small business units. So if you think of it in terms of economic resilience, then we do have that kind of response diversity. […] And then I think it also comes back again to the mixture of uses and activities we have going on in the borough perhaps." (Interview L12)
"I mean certainly talking in more general terms, do you know London Bridge, the area? Tulip Street is the street that runs in the middle of our neighborhood, it is private, owned by one developer. It's all glass, steel, granite surfaces, and it's spotlessly clean and safe and everything. There is a real feeling also among the businesses in there that they don't want this one-size-fits-all approach steam-rolering into the rest of London Bridge. They want to see a diversity in terms of the business mix and tenant mix and nightlife provision and so on." (Interview L9)

Economic diversity is not an unfamiliar concept in the UK, particularly in London. Quite the contrary, strengthening London's economy by diversifying business has been a long-term strategy. Based on this experience, worthwhile policy options for enhancing economic variety can be drawn from the London case. These range from harnessing spatial redevelopment opportunities to change use and create new office space (such as start-up space or co-working space), developing clusters of research and innovation or green enterprises, to creating tax incentives for small- or medium sized enterprises in certain areas. Concrete directions are found in the London Plan and the borough level London Bridge Plan which give rise to the following additional indicator:

Strengthening mixed use developments by creating incentives for small- and medium-sized enterprises, promoting clusters of research and innovation, supporting changes of office surplus use to other uses and/or identifying opportunities for new workspace development

6.3.5 Flatness

6.3.5.1 Room for autonomous change

The researcher proposes a slight amendment of the initial indicator "Affected communities are provided guidance on flood-resilient construction" towards including the aspect of funding and flood-resistance measures: Provision of funding and guidance on flood-resistance measures, flood-resilient construction and property retrofitting.

In contrast to the Netherlands, there is no steady, dedicated centralized financial resource to invest in the construction and reinforcement of flood defenses in the UK. Since decisions about flood alleviation schemes are mainly based on environmental and economic considerations, not all parts of and around London are sufficiently protected. Consequently, the strategy is to make certain parts of the population learn to live with flooding events. "*We can reduce flood levels by keeping a high tide out but you gotta do it every time which is a bit of an imposition on the [Thames] barrier [and affects its lifetime]. So to avoid that in the future we're gonna make people live with more flooding in West London*." (Interview L11).

Against this backdrop self-sufficiency and property protection measures on behalf of citizens become salient and are actively supported (Interview L11). Since interviewees consider this "*a case of people's awareness and willingness to be proactive*" (Interview L8) a variety of information sources and best practice guidance produced by the EA, DEFRA or CIRIA are available for implementing what is referred to as property level protection (DEFRA 2014; Environment Agency n.d.; Bowker et al. 2007). It entails the use of flood resilient materials, having safe means of escape or considerations for interior design such as locating electrical circuits above expected flood levels to ensure that utilities (electricity, water, gas) can continue to operate when the building is flooded (Interview L1 and L5). Communication of best practice to the audience, raising awareness and pointing citizens in flood-prone areas to these sources of information are primary measures undertaken by the EA and local authorities for citizens to recognize their opportunities for autonomous flood-risk reducing action (Interview L1 and L13).

In addition, interviewees and policy documents stress the importance of funding schemes to incentivize the population to invest in flood-proofing measures of and in their own homes. Reportedly several funds such as home improvement grants, loans or subsidies were made available on local and national level. A wide-reaching grant scheme, initiated by DEFRA and the EA, which provided free property level flood protection to households previously flooded, decisively increased the uptake of measures (Interview L6, L11 and L13; Greater London Authority 2011; Pitt 2008; DEFRA 2005). Such a subsidy scheme is currently also being considered to engage more private parties in SUSD measures on their properties (Interview L2; Greater London Authority 2015a).

What is worth mentioning, is the element of uncertainty whether awareness raising and information provision actually translate into preparedness action on behalf of citizens. More research into underlying motivational factors is therefore desirable.

"I think that community bit is something we are very keen on. Logically it makes sense but it is very difficult to implement. So putting some guidance and information out there for people, it is difficult to mandate anybody to take any action at that level […] I think perhaps asking questions about actually do people change their behavior in response to warnings and trying to understand what motivates them a bit more." (Interview L6)

6.3.6 High Flux

6.3.6.1 Availability of and access to resources

Effective emergency response comes down to the local level. Even when there are fixed protocols in place on a higher level, there is no guarantee that these will work out on the ground unless some preparatory ground work is done. "*The basis of how emergencies are managed in the UK it is obviously through the Civil Contingencies Act and bringing together the emergency actors […] the main thing is coordinate it from top to bottom."* (Interview L11). Formal emergency plans on behalf of local authorities are considered as pivotal as the awareness of communities of how to react according to plan (Interview L10).
Social resilience is gaining salience on the national agenda as represented by its anchoring on national level in a Strategic National Framework on Community Resilience (following SNFCR) issued by the Cabinet Office in 2011 (Cabinet Office 2011). Authorities actively encourage citizens and neighborhoods to develop community flood plans outlining preparatory measures that can be undertaken on a local level, emergency planning and evacuation procedures (Interview L1, L10 and L13). Apart from improved capabilities for autonomous response and coping physically and mentally with flood risk, such initiatives can facilitate increased coordination during a flooding event and safeguard appropriate assistance of vulnerable people (Department for Environment / Food and Rural Affairs 2015). Also the Pitt Review, an evaluation of a major flooding in 2007, identified collaboration among citizens and with Local Flood Authorities during emergencies crucial for quick and efficient flood response (Pitt 2008).
Furthermore, regular emergency exercises to keep responsibilities in mind are mentioned as a prerequisite for swift and efficient emergency response which pertains both to all levels of emergency responders and communities that take responsibility for erection of demountable defenses (Interview L6 and L10). "*The way they are dealing with that is every five years there is sort of a big rehearsal so the people will then reinforce reminded that they live in an area at risk from flooding and therefore we are gonna do a little practice run and see if everything is in place […] see how people get their stuff together and mobilize things*." (Interview L10)
The researcher therefore proposes the following adjustment of the initial indicator:

Presence of fixed protocols (in calamity, continuation, recovery plans) with clearly defined tasks in the chain of emergency responders including citizens on local levels (i.e. through community flood plans), which are regularly enacted.

6.3.6.2 Collaboration, social & institutional networks

In the course of the research it became clear that the initial indicator requires refinement to be functional for recovery. In order to advance the speed of recovery, partnerships and networks must be narrowed to those that improve coordinated flood risk management, emergency response and/or community response capacities. The SNFCR draws attention to the importance of communities to work in partnership with local authorities, emergency services and other responder organizations during and after emergencies. This safeguards that community activities complement the work of the other bodies (Cabinet Office 2011).
Interviewees identified several practices that informed the amendment of the initial indicator. The EA for instance does have a prolonged arm for the swift local mobilization of required resources by partnering with six different large contractors working all over the country to make flood defenses. Apart from being well-versed and knowledgeable in undertaking flood risk management schemes, these contractors have access to a much wider set of resources than the EA such as material or temporary labor which can be quickly mobilized (Interview L10).

Another example is the set-up of flood action groups or flood forums local communities put together to pool local expertise and capacities. In the case of a flooding these are integrated into the wider response to support the overall body of knowledge with regards to what to put when, why and where (Interview L10). Case studies showed that these entities improved partnership working between emergency responders and citizens on the ground (Department for Environment / Food and Rural Affairs 2015).

A third practice identified are mutual aid agreements between local resilience forums on borough level, for instance between police forces, fire or rescue services, but also going up to the national level including the EA (Interview L6). By these agreements different entities agree to share pumps, boats or any kind of required equipment in case of an emergency. In addition, within the Local Resilience Forums there are Strategic Coordination Groups with representatives of all relevant organizations and sectors in the borough. These are brought together by the Resilience Forums to seize opportunities for support to others and determine their state of readiness (HM Government 2016).

Changes to the initial indicator are therefore proposed as follows:

Formal and informal partnerships and networks between emergency responders and citizens that advance the speed of recovery (i.e. flood groups, flood forums, mutual aid agreements, church groups)

Instead of: Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs

A decisive aspect for strengthening social cohesion, currently not sufficiently addressed by the initial indicator are integrative, participatory measures and physical places that link citizens. *"They [referring to residents of the London Bridge area] like things they can take part in and have ownership of, so that's something that I think we can bring to the table, because we can do small projects here that cost 200,000 € and do something individual and particular to that location and space, so then really have it that everybody is invited into that space. We are not doing it for one type of person, we are not doing it just for the employees, we are also doing it for the residents, the older and the younger people. So I think that's our way of thinking about it, a softer approach, more human-scaled approach to the public realm."* (Interview L9)

Collaborative physical and virtual spaces which connect local businesses, organizations and citizens on a district level are a powerful instrument to encourage engagement and collaboration. Facilities which offer room for exhibitions, cultural programs or events are an integrative part of the London Bridge Plan (Team London Bridge Business Improvement District n.d.). By providing space for get-togethers they can positively contribute to "*that sort of neighborhood-feel, whether you know your next-door-neighbor business, whether that business knows the policy officer, the homeless worker down the road […] a sort of a catalyst for making communities happen*." (Interview L9)

Therefore the researcher opts for the below mentioned indicator amendment.

Integrative, participatory measures, physical and virtual places that link citizens

Instead of: Prevalence of platforms of exchange among actors

6.3.6.3 Having options for flexibility in response

It was previously mentioned that having options in response is strongly linked with social class and wealth of individuals. To render the initial indicators functional for policy-making, a feasible starting point is looking at those citizens or citizen groups which do not have the monetary resources to shift livelihoods, modify physical structure, or to repurpose resources and means. The second step consists of investigating by which measures the respective capabilities of these particular citizens or citizen groups can be strengthened.

One interviewee pointed out a project called Climate Just the output of which shows a map of social vulnerability to flood risk based on a set of indicators identified. This map is fed with respective census data for the UK (see Fig. 6.4). "*We structured it about what is the issue around flooding, what is the deal, who is vulnerable? For example, people in rented housing, so why is that an issue, explaining because there cannot be changes to their property*." (Interview L4). This project along with the indicators identified for social vulnerability help to identify the target group for potential measures (see Fig. 6.4).

Especially two categories are relevant in this respect.
The first one is income, which is broken down to the following proxies:
- Unemployment (percentage of working population unemployed)
- Long-term unemployment (percentage of who are LTU or who have never worked)
- Low income occupations (percentage in routine or semi-routine occupations)
- Households with dependent children and no adults in employment
- Pensioner households
- Social renters (households renting from social or Council landlords)
The second one is flood insurance, which is broken down to:
- Low insurance availability /affordability (percentage area potentially exposed to severe flooding)

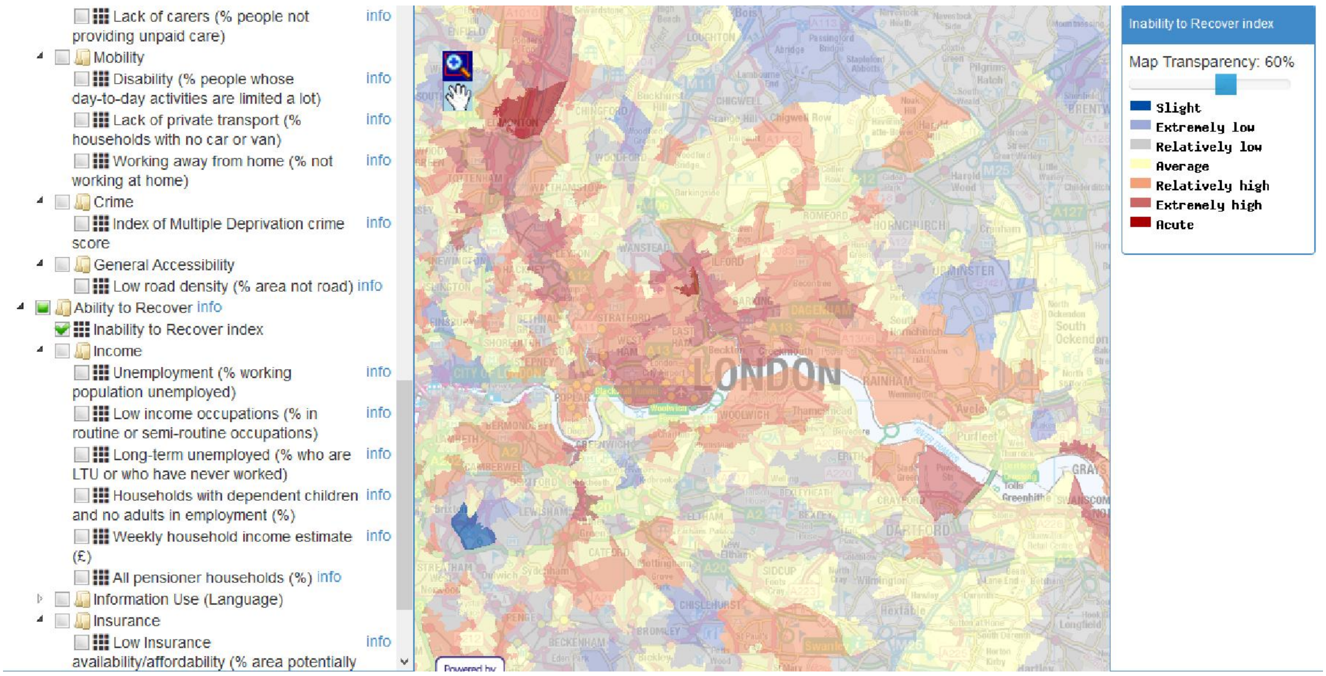

Fig. 6.4: Climate Just Map – Inability to recover index (aggregate indicator)

It became clear by the interviews that for the context of flood risk, a long-term change of physical location is not required, since temporary housing is provided by government schemes for affected citizens. Thus, flexibility in response comes down to having the options to reduce individual flood risk by having the financial means to flood-proof physical structures (property level protection) and/or being compensated for flood damage and loss (which requires access to an insurance scheme or a recuperation fund). Based on these criteria, the following alternative indicator is proposed:

Vulnerable groups in areas exposed to flooding (i.e. low-income occupations, unemployment, pensioner households, social renters) have access to funding mechanisms to reduce flood risk to physical structures (property protection), to flood insurance to receive compensation payments in case of flood damage and loss

Instead of: Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required; Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it.

Noteworthy, we find a very similar indicator though not as detailed already represented in High Flux in the intermediate principle “Availability of and access to resources”: Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (for instance relocation housing programs).
Yet, there is a slight difference between the two, since having options for flexible response is more aimed at proactive arrangements whereas the former can relate to ad-hoc provisions as well. Considering the attempted use of the framework by policy-makers, simplification rather than increased complexity is recommended. Therefore, the two aspects are united in one single indicator:

Vulnerable groups in areas exposed to flooding (i.e. low-income occupations, unemployment, pensioner households, social renters) have access to funding mechanisms to reduce flood risk to physical structures (property protection), to flood insurance for compensation payments in case of flood damage and loss, and other support services required for their safety and resuming livelihoods after a flooding event.

6.3.6.4 Managing connectivity of critical sectors, infrastructure and natural habitats

In densely populated areas the connectivity of public transport options such as bus, tram, train, speed train, river lines, bicycle routes and underground play a major role for a quick movement of people and services. In London particular emphasis is put on assessing and improving the connectivity of public transport options. TfL developed a measure of connectivity by public transport called “Public Transport Access Level” (PTAL) which informs planning processes all over London and can be visualized in maps (see Fig. 6.5). The following indicators inform its calculation: walking distance to nearest station/stop, waiting times at nearest station/stop, several services available at nearest station/stop, major rail stations are nearby (Transport for London 2015a).

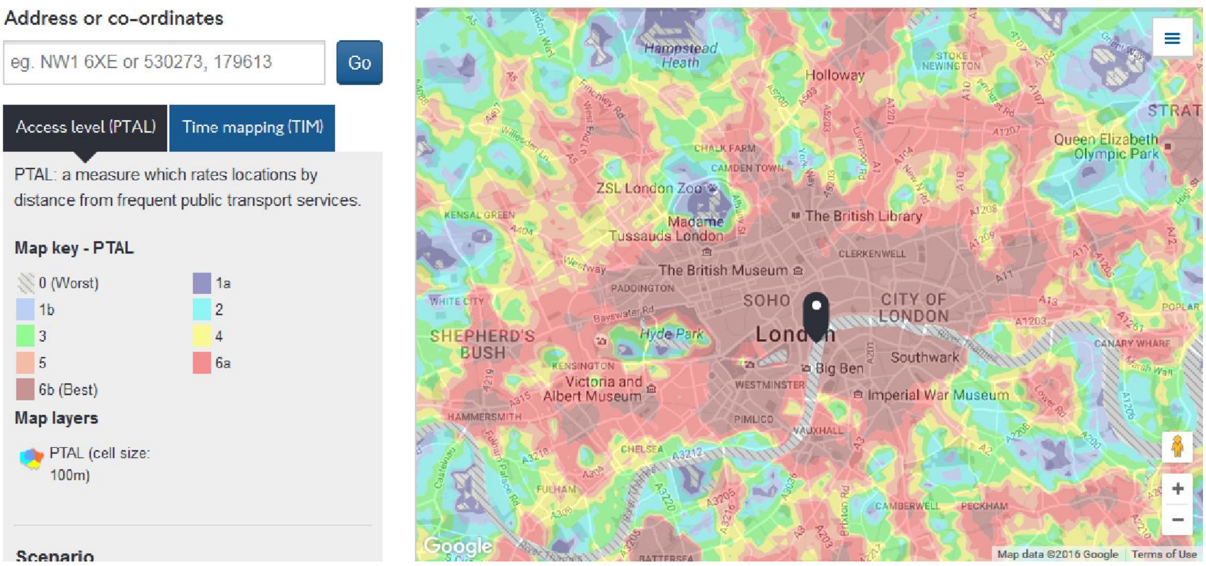

Fig.6.5: WebCAT Tool TfL showing PTAL for London

The importance to improve connectivity and interchange between different forms of transport is also reflected by its adoption in the London Plan. Therein, the following actions are stated to be planned: extension of the London Underground Network, providing new river crossing for riverine transport, implementing a high frequency service on the London Rail Network, improvement and extension of London's national and international transport links for passengers and freight, improvement of public transport connections to airport, ports and rail terminals (Greater London Authority 2015b).

Accessibility to areas and neighborhoods decisively affects the citizens' ability to respond to emergencies. Poor accessibility to an area implies a reduced response time of residents to emergencies. Recognizing its importance, the Climate Just project developed a proxy indicator to measure general accessibility to an area and neighborhood: road density, which is calculated by the percentage of area that is not road. Fig. 6.6 visualizes this indicator for the greater London area.

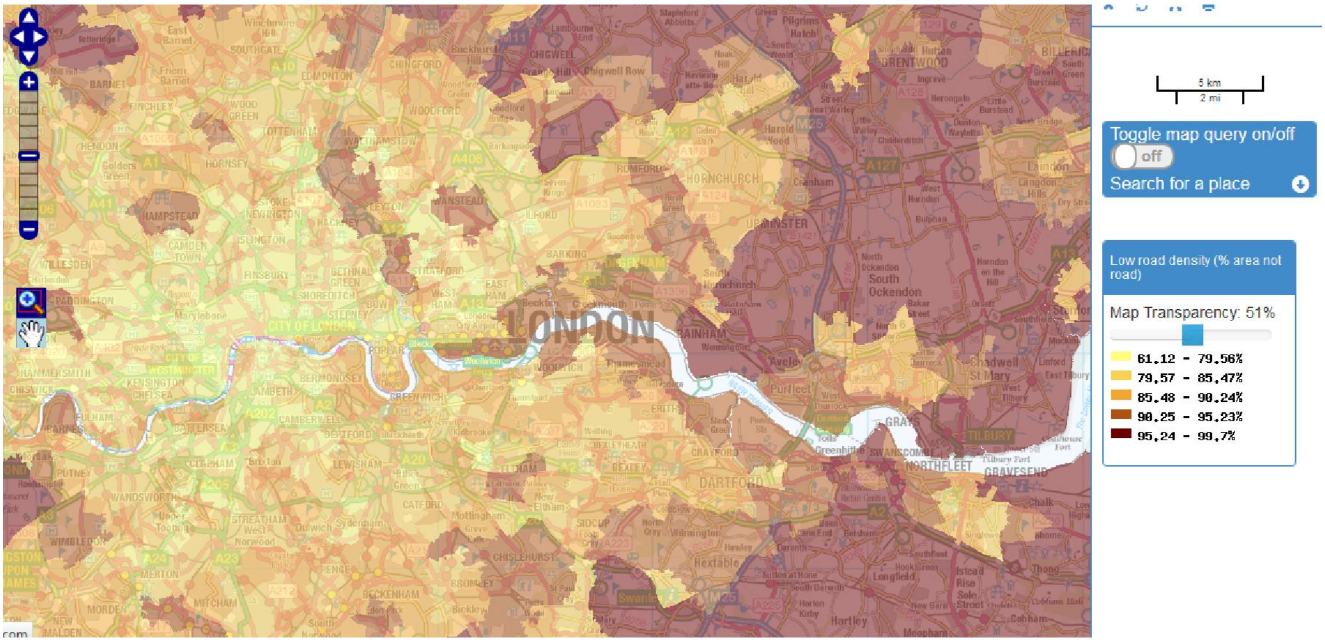

Fig. 6.6: Percentage of area not road as a proxy indicator for general accessibility
(Source: http://www.climatejust.org.uk/map)

Having outlined the importance of accessibility and connectivity of urban areas, knowledge about the current state to inform improvement measures is considered an integrative part of resilience-building. Thus it is opted to be included into the framework with the following indicator:

Measures to calculate and improve accessibility to urban areas and connectivity of (public) transport options

6.3.7 Learning & Reflectivity

6.3.7.1 Institutional learning capacity & reflectivity

The initial indicator "institutions adopt new routines, patterns of collaboration and engage new stakeholders in projects" is not specific enough to reflect on the barriers to resilience-building experienced in organizations and described by interviewees. The adoption of long-term thinking into practice and procedures, and changes in persistent routines are stated to be major challenge. For this reason the researcher opts for a replacement indicator.

In part, the problem is described to lie in the entrenched perception of climate adaptation as risk management. Consequently, the goal is to "*put [them] back to what it was before*", "*getting back to business as usual […] without thinking about the opportunity to do things differently and just take the long-term view*." (Interview L1 and L5). However, such behavior contradicts the foundations of resilience and inhibits harnessing disturbances as a learning momentum to initiate change. "*But the key point is that we need to get back to where we will be more resilient and realize that we are on a pathways with the changes that the climate will bring, with a radically different future. So it needs to be resilience linked to a journey instead of returning to what it was because it won't be*." (Interview L5)

Respondents described the difficulty of cultivating resilience-thinking in organizations in a way that goes beyond some procedural implications, such as long-term positions with infrastructure investments (Interview L4). Also, recognizing the momentum when to initiate procedural or operational changes in order to better adjust to changing climate events is seen as a challenge. This is outlined by the following interview section:
"*[…] there is not an immediate problem pushing it and there is no long-term design change but we are saying we want to do something differently, so it is having the real imperative to warrant investing money in it, and the time and the change of process, or loss of operational service […] but at what point do extremes become so frequent that we actually have to stop and say, do we need a whole other process here or do the tracks need to be made of something different, when the current mitigation is not sufficient, actually to step back and say we need a different response to this.. it's about understanding when our current ways of dealing with problems are no longer adequate I guess.*" (Interview L7)

Against the backdrop of these findings, organizations and businesses will have to find ways to provide required internal structures and mechanisms that allow for these capacities to develop, which might imply radical changes. Therefore, the following replacement indicator is proposed:

Integration of long-term resilience thinking into processes and procedures and recognizing when changes to standard practice are required.
Instead of: Institutions adopt new routines, patterns of collaboration and engage new stakeholders in projects

6.3.8 Flexibility

6.3.8.1 Flexibility in spatial planning

Findings stress that the initial indicator "Spatial design allows for additions or deletions to the quantity of space and land dedicate to particular uses" requires adjustment to be functional. The underlying reasoning is that in densely built-up spaces, spatial design alone cannot sufficiently allow for these functions unless policies are in place that make required interventions into space and land-use possible at a later stage.
Both the London Plan and the RFRA make recommendations for setting back developments from river banks to allow for maintenance and upgrading of flood defenses (Greater London Authority 2015b; Environment Agency 2009a). Furthermore, local planning authorities report about planning requirements imposed by higher level authorities: "*There are requirements on us to safeguard space around existing flood management structures, both to facilitate their existing management but also I think the EA has been saying we need to look at this into*

more detail actually in our policy around not preventing the future upgrading of those flood defenses. I am thinking here particularly of the river defenses we have along the Thames and we get to the Thames Estuary Strategy and the key part of that for Southwark is about maintaining, thinking about the future need for raising these river flood defenses." (Interview L12)

Several policy and legal options are described for spatial reservation in order to safeguard space for future flood defenses or additions to spatial use: from introducing timed land use (such as industrial use for several decades with an expiration date through a built-in clause) to compulsory purchase of land justified by overriding national interest (Interview L11). To account for the importance of the policy element in driving flexibility in spatial planning, the researcher suggests the following indicator amendment:

Respective policies are in place that safeguard additions or deletions to the quantity of space dedicated to particular uses at a later stage or interventions into land-use if required.

Instead of: Spatial design allows for additions or deletions to the quantity of space and land dedicated to particular uses

6.3.8.2 Flexibility in measures

One well-established approach for dealing with uncertainty, especially with regards to structural interventions is building in allowances or margins according to climate projections.

In the UK, climate projections are provided by the EA in terms of probabilistic scenarios (low, medium, high) and companies choose which scenarios to use for their strategy development. In consideration of uncertainties of these scenarios, a span of tolerance is usually built into assets, for instance a range of different temperatures for which rail tracks or highways are suited (Interview L7).

When it comes to flood risk management, similar models for future predicted flood depth and flow levels of the Thames exist to inform future-proof bridge development according to which developers are required to design (Interview L13). Furthermore, building in allowances for future sea level rise and high tides was described as common practice for flood defenses of any kind since the 1970s (Interview L5 and L10). This was also discovered to be common practice in Rotterdam. The researcher therefore opts for the integration of this approach into the framework with the following indicator:

Building in allowances according to future climate projections

The researcher proposes a second adjustment in this category.

The flexible adaptation pathways approach designed for the Thames Estuary 2100 project touches on an additional option for long-term, adaptive flood management. The latter set the path for flood risk management under conditions of uncertainty and has become a benchmark. Its strategy consists of sequencing the implementation of different sets of measures over time, thereby facilitating incremental adaptation while keeping options open to deal with future climates (Reeder & Ranger 2010). For determining the time spans of required interventions and antecedent lead time for decision-making, key thresholds of the current flood management system and each of the proposed interventions[18] were identified (i.e. a certain height of the water level) (Interview L1, L6, L7 and L11). The output consists of a route-map with four adaptation measures "packages" (called high-level options) that can be implemented over time (see Fig. 6.7) (Reeder & Ranger 2010).

[18] There are four key thresholds identified: (1) limit to reinforcing system of walls and embankments, (2) the level of sea level rise where the Thames Barrier cannot deliver the target protection level of 1 in 1000, (3) limit of reinforcing the Thames barrier including modifications, (4) overall limit to adaptation of the current flood protection system (5m sea level rise) when radical changes are required (Reeder & Ranger 2010; Environment Agency 2009a).

"So each option was a decision pathway or route which takes you from where we are today to the extreme case, so that sort of made it clear if we want to stay in London with a 4 meter sea level rise we need a barrier and then it gave us the limit for that as well which is about 5 meters or a bit more, so that sets a very long-term perspective, so it gives you the information that if you get to 5 meters then you oughta use the pump and to pump the Thames over the barrier or you have got to radically change the way you exist in a flood plain in London." (Interview L11)

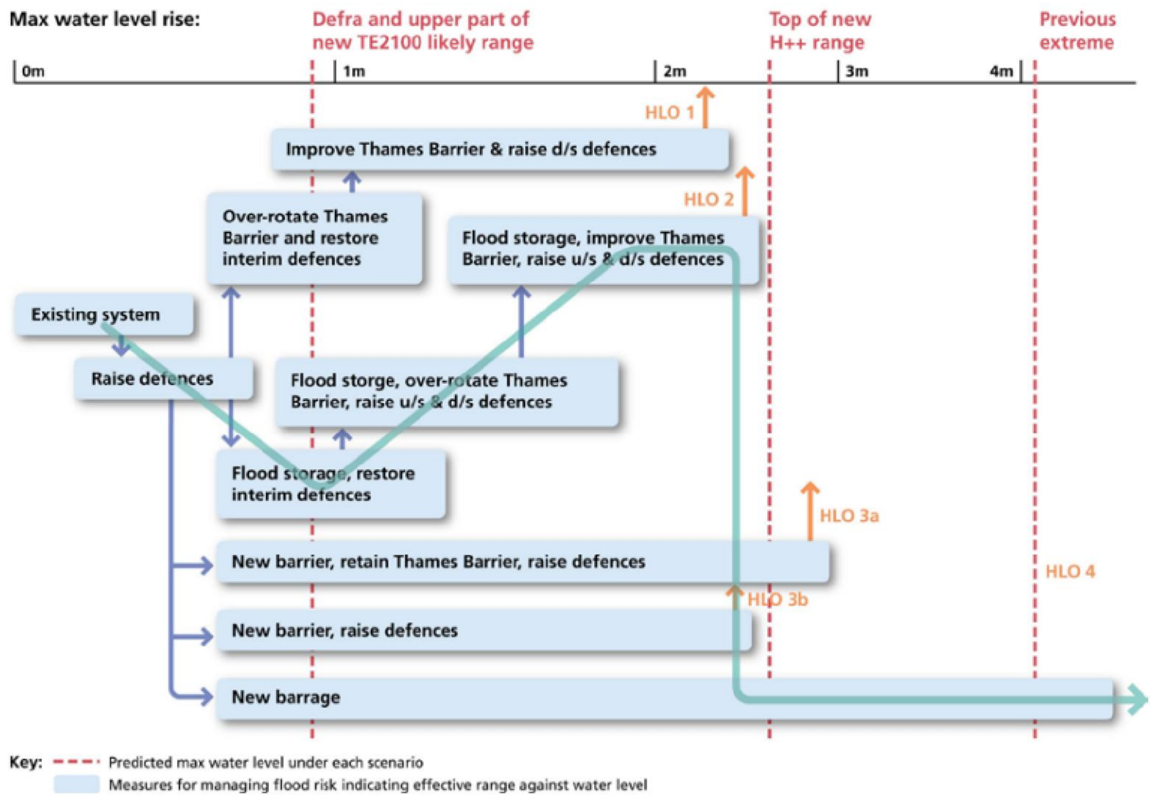

Fig. 6.7: The four High-level adaptation options (HLO) developed for TE2100 including pathways and options switches (indicated by the blue line) based on threshold levels increase in extreme water level (Reeder & Ranger 2010).

The flexible adaptation pathways approach allows for adjusting strategy if changing conditions require it while preventing large infrastructural investments. Due to its importance as an international best practice for long-term adaptive flood risk management, it extend the current indicator with this option, as follows:

Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: options are designing measures for reversibility or sequencing of planning decisions and required sets of interventions according to key thresholds in the current flood risk management system.

6.4 Reflection on the London case and the practicality of the indicator set

The reflection on the London case follows the same structure as for Rotterdam. In the first chapter contextual factors, such as the flood risk management tradition, spatial conditions and strategic framing are looked at, and their influence on preferred policy directions and principles is determined.
The second chapter gives an overview of non-functional principles and indicators and detects overlaps with the Rotterdam case to draw final conclusions about their feasibility. Furthermore, due to London's emphasis on

community resilience, practicality improvements of indicators in the issue areas of public awareness creation, self-sufficiency, social networks and participatory approaches in flood risk management are outlined.
The final framework with the changes proposed in chapter 5 and 6 can be found in Appendix 7.

6.4.1 Preferences for policy directions and principles in London

Whereas Rotterdam is tending towards "plan & prepare" and "adapt", London is more evenly spread across the different policy directions of "absorb", "recover" and "adapt". One interviewee comprehensively captures the major differences in flood risk management between the Netherlands and the UK in a nutshell:
"…They [referring to the UK] say we won't pay the government to put all the money into the prevention, it is better to absorb and recover. Quickly recover is they think easier, because if you don't have the investment what we have, centuries of levee management, to bring it to that standard that is an enormous burden financially. Therefore they think a resilient system is not only flooding but also earthquakes, or fires or tornados, all kinds of natural disaster can occur, you cannot prevent all of it. So if you have a quick recovery scheme, then you can adapt it to flooding, to earthquakes, to fires or tornados. It is a quite different approach between the more Western European, the NL, Germany where government come in and take care, and the more Anglo-Sachsen way of the people have their own responsibility and they have to take care for themselves. The government is only there to help them recover, not to prevent." (Interview R9)

These discrepancies affect priorities allocated to distinct resilience principles.
In the UK flood risk is being managed in an adaptive way since a secured central financial resource for continuous investment in flood protection safety standards is absent. There are no formal British safety standards for coastal and riverine flood defense and design standards for return periods are much lower. The reinforcement of existing schemes or the implementation of new ones is mainly based on cost-effectiveness and economic value of the area. Consequently, financial hubs like London have higher levels of protection (which is the same for Rotterdam according to the new protection standards).

With the overall probability of flooding events to occur being higher, more frequent, though less catastrophic than in the Netherlands, recovery mechanisms are continuously improved and citizens in certain parts are expected to learn to live with flooding events. Therefore, much more emphasis is put on recovery, especially self-sufficiency, room for autonomous change and social networks. *"I think in comparison to the NL, here in the UK we are little bit more open to thinking about flood risk management, what we do if we have a failure of the system or an overtopping."* (Interview L11)
In contrast to Rotterdam, pursuing community awareness and resilience forms part of the strategic approach towards flood risk management in the UK and London.
Accordingly, strategies revolve around how to encourage people (with subsidies and guidance) to make their homes flood-resistant and flood-resilient, take autonomous action for preparedness and response, for instance via flood risk action groups, and make them understand and act upon flood risk information. "*When we look at the adaptation, what the vulnerability is, we look at a wider consideration of the issues. So it's about what are the people's ability to absorb information, or even access information and act upon it because that is giving an indication about how resilient a community is, or it could be if you were able to provide accessible information and give them ownership. But that is for me as important as what is the standard of protection of your flood defense."* (Interview L2)
Citizens are expected to take proactive measures against riverine and coastal flooding and respond autonomously. Therefore, property level protection is critical in the case of London, as opposed to Rotterdam. It entails making buildings more resilient, for instance through the use of flood resistant materials, flood-

conscious interior and exterior design. It is specifically targeted by policies, such as the NPPF, which requires new corporate and infrastructural assets in flood-prone areas to remain safe throughout their lifetime by employing flood-resistant or flood-resilient construction.

The emphasis on community resilience also has implications for broad stakeholder engagement in flood risk management which is much more pronounced in the UK in comparison with the Netherlands. Apart from leaving the choice for the type of flood protection to citizens, responsibilities are explicitly devolved to them, for instance by letting them operate secondary defenses or elaborate community flood plans.
Due to the more frequent occurrence of flooding events in the UK, inclusiveness is also more pronounced than in the Netherlands, especially with regards to the provision of supportive services for vulnerable groups to safeguard their safety and for quickly resuming livelihoods after a flooding event. In London, initiatives like Climate Just, the creation of an affordable flood insurance scheme Flood-re and pilot projects implementing property level protection in flood-prone areas indicate that the latter are considered crucial.
Furthermore, the companies and citizens are engaged in tackling surface water flooding by applying SUSD measures on private property. Similar to Rotterdam, large parts of London rely on a combined sewer system prone to overflow. Since digging up and expanding the sewer system is too expensive and would cause too much disruption in the city, increasing dependence on private parties to make required adjustments on their properties is noticeable. This strategy forms part of a pursued behavioral change towards (waste) water resource management.

Due to the importance of a financial center such as London to stay operational under adverse circumstances, vulnerability and accessibility to critical infrastructure (robustness, connectivity) are important pillars in London, similar to Rotterdam. It is also an example of strategic framing.
Under the explicit objective of sustainable development, tackling congestion and improving access to and within areas served by networks, alongside efficient transportation and delivery of freight, it forms an integrative part of the London Plan. Vulnerability aspects of critical infrastructure are also covered in the UK CCRA, and the Adaptation Reporting Power. The latter is a former obligation for infrastructure operators to report on risks and vulnerabilities with regards to a changing climate and the measures set to tackle these.

Just as Rotterdam, London also puts a strong emphasis on “adapt”, and thus on flexibility and learning.
Learning opportunities from previous flooding events are much more frequent and anchored in evaluation reports with recommendations for policy changes, most of which are followed up. Participatory learning approaches are more prevalent than in Rotterdam due to a broader set of diversified networks in the field.
Concerning flexibility, the absence of a secured budget makes London less path dependent in flood infrastructure investments, and allows for more diversity in measures. For flexibility in measures, similar to Rotterdam, a long-term planning horizon is followed with the TE2100 and its flexible adaptation pathways. Just as Rotterdam, limited space in London affects the range of possibilities for flexibility in spatial planning. Policies for spatial reservation are a way to safeguard adjustments in land-use at a later stage.

6.4.2 Scope and options for improving the practicality of indicators

To summarize the options for indicator improvements based on the London case, and to make comparisons with the Rotterdam case, the researcher uses the same three categories as in the reflection on the Rotterdam results.

1) ***Indicators (or intermediate principles) were found to be non-functional***

2) The case indicates another practice than the one exhibited by the initial indicator which might compensate for non-functional indicators

There are considerable overlaps between Rotterdam and the London when it comes to non-functional indicators and partial overlaps for respective compensation mechanisms.

Spatial diversity of critical functions is described as something being thought of but too difficult and costly to implement (chapter 6.2.3.1). Instead, strategic planning for infrastructure placement is influenced by the provision of the NPPF which requires their vulnerability assessment from a flood risk and impacts perspective. Since this indicator seems hardly translatable into practice in the two cases, the researcher proposes to exclude it.

The second overlap between London and Rotterdam refers to the absence of duplication of critical functions from current practice. In line with the findings in Rotterdam, the focus in London is instead on implementing cost-efficient redundancy mechanisms in infrastructure networks and assets (see chapter 6.1.6). In addition, in contrast to Rotterdam, flood-resistant and flood-resilient measures are encouraged (see chapter 6.1.4) and seems to offer alternatives. Due to its apparent non-functionality in the two cases, the researcher recommends that the respective indicator be removed from the framework.

Thirdly, both cases confirm that institutions do not withhold financial resources for required public hazard-related expenditures. In the UK, responsibilities are usually divided over several authorities which makes the indicator obsolete. In addition such expenditures are accounted for within general budgets for repair and maintenance of organizations. Based on the findings in the two cases, there is a high likelihood for this indicator to fail also in other cases, therefore it should be abolished.

The London case yielded a solution for two indicators previously identified to be problematic in the Rotterdam case: Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required; Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it.
The two indicators were not understood by policy-makers and therefore need to be broken down into concrete actions to be taken to achieve this end state. The researcher identified a replacement indicator by looking at those parts of the population unable to fulfill above-mentioned conditions, namely vulnerable groups in areas exposed to flooding, and identifying required support services for them to resume livelihoods after a flooding event.

3) An established practice sheds light on further specification and clarification of indicators, for instance by illustrating different options or opinions of how to implement them.

The London case is particularly suited to inform indicator improvements across issue areas of community resilience. These are awareness creation, risk communication (Preparedness & Planning ahead), self-sufficiency (Flatness), flexibility in response (High Flux), social networks and participatory approaches in managing and responding to flood risk (High Flux).
Public involvement starts with monitoring public and institutional attitudes to flood risk in order to determine the level of acceptable risk as a decision criterion for course and timing of adaptation measures (chapter 6.3.1.1). In order to strengthen community resilience, authorities look at how to improve flood risk communication and removing barriers for citizens to act on information provided over various channels (chapter 6.3.2.1).
Public involvement in flood response is also evident in attempts to include citizens into planning and delivery of flood response measures on a local level. For instance, authorities actively encourage citizens and

neighborhoods to develop community flood plans which outline preparatory, local measures, emergency planning and evacuation procedures (chapter 6.3.6.1). These are supposed to speed up emergency response.

The expertise in flood response and recovery across the UK was also harnessed to make adjustments to existing indicators. The researcher found that partnerships and networks need to be narrowed down to those that improve coordinated emergency response and community response capacities in order to be functional for recovery. Examples of existing arrangements in the UK are community-led flood action groups pulling together local expertise and capacities which are integrated into the wider, higher level response structure in case of an emergency. Moreover, with mutual aid agreements, parties commit to share resources and human capacities during emergencies (chapter 6.3.6.2).
Even though integrative, participatory measures and physical places that link citizens and contribute to strengthening the neighborhood feel in districts are not directly related to flood risk management, they are considered a vehicle to improve social cohesion (chapter 6.3.6.2).

Economic diversity, transport connectivity and flexibility in measures are three other issue areas where indicators were added or changed to better represent policy options.
For instance, the London Plan and London Bridge Plan (borough level) outline ways to enhance economic variety which is a common approach to strengthen London's economy. These consist of developing physical clusters for research and innovation, tax incentives for small- and medium sized enterprises in certain areas or creating new office space by harnessing spatial redevelopment (chapter 6.3.4.1).
Besides critical infrastructure, a focus area of connectivity concerns accessibility and connectivity of urban areas with different transport options. From a resilience perspective, accessibility to areas and neighborhoods influences the citizens' ability to respond to emergencies. Measures to calculate accessibility to urban areas by public transport (such as the one developed by TfL) along with informed projects to improve the latter are therefore considered crucial for resilience-building (chapter 6.3.6.4).
An exemplary approach for adaptive flood risk governance under conditions of uncertainty was developed in the TE2100 project. Considered as best practice when it comes to flexibility in measures it was added to the option portfolio. The underlying concept of flexible adaptation pathways is to sequence the implementation of different sets of measures over time, thereby facilitating incremental adaptation while keeping options to deal with future climates open (chapter 6.3.8.2).

7 Discussion and reflections on the diagnostic tool

7.1 Proposed refinement and adjustments of the framework

In general, practitioners did not have trouble understanding the framework and discerning the principles into four distinct phases/policy directions. Some interviewees did stress the similarity with known concepts. The framework's structure was frequently compared to the multi-layer safety approach (in Rotterdam) or the policy directions in the LCCAS (in London). This pointed out familiarity with the phases and made it easier to get respondents to talk in which phases they consider them and their organization to be active.
The development of a diagnostic tool was widely appreciated, as represented by the following responses:
"What you are doing, diagnosis tool for urban resilience can really help us in the discussion with the cities and municipalities. We are talking about stress tests but resilience is more than only stress tests and I am looking for some ways to and we as a WB to discuss these topics with the municipalities." (Interview R20)

"Like I said in my email this is something we are really interested in, not only in a flood sense but also across all sorts of different capabilities." (Interview L6)

While respondents believed the framework to be rather complete, they addressed some interesting points for improvement which will be addressed next in addition to some thoughts about improving the usability of the principles for policy-makers.

Some interviewees saw a need to reduce the complexity of the framework due to the long list of indicators. A way to shorten the framework could consist of abolishing the phases and solely provide a list of principles without a clear indication about which policy directions they might strengthen. In the current framework, overlaps of certain categories are noticeable, with diversity coming into play in the "absorb" and "recovery" phase, or collaboration cutting across Homeostasis, Institutional diversity and Social networks. These scattered components could be reintegrated into one overall principle. Such a differentiation of resilience principles or qualities is for instance made by the 100 Resilient Cities Network. Certainly this implies a simplification but it would be at the expense of the diagnostic value of the tool. Strengths or deficits in certain policy directions would not be identifiable anymore, neither a comprehensive visualization of room for improvement.

Another way to improve the utility of the framework could be by using an instrument other than indicators to better capture progress towards fulfilling a principle, and different options for their attainment.
The use of indicators was at times perceived a challenge when it comes to improving functionality and a more flexible instrument was wished for. The researcher considered its form as a trade-off between a certain level of abstraction and delivering enough detail for assessment without adding examples of potential measures. Furthermore indicators cannot account for different stages of progress. At times current activity would have to be scored with zero despite clear efforts on a preparatory level, which the indicator could not account for. This was for instance the case in Rotterdam where no formalized evacuation plans have been established yet, but the problem analysis to inform crisis and evacuation management is just being performed.
Since the tool should be able to evaluate the status quo of resilience, more fine-tuning is required for policy-makers to exactly locate their current state. The tool could for instance resemble a ladder of achievement, outlining different levels of progress.
Another weakness of indicators is the lack of integration of different equivalent options to achieve the principle. The cases of London and Rotterdam clearly showed that framing, political, institutional and societal contexts determine to a great extent which principles are easier or more difficult to attain, and that there are different pathways that can be taken based on these constraints. There is no one-size-fits-all solution to tackling these principles and the tool should account for these. However, the current instrument of indicators does not allow for depicting a variety of equal options.

Since a scoring of the cities was deliberately not made, it was not required to measure their performance for each of the indicators in this research. However, to promote the uptake of the tool, and make it easier for policy-makers to assess the indicators in their cities, a more detailed scoring on each of the indicators would be required. For doing so, they might want to know what a low, intermediate or high value on the indicators entails. The operationalization of these three categories should be added for each of the indicators, which would go beyond the scope of this paper.
In this context, it might be worth thinking about a weighting of certain indicators. Several indicators are reappearing across different principles and might therefore have more weight than others that only appear once. The same applies to indicators that were identified as prerequisites for others to occur. Examples are: clearly defined responsibilities which were identified by interviewees as a base for actor and stakeholder

diversity, broad stakeholder participation, collaboration, swift emergency response (fixed protocols) and risk ownership (promoting autonomous response).

Findings highlight that some changes to particular principles could be made.
First, the integration of functional diversity into functional redundancy seems feasible based on the observation that several practitioners confused the concept of functional diversity with redundancy. For instance, creating community resilience to flooding events in addition to physical flood protection was reported to make the system more redundant, while in fact it represents functional diversity by the use of different approaches towards flood risk management alongside each other (Interview L6, R9).
In effect, both mechanisms (functional diversity and redundancy) aim at a similar effect: maintaining function by providing additional capacities (either more of the same or elements of different nature). Since the above mentioned findings confirm that there is awareness of both that are just summarized under one term, it does make sense to put the two in one category. Also scientific literature frequently treats them as one category (see Biggs et al. 2012; Liao 2012).

Specifically for flood risk management, the feasibility of "having options for flexibility in response" might be questioned. Since the initial indicators were not comprehensible for interviewees they were replaced by one closer to practice, referring to access to financial resources for vulnerable groups. A very similar indicator had already been established in the intermediate principle "availability of and access to resources", also supporting High Flux. Another indicator in "having options for flexibility in response" could be shifted to High Flux since it mostly supports rapidity in response: "mobile resources for flood mitigation on behalf of authorities involved in flood-risk management".
Likewise, all the remaining indicators (i.e. presence of a diverse economy, financial mechanisms for fostering local business development and innovation; development of education programs and curricula) all equally support "room for autonomous change" by strengthening the base for self-directed action and innovation during and after disturbances on behalf of citizens. Therefore they could be shifted to this category.

7.2 Reflection on its application to other sectors and resilience domains

According to Tyler et al. (2014) there are no universal indicators applicable across all sectors and geographic locations because climate adaptation and resilience require localized, context-specific responses. This argument is confirmed by this research. Only looking at two cases, the researcher was confronted with the trade-off between staying on an abstract level and providing context-specific indicators. Abstract indicators that lend themselves to wider applicability mostly prove incomprehensible for policy-maker and practitioners and are therefore opted against. In addition, interviewees advocated against a framework including several resilience domains and sectors. This envisions the challenge for making a framework applicable for other sectors and resilience domains.

Nevertheless, a step was made into this direction by differentiating between a general set of indicators for wider use in different types of disturbances and a set tailored to flood risk management. For several principles the general set worked well without requiring an extra one of specific flood risk management indicators. Among these are information management and sharing; broad participation, stakeholder engagement & inclusiveness; institutional learning capacity; institutional flexibility; experimentation and innovation. Others are very flood-risk specific, such as robustness through infrastructure or impact- and risk-reducing planning and would therefore require changes in order to be applicable to other resilience domains.

In fact, an informed statement about applicability to other sectors and policy domains can only be made after using the tool in other cases. Further research should be conducted to test, further develop and expand the diagnostic tool. Additional testing of the tool on a broader set of case studies in the same and other issue areas of climate resilience as well as in different contexts will enhance its validity, reliability and generalizability. So far only cities in developed, European countries were tested but it is assumed that the importance of principles shifts in developing countries. This could be for instance the case for inclusiveness and equity standards but also availability of and access to resources, given that disparities between rich and poor are much higher and that vulnerable groups are often forced to live in high-risk areas.
Besides, additional case studies about flood risk management, also those covering other climate resilience domains such as heat stress and freshwater provision are desirable. It would be interesting to see whether the established general indicators are applicable, whether the ones found for flood resilience are tailorable to other fields, and have studies add to the sets of issue-specific indicators.

7.3 Limitations of the method and research

This research and the chosen method are subject to limitations which mostly relate to limited time resources given the scope of a master thesis.

The first limitation of the method is linked to the fulfillment of the two-fold use of the tool. The initial intention was to make it work for the (1) evaluation of the resilience of the current state and (2) the evaluation of adaptation plans and projects against their integration of resilience principles.
Yet, during the research process the two different uses were found to require different sets of indicators. For the evaluation of baseline conditions, output indicators (representing a measurable status quo) are more suited whereas the evaluation of adaptation plans requires process indicators that depict an action to achieve them. A good example is the initial indicator “level of social cohesion” which is an indication for the baseline but proved to be non-functional for the assessment of adaptation plans due to a lack of knowledge about how to improve the level of social cohesion on behalf of practitioners.
Since limited time and resources prevented focusing on the development of both indicator types, the researcher decided to give priority to process indicators. This decision was made in accordance with the primary research objective of designing a tailor-made diagnostic tool to policy-makers for strategic resilience-building. For the future use of this tool, further elaboration on output indicators would be desirable along with reflections on whether it might be feasible to make two separate tools with different indicator types.

Furthermore, working with principles that exhibit abstract mechanisms prove to be challenging in an interview setting. Respondents needed to come up with ad-hoc associations and an immediate response without having time to develop ideas that might have affected the range of collected data. A workshop setting could have provided more time for an explanation of mechanisms. In such a setting, respondents could get a better grasp of the principles, more room for reflection and identifying barriers. Unfortunately this was not possible since scheduling interviews with respondents was difficult even on a one-by-one base due to their busy time schedules, especially for London.

A minor limitation of the tool is that it requires collecting specialized knowledge across a variety of fields and actors: natural conservation, spatial planning, business continuity management, emergency response, critical infrastructure to name but a few. The restricted time frame and resources of the researcher along with the limited duration of interviews hindered an in-depth investigation of all the issue areas at stake. For future research, it is therefore advisable to split the workload between different researchers.

Finally, it should be mentioned that the data may be biased according to the subjective perception and issue knowledge of interviewees. However, these potential biases are not considered to have a major influence on the quality of the results, mainly because the cities were not scored on their performance in each principle but rather only checked for the presence or absence of those principles.
In addition, steps were taken to counteract potential bias. First, the researcher sought data triangulation by relying on a variety of policy documents, other relevant material and interviews. Second, the results were presented in a workshop attended by climate adaptation professionals from Utrecht University, some of which have research experience in this field in Rotterdam. This should have reduced bias to a minimum while increasing the validity of the findings.

7.4 Theoretical and practical contribution of this research

Despite these limitations, this research makes an important theoretical and practical contribution to the field of resilience science.

First, by providing clarification of the resilience concept. In the introduction, missing conceptual clarity of resilience and disagreement in the scientific domain were described to hamper the elaboration of consistent, integrated resilience frameworks. This paper addressed this issue. It systematically built a comprehensive tool from solid theoretical underpinnings of resilience and by drawing on and mainstreaming perspectives from multiple relevant disciplines. By elaborating on conceptual overlaps and working out their intersections it showed that the different perspectives can indeed be merged. Furthermore, this research clearly went beyond isolated ad-hoc lists of characteristics by putting emphasis on their descriptions of how the principles relate to each other, for instance by making use of the same indicators or by exhibiting prerequisites for other principles to occur.

Second, this research critically reflected on the practicality of resilience principles and respective indicators for policy-makers. It singled out indicators and intermediate principles not suited for practice and improved the functionality of the current set of indicators according to detected needs and barriers.

Third, this paper followed up on the previously stated absence of guidance on how employed mechanisms contribute to and strengthen urban resilience. In the description of the principles, a clear indication was provided about how they are supposed to affect the system and thereby reinforce its resilience. These descriptions were used in the interviews to explain the principles to policy-makers and practitioners and improve their understanding of resilience mechanisms. Besides its assessment function, the framework has translated resilience mechanisms into concrete policy actions, which will help the latter parties better integrate resilience-thinking and building into their daily business, policy practice and program development.

7.5 Recommendations for further research

In the course of this research it became clear that several underlying problems related to attaining certain principles cannot be solved by improving the practical functionality of indicators but lie in existing institutional structures and routines.
This is for instance the case for “Integrated planning, coordination and collaboration” where current institutional structures and routines were described to hinder integrated information exchange across boundaries.

Another example refers to the involvement of non-governmental stakeholders into decision-making, agenda-setting and planning of interventions. Several interviewees reported this to be the case, pointing out successful small-scale projects such as the planning process of the water square in Rotterdam. This co-creation of solutions might work in pilot projects but does not seem to be administered on a larger scale in policy-making.

For anchoring long-term resilience thinking in processes and procedures there are several challenges ahead, which can be translated into the following questions:
Are institutions fit to implement and integrate resilience mechanisms such as flexibility in institutional structure, reflectivity, collaborative practice or multiple stakeholder engagement? Are current structures able to administer and accommodate required procedural changes and changes in the mindsets? How do you cultivate these qualities in organizations and individuals? How many people need to develop adaptive capacity?
At this point the researcher ties up with a thought brought up in a lecture by Simion Davoudi at Utrecht University (May 13, 2016), professor of environment policy and planning at Newcastle University. In that lecture she addressed whether we might need new institutional structures and governance modes, or even new instruments to tackle resilience challenges. According to her, these questions are unanswered in discussions about social-ecological resilience. Based on the findings in this paper, the researcher confirms the call for further research in this respect.

This paper could not sufficiently add to strengthening of the empirical evidence underlying the resilience principles, especially with regards to the links between the principles and their actual impacts on resilience.
An empirical base for several principles, such as diversity, redundancy and flexibility was established from an ecological perspective, but it is still largely missing for complex SES where the same principles are assumed to work. Yet, if policy-makers are to be convinced to adopt such a tool, a stronger evidence base needs to be created. Measuring impacts on resilience has been previously addressed as one of the major challenges in science and remains an important agenda for future empirical research.
Progress in this field could also help find answers to questions about quantitative measurements for the qualitative indicators established, which might come up for policy-makers. This was a challenge the researcher came across herself during the valuation process of the results: how many stakeholders should be involved in order to be resilient, do they have to be involved in all steps from planning decisions to the implementation of projects? How different do institutions have to be in size, culture and internal structure in order to count as diverse? These questions remain unanswered at that point.

In general it might be interesting to investigate whether some principles are more crucial than others for resilience. This is especially salient due to the research findings that attainment of all principles is neither possible nor desirable depending on the context. Several interviewees made references to perceived compensation mechanisms for absent indicators. These arguments would need to be assessed for their validity form a resilience perspective.

8 Conclusion

The aim of this thesis was to develop a diagnostic tool for policy-makers to assess the current and projected state of urban resilience. They can do that by checking conditions in organizations, critical infrastructure etc. or measures proposed in adaptation plans on their fulfillment of resilience principles. By doing so, the researcher sought answers to the following question: ***How to design a diagnostic tool to evaluate the resilience of cities and their climate adaptation plans?***

The researcher adopted a three-fold approach which consisted of:
(1) building the tool;
(2) testing the tool on two case studies, Rotterdam and London, focusing on one issue area of climate resilience, namely flood risk management; and
(3) improving the tool's utility (indicators) for policy-makers against its current adoption in strategies, measures and institutional contexts in the two cases.

Building the diagnostic tool involved several steps. First, by drawing on the prominent concepts of engineering, ecological, social-ecological and urban resilience, four major resilience features were established:
(1) Preparedness & foresight, (2) Absorb disturbance, (3) (Quickly) recover from disturbance by self-(re)organization, (4) Adapt to changing circumstances. Used as building blocks of the tool, they are to be seen as different policy directions that policy-makers can adopt to build resilience.
Second, the researcher reviewed scientific field-specific literature across the disciplines of disaster resilience, ecological resilience / ecosystem management, adaptive governance, economic resilience, urban / spatial planning, flood risk management and IAWM to identify popular mechanisms stated to enhance resilience (termed principles). An existing set of principles previously tested in climate adaptation contexts formed the starting point: Homeostasis, Diversity, Redundancy, Buffering, Flatness and High flux; Anticipation & foresight, Preparedness & planning ahead, Learning and Flexibility were added based on the literature review. To account for differing notions of these principles depending on the discipline and to improve its diagnostic value for practitioners, principles were further broken down into intermediate principles. In addition to a general set of indicators, applicable to a variety of different disturbances, the researcher developed another one tailored to the domain of flood risk management.

Assuming that not all the theoretically based indicators or principles were fit to work in practice, the researcher explored their functionality for policy-makers and practitioners in two illustrative case studies and their flood risk management approaches: Rotterdam and London. The goal of the testing was to find out which ones pose problems, why and how these can be overcome.
(1) Lack of knowledge or awareness, (2) indicators being non-functional in practice, and (3) institutional, political and resources-related barriers, were all explanations identified for a lack or limited adoption of indicators, or whole principles. Furthermore, strategic framing for economic or political purposes turned out to influence the endorsement of certain policy directions and principles and thereby their desirability.
The indicators standing out in both cases as non-functional and unrealistic, mostly due to cost-effectiveness or spatial conditions, were proposed to be excluded (i.e. prohibiting property development in flood-prone areas; duplication and physical distribution of vital functions). The same applied to those that were too abstract to generate any responses (i.e. having options for flexibility in response; level of social cohesion) and those too specific to be used in the diagnostic tool (i.e. maintaining stocks and provision mechanisms for food, medicine, and water supplies in case of disruption; employing modular elements in buildings).
For some of the non-functional indicators, the researcher identified alternative, compensatory measures which informed the improvement of indicators. For instance, interviewees indicated that performing flood

vulnerability assessments of assets (Robustness) and checking for critical points of accessibility to critical infrastructure during adverse events (Connectivity) could compensate for the spatial distribution of assets.
In other instances, an established practice shed light on further specification and clarification of indicators, for instance by illustrating other options for implementing them. Existing arrangements in the UK for instance made it clear that institutional partnerships and networks need to be narrowed down to those supporting coordinated, emergency response and community response capacities so that they can be useful in recovery.

This paper also reflected on the improvement of the tool in general.
Other instruments than indicators might be able to depict different pathways for fulfilling a principle and different stages of progress. This way the tool could better account for differing political, institutional, societal contexts that were discovered to decisively influence attainability and desirability of principles. It was also argued that a scoring tool, indicating what a low, intermediate or high value for the indicators entails, should be added in order to make assessment for policy-makers easier.

The researcher found that several hurdles in the way of the adoption of particular principles could not be overcome through the improvement of the practicality of their indicators since they are rooted in unsuitable institutional structures and routines. Future research should therefore scrutinize whether new institutional structures and governance modes, or even new instruments to tackle resilience challenges are required.
However, these efforts need to go hand-in-hand with furthering practical and pragmatic solutions building on a thorough understanding of resilience. A first step was made by this research by deriving concrete policy actions from popular resilience mechanisms, which will help parties better integrate resilience-thinking and building into their daily business, policy practice and program development.

This research made it clear, that the major pillars of resilience are already understood by practitioners since most of them form part of other, known concepts such as sustainability and climate mitigation. From that, opportunities arise to tie in resilience-building with existing agendas and approaches by creating co-benefits, a strategy already well-established in Rotterdam. The most feasible way to drive it forward is therefore to demystify resilience and make sure that policy-makers and practitioners alike comprehend and appreciate the resilience benefit of what they are already doing.
For those grey areas of resilience that are difficult to explore, such as anchoring long-term resilience thinking in daily procedures and routines, a closer collaboration between science, which can describe the desirable output from a resilience perspective, and practitioners, knowledgeable of the practical limits, is recommended in order to jointly develop solutions that are understood and fit to be adopted.

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Appendix 1: Overview of reviewed resilience literature

Source	Disciplinary field	Application	Principles / Indicators
Godschalk (2003)	Disaster resilience / community resilience	Cities as resilient systems where technological and social components interact	Redundant, diverse, efficient, autonomous, strong, interdependent, adaptable, collaborative Monitor vulnerability reduction, build distributed hazard mitigation capability, develop broad hazard mitigation commitment, operate networked communities, adopt recognized equity standards, assist vulnerable neighborhoods and populations, mitigate business interruption impacts
Cutter et al. (2010)	Disaster resilience / community resilience	Disaster resilience index / set of composite indicators for quantifying disaster resilience	Contains no principles but a whole set of indicators for social, economic, institutional, infrastructure resilience and community capital
Cutter et al. (2008)	Disaster resilience / community resilience / political ecology / ecosystems / planning	Relationship between vulnerability and resilience Disaster resilience of place (DROP) model Ecological, social, economic, institutional, infrastructure resilience and community competence	Adaptive capacity / absorptive capacity / inherent resilience Set of indicators for ecological, social, economic, institutional, infrastructure resilience and community competence
Bruneau et al. (2003)	Disaster resilience / community resilience	Resilience framework for structural mitigation / system and community performance measures / discerns between four interrelated dimensions of community resilience: technical, organizational, social, economic	Robustness, redundancy, resourefulness, rapidity
Norris et al. (2008)	Disaster resilience / community resilience	Disaster readiness	Economic development (resource volume & diversity, resource equity & social vulnerability), social capital (networks, social support, community bonds, roots & commitments), information & communication (systems & infrastructure for informing the public), community competence (collective action & decision-making, collective efficacy & empowerment)
Berkes & Ross (2013)	Community resilience	Community resilience, agency, self-organization	Engaged governance, social networks values & beliefs, knowledge, skills & learning, leadership, people-place relationships, diverse & innovative economy, community infrastructure
Barnett (2001), Wardekker et al. (2010)	Ecological resilience / system dynamics / disaster resilience	System stability, risk management, urban climate adaptation and policy options	Homeostasis, omnivory, high flux, flatness, buffering, redundancy

Biggs et al. (2012, 2014)	Ecological resilience/ governance	Managing ecosystem services	Maintain diversity & redundancy, manage connectivity, manage slow variables & feedbacks, foster complex adaptive systems thinking, encourage learning, broaden participation, promote polycentric governance
Nelson et al. (2007)	Ecological resilience / governance	Resilience and adaptation	Self-organization, capacity to learn, capacity to absorb change, capacities for incremental and transformational system adjustments
Gunderson (2009)	Ecological resilience / social resilience	Common traits of social and ecological resilience	Ecological diversity, natural and social capital, experimentation and learning, anticipation (predictive capacity of occurrence and impacts of events), preparedness
Folke et al. (2005)	Ecological resilience / adaptive governance / ecosystem management	Adaptive ecosystem-based management	Building knowledge and understanding of ecosystem dynamics, combination of different types of ecological knowledge to interpret and continuously respond to ecosystem feedback, capacity to learn from previous experience, social memory, encourage learning and experimentation, building adaptive capacity to deal with uncertainty and surprise, flexible institutions and social networks, institutional linkages, multi-level governance
Rose (2004)	Economic resilience	Application to earthquakes	Inherent vs. Adaptive resilience
Martin & Sunley (2014)	Economic resilience	Conceptualization of regional economic resilience	Robustness, modularity, structural diversity, structural redundancy, diversified specialization
Buuren et al. (2015)	Governance	Climate adaptation in the Netherlands	Flexibility of institutions and decision-making processes
Gupta et al. (2010), van den Brink et al. (2014)	Adaptive governance	Adaptive capacity (wheel)	Fair governance (legitimacy, equity, responsiveness, accountability), variety (problem frames & solutions, multi-actor, -level, -sector; diversity, redundancy), learning (trust, single loop & double loop learning, discuss doubts, institutional memory), room for autonomous change (access to information, act according to plan, capacity to improvise), leadership (collaborative, entrepreneurial, visionary), resources (finances, human resources, authority)
Lebel et al. (2006)	Governance	Governance attributes for resilience	Participatory, polycentric, multilayered, accountable (authorities), just (in distribution of benefits and risks); ecological and social diversity, combine and integrate different kinds of knowledge

Tyler & Moench (2012), Moench (2014)	Governance	Urban resilience with a focus on systems, actors and institutions, differentiation between governing system and system to be governed	Characteristics of a resilient system: Flexibility & diversity, redundancy & modularity, safe failure; agent capacities: responsiveness, resourcefulness, capacity to learn; characteristics of resilient institutions: rights and entitlements linked to system access, transparent, inclusive & accountable decision-making processes, access to relevant information, promoting generation and application of new knowledge
da Silva et al. (2012)	Governance, system dynamics	Conceptual model and resilience characteristics for analysis of urban systems based on evidence from the ACCCRN: infrastructure networks, knowledge networks, institutional networks	Flexibility, redundancy, resourcefulness, safe failure, responsiveness, capacity to learn, dependency on local ecosystems
Arup (2014), Rockefeller Foundation (2015), da Silva & Morera (2014)	Governance, disaster resilience, economic resilience	urban resilience	Reflexive, robust, resourceful, redundant, flexible, inclusive, integrated
Tanner et al. (2009)	Governance	Climate resilience building framework related to good governance based on case studies	Decentralization & autonomy, accountability & transparency, responsiveness & flexibility, participation & inclusion, experience & support
Wardekker et al. (2010)	Governance / disaster resilience	Urban climate adaptation	Foresight & Preparedness, compartmentalization, flexible planning and design
De Bruin (2004)	Disaster resilience / flood resilience	Flood risk management	Amplitude of impact, graduality of impact, recovery capacity
Liao (2012)	Flood resilience / flood hazard management	Building a theory on flood resilience based on the application of ecological resilience	Self-organization (in terms of distributed, localized flood response capacity), learning from past flooding experiences, redundancy, diversity, flexibility
Raadgever et al. 2015	Flood resilience / flood hazard management	Practical aspects and phases of flood risk management and governance through case study research (STAR-FLOOD project)	Several indicators taken from this literature, no specific principles
Schelfaut et al. (2011)	Disaster resilience / flood resilience	Flood risk management, risk communication, governance	Risk communication and perception, flood policy and institutional interplay, flood management tools
Zevenbergen et al. (2008)	Disaster resilience / flood resilience	Multiple scale system-based approach to flood resilience	Detailed flood risk modelling and assessment, flood resilience measures adopted at a street or building level, dual-use options, long-term planning, coupling urban transformation and restructuring with flood mitigation measures
Mees et al. (2014)	Flood risk governance	Legitimacy of flood risk governance in three cities	Interest representation, participation, deliberation, stakeholder acceptance

Davoudi et al. (2013)	Evolutionary resilience / Spatial planning	Climate adaptation strategies	Persistence (being robust), preparedness (learning capacity), adaptability (being flexible), transformability (being innovative)
Eraydin & Taşan-Kok (2013)	Spatial planning / Governance	Application of resilience-thinking in urban planning	Recovery, connectivity, social capital building, adaptability / flexibility, robustness, transformability
Lu & Stead (2013)	Spatial planning / Governance	Resilience-thinking in spatial planning	Attention to the current situation, attention to trends & future threats, ability to learn, ability to set goals, ability to initiate actions, ability to involve the public
Sheltair Group (2003)	Spatial planning / Governance	Adaptation strategies for urban systems in Greater Vancouver	Protecting and connecting webs of green and ribbons of blue, integrated infrastructure networks, connectivity, diversity, shock-resilient cells and backup systems, flexibility, expandability, convertibility, modularization
Huntjens et al. (2010)	Adaptive and integrated water management (AIWM)	Identification of general patterns in AIWM and their role in coping with the impacts of climate change on floods and droughts	Information management and exchange, collaboration, awareness raising and education
Pahl-Wostl (2007)	Adaptive and integrated water management (AIWM)	Adaptive capacity of the water system	Participatory implementation and monitoring, information management and sharing, multi-party interactions in actor networks, horizontal and vertical collaboration of institutions, sectoral integration, coordinated responsibilities, social learning, awareness and creating knowledge about CAS and ecosystems

Appendix 2: Overview interpretation of concepts

Capacity to learn from past experience

Author(s)	Concept / Principle	Description
Davoudi et al. 2013	Learning capacity	The social learning capacity of a system determines its level of preparedness for disturbances. A learning-based approach is best suited to the uncertainty of SES.
Da Silva & Kernaghan 2012	Capacity to learn	Learning processes are constituted by an interplay of experience and failures In a resilient system, actors need to be granted the option to learn from past experience and failures in order to avoid their repetition.
Tyler & Moench 2012	Capacity to learn	Refers to the ability to internalize past experiences and avoid repetition of failures which serves as the base for improving performance by innovation. A prerequisite is that the required knowledge is built and stored over time.
Cutter et al. 2008	Learning	Learning contributes to the adaptive resilience of a system and is especially salient when the buffer capacity of the system (absorptive capacity) is exceeded. It manifests in "*beneficial impromptu actions are formalized into institutional policy for handling future events and is particularly important because individual memory is subject to decay over time*" (Cutter et al. 2008, p.603)
Liao (2012)	Learning from previous flooding events	Flooding as an agent for resilience since every flooding event offers a chance to learn in terms of building knowledge, readjust processes.

Homeostasis

Author(s)	Concept / Principle	Description
Biggs et al. 2012, 2014 Folke et al. 2005	Manage slow variables and feedbacks	Building knowledge and understanding of ecosystem dynamics – changes in slow variables and regime shifts. Monitoring is a form of feedback that provides information about the state or responses of the SES to the actors for them to change or adjust the management of SES
Resilience Alliance 2010	Enhance stabilizing feedbacks	Stabilizing feedbacks that sustain natural and social capital can improve resilience
Wardekker et al. 2010	Homeostasis	Implementing several stabilizing feedback loops that counteract disturbance
Barnett 2001	Homeostasis	A system consists of feedbacks between its components that direct the system by triggering changes and driving responses. In a resilient system these feedbacks are known and geared accordingly.

Robustness & Buffering

Author(s)	Concept / Principle	Description
Folke 2006	Persistence / Robustness / Buffer capacity	Being robust to disturbance is one dimension of (ecological) resilience in social-ecological systems
Cutter et al. 2008	Mitigation	Mitigation is any taken action to reduce or avoid risk or damage from hazard events = pre-event measures. Similar to adaptive capacity, mitigation can increase a society's or system's resilience to disturbance.
Tasan-Kok et al. 2013	Mitigation	Mitigation describes preventing and reducing damage to people, property, and resources before a disaster occurs; it is defined as the most important role of urban planning; mitigation can increase the robustness of a system
Davoudi et al. 2013	Robust / persistent	Being robust and persistent enhances a system's chance of resisting disturbance and forms one of the four pillars of Davoudi et al.'s resilience framework
Bruneau et al. 2003	Robustness	Strength of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function
Norris et al. 2008	Robustness	Is defined as the strength of a resources with a low probability of deterioration
Da Silva & Morera 2014	Robust	The focus is mainly on physical assets that are well constructed and managed for withstanding impacts of disturbances without losing function and major damage. It also refers to overall robust design that accounts for potential system failures in order to make failure predictable and safe
Da Silva & Kernaghan 2012	Robustness	Inherent strength of urban infrastructure
Liao 2012	Robustness	the physical strength to withstand a disturbance without functional degradation
Tasan-Kok et al. 2013	Robustness	An adaptive system is both robust and flexible. Robustness is the ability to withstand a given level of stress without suffering degradation or loss of function
Cutter et al. 2008	Robustness	Property of infrastructure that reduces the probability of failure
Davoudi et al. 2013	Persistence	Long-term ability to withstand stress (robustness is more short-term oriented)
Tyler & Moench 2012	Robust	The engineering approach towards robust systems focuses mainly on structural protective measures and relies on the strength of individual components to ensure maintaining function after disturbance
Gunderson 2009	Buffering	Reducing and moderating the impacts by a disturbance, i.e. levees and canals provide buffer against floodwaters. Disaster effects can be buffered by technological interventions
Wardekker et al. 2010, n.a.	Buffering	Ability to absorb disturbances to a certain extent (i.e. by over-dimensioning essential capacities for critical thresholds are less likely to be surpassed)
Barnett 2001	Buffering	A system with capacities exceeding needs can draw on these capacities in times of need and is therefore more resilient

Adger & Tompkins 2004	Buffering	The ability of a society to buffer disturbance is one aspect of a resilient society

Diversity

Author(s)	**Concept / Principle**	**Description**
Wardekker et al. 2010	Omnivory	Diversification of resources and means reduces vulnerability
Barnett 2001	Omnivory	The diversification of resources and of the means by which resources are delivered helps to better accommodate external shocks
Walker et al. 2004	Diversity	Diversity as an attribute required for transformability

Functional & response diversity		
Author(s)	**Concept / Principle**	**Description**
Godschalk 2003	(Functional) diversity	Many functionally different components to protect the system against threat
Tyler & Moench 2012	Flexibility / diversity	Functional diversity: a variety of ways to meet a given need
Walker et al. 2004	Diversity	Diversity as an attribute required for transformability Functional diversity (education, expertise, and occupations)
Biggs et al. 2012, Biggs et al. 2014	Ecological diversity in ecosystem management	Biodiversity supports the provision of ecosystem services, which enhances response diversity and redundancy
Folke 2006	Biodiversity	Biological diversity plays a paramount role in complex adaptive system for self-organizing ability, in the two ways of absorbing disturbance and re-organize following disturbance (response diversity)
Carpenter et al. 2001	Ecological / Biodiversity	Ecological diversity: biodiversity, functional diversity
Adger et al. 2005	Ecological diversity	Ecological diversity, diversity of economic livelihood options
Sheltair Group 2003	Maintaining and increasing diversity in urban systems / ecological diversity	Components of the urban systems should be strategically designed for diversity (i.e. technologies, resources); ecological and vegetation species diversity enhances absorptive capacity towards unpredictable events.
Martin & Sunley 2014	Diversity as redundancy mechanism / functional diversity / economic diversity	Redundancy through diversity of elements with overlapping, complementary functions. A particular function or performance of the system can be achieved in various ways by the different system elements prevalent and different means they provide (i.e. heterogeneous population). Also applies to economic diversity in terms of variety of different industries and businesses.

Spatial diversity of critical functions		
Author(s)	**Concept / Principle**	**Description**
Tyler & Moench 2012	Flexibility / diversity	Spatial diversity: key assets and functions are physically distributed to spread risk

Biggs et al. 2012 Adger et al. 2005	Spatial diversity	Diversity in SES encompasses spatial heterogeneity. It helps that landscape patches remain unaffected and can thereby maintain the provision of ecosystem services.
Sheltair Group 2003	Spatial diversity as redundancy mechanism	By being spatially distributed across a region or city, system components can withstand a sudden loss in connectivity and maintain function. This is especially salient when transportation and distribution options (for water and gas) are limited and therefore prone to disruption.

Actor & stakeholder diversity		
Author(s)	**Concept / Principle**	**Description**
Biggs et al. 2012, Biggs et al. 2014	Diversity of users in ecosystem management	Diversity of users and managers (age, gender, financial means) brings a diversity of knowledge to better understand ecological changes
Biggs et al. 2012, Biggs et al. 2014	Diversity (Ecosystem management)	Diverse groups of actors with different roles, overlapping functions which respond differently to changes, and a diversity of perspectives enhances the capacity of problem-solving
Folke et al. 2005	Diversity	Response diversity can be enhanced by collaboration of a diversity of stakeholders operation at different levels
Gupta et al. 2010 Van den Brink et al. 2013	Variety	Multi-actor, multi-level, multi-sector: involvement in governance process

Institutional diversity, multi-level governance systems & linkages		
Author(s)	**Concept / Principle**	**Description**
Biggs et al. 2012, Biggs et al. 2014	Diversity (Ecosystem management)	Diversity in governance systems: organizations with different sizes, cultures, funding mechanisms, internal structures, diverse groups of actors with different roles, overlapping functions which respond differently to changes, and a diversity of perspectives enhances the capacity of problem-solving
Folke et al. 2005	Diversity	Response diversity can be enhanced by a high level of institutional linkages between communities, government agencies, NGOs Collaboration of a diversity of stakeholders operation at different levels Polycentric governance systems with nested, quasi-autonomous decision-making units
Lebel et al. 2006	Diversity	polycentric and multilayered institutions facilitate a better fit between knowledge, action, and social-ecological contexts and thus enhances a system’s adaptability
Gupta et al. 2010 Van den Brink et al. 2013	Variety with 3 different dimensions	(1) Variety of problem frames: multiple opinions and problem definitions (2) Multi-actor, multi-level, multi-sector: involvement in governance process (3) Diversity of solutions: multiple policy options
Resilience Alliance 2010	Institutional diversity	Diversity of perspective in a SES and knowledge enhance the understanding of key components of a SES

Walker et al. 2004	Institutional variety	Diversity as an attribute required for transformability

Redundancy

Author(s)	Concept / Principle	Description
Folke et al. 2005 Low et al. 2003	Redundancy	Redundancy in institutions and overlapping functions across levels facilitate absorbing disturbance and spreading risk (Low et al. 2003). Redundancy of actors, actor groups and their roles contribute to reorganization and enhance adaptive capacity.
Norris et al. 2008	Redundancy	Redundancy refers to the extent to which elements are replaceable which is a widespread mechanism in both technological (power grids, infrastructure) and social systems (actors create large social networks, several problem solving options). Redundancy implies the condition of ''resource diversity.''
Biggs et al. 2012, 2014	Redundancy	Functional redundancy: presence of multiple components / species or SES elements that perform the same function and thus have the capacity to fully substitute each other
Cutter et al. 2008, 2010	Redundancy	Redundancy in infrastructure as a means to reduce failure probability
Adger et al. 2005	Redundancy	Functional redundancy
Gunderson 2009	Redundancy	Biodiversity: Functional redundancy
Godschalk 2003	Redundancy	Several functionally similar components that prevent system failure by compensating failure of other parts.
Elmqvist 2014	Redundancy	investing in multiple and alternative connections in governance and institutions at the local and global scale engaging in collaboration as a way towards resilience
Liao (2012)	Redundancy	Redundancy goes beyond its interpretation according to engineering resilience by overcoming the idea of duplicating the same elements. According to Liao (2012) it implies the functional replication across scales (micro to macro level), and diversity (in flood response)
Norris et al. 2008	Redundancy	Extent of replicability of elements in the case of disturbance or disruption. In the social sphere, redundancy refers to having larger social networks, several means for problem-solving; it is represented by "resource diversity" for communities which makes them better able to cope with a disturbance that possibly eradicates a resources they heavily depend on
Gupta et al. 2010 Van den Brink et al. 2013	Redundancy	Forms part of Variety and implies the implementation of over-lapping measures and back-up systems (duplication)
Eraydin & Taşan-Kok 2013a	Redundancy	Systems are created to have multiple nodes that ensure that failure of one component does not cause the entire system to fail
Folke et al. 2005	Redundancy	Institutional redundancy and overlapping functions across levels facilitate absorbing disturbance and spreading risk

		Redundancy of actors, actor groups and their roles contribute to reorganization and enhance adaptive capacity
Tyler & Moench 2012	Redundancy	Redundancy, modularity: refers to spare capacity for contingency situations with high demand (buffer stocks for compensation if flows are interrupted); multiple options of service delivery connected components that can compensate failure of other parts
Norris et al. 2008	Redundancy	Redundancy refers to the extent to which elements are replaceable which is a widespread mechanism in both technological (power grids, infrastructure) and social systems (actors create large social networks, several problem solving options). Redundancy is a condition for ‘‘resource diversity.’’
Da Silva & Morera 2014	Redundancy	Redundancy refers to spare capacity purposely created within systems so that they can accommodate disruption, extreme pressures or surges in demand. It includes diversity: the presence of multiple ways to achieve a given need or fulfil a particular function. Examples include distributed infrastructure networks and resource reserves. Redundancies should be intentional, cost-effective and prioritized at a city-wide scale, and should not be an externality of inefficient design
da Silva & Kernaghan 2012		Redundancy: Superfluous or spare capacity to accommodate increasing demand or extreme pressures. Redundancy is about diversity and the ability to adopt alternative strategies through the provision of multiple pathways and a variety of options. Some components of the urban system serve similar functions and can provide substitute services when another component is disrupted
Wardekker et al. 2010	Redundancy	Overlapping functions that compensate for failure of one function and having multiple instances of something available (buffers stocks, spare capacity)
Barnett 2001	Redundancy	Overlapping functions in a system can accommodate change by maintaining vital functions even when elements fail (aspect of interchangeability)

Overlapping functions and roles		
Author(s)	**Concept / Principle**	**Description**
Folke et al. 2005 Low et al. 2003	Redundancy	Redundancy in institutions and overlapping functions across levels facilitate absorbing disturbance and spreading risk (Low et al. 2003). Redundancy of actors, actor groups and their roles contribute to reorganization and enhance adaptive capacity.
Norris et al. 2008	Redundancy	Redundancy refers to the extent to which elements are replaceable which is a widespread mechanism in both technological (power grids, infrastructure) and social systems (actors create large social networks, several

		problem solving options). Redundancy implies the condition of ‘‘resource diversity.’’
Biggs et al. 2014	Redundancy in organizations	Different organizational forms prevalent in a governance system (i.e. NGOs, community groups, government departments) can overlap in function and provide a diversity of responses. This can also apply to the social sphere: communities that are well-connected frequently have overlapping functions. These enhance creativity and adaptability.
Biggs et al. 2012	Overlapping functions and roles	Polycentric, multi-level governance systems with overlapping functions and roles provide ground for functional redundancies. Broader levels of governance (national, international level) might fill in for lower levels should they fail or collapse or the other way round.

Functional redundancy		
Author(s)	**Concept / Principle**	**Description**
Biggs et al. 2012, 2014	Redundancy	Functional redundancy: presence of multiple components / species or SES elements that perform the same function and thus have the capacity to fully substitute each other
Adger et al. 2005	Redundancy	Functional redundancy
Gunderson 2009	Redundancy	Biodiversity: Functional redundancy
Barnett 2001	Redundancy	Overlapping functions in a system can accommodate change by maintaining vital functions even when elements fail (aspect of interchangeability)
Godschalk 2003	Redundancy	Several functionally similar components that prevent system failure by compensating failure of other parts.
Eraydin & Taşan-Kok 2013a	Redundancy	Systems are created to have multiple nodes that ensure that failure of one component does not cause the entire system to fail
Martin & Sunley 2014	Redundancy	Supports robustness by the presence of multiple means to sustain system performance. “*Refers to a situation in which there are identical or similar components or subsystems (modules) which can replace each other when one fails*.” (Martin & Sunley 2014, p.7) Yet, this is acknowledged to rarely be the case.
Martin & Sunley 2014	Structural redundancy	Substitution potential of certain sectors or companies for one another in case other fails facing disruption.
Liao (2012)	Redundancy	Redundancy goes beyond its interpretation according to engineering resilience by overcoming the idea of duplicating the same elements. According to Liao (2012) it implies the functional replication across scales (micro to macro level), and diversity (in flood response)

Spare capacities & back-up resources		
Author(s)	**Concept / Principle**	**Description**

Gupta et al. 2010 Van den Brink et al. 2013	Redundancy	Forms part of variety and implies the implementation of over-lapping measures and back-up systems (in terms of duplication)
Tyler & Moench 2012	Redundancy	Redundancy, modularity: refers to spare capacity for contingency situations with high demand (buffer stocks for compensation if flows are interrupted); multiple options of service delivery connected components that can compensate failure of other parts
Da Silva & Morera 2014	Redundancy	Redundancy refers to spare capacity purposely created within systems so that they can accommodate disruption, extreme pressures or surges in demand. It includes diversity: the presence of multiple ways to achieve a given need or fulfil a particular function. Examples include distributed infrastructure networks and resource reserves. Redundancies should be intentional, cost-effective and prioritized at a city-wide scale, and should not be an externality of inefficient design
da Silva & Kernaghan 2012		Redundancy: Superfluous or spare capacity to accommodate increasing demand or extreme pressures. Redundancy is about diversity and the ability to adopt alternative strategies through the provision of multiple pathways and a variety of options. Some components of the urban system serve similar functions and can provide substitute services when another component is disrupted
Wardekker et al. 2010	Redundancy	Overlapping functions that compensate for failure of one function and having multiple instances of something available (buffers stocks, spare capacity)

Compartmentalization & Modularity		
Author(s)	**Concept / Principle**	**Description**
SheltAir Group 2003 Wardekker et al. 2010	Compartmentalization and shock-resilient cells	A cellular structure which among other can be applied to land use arrangements and critical infrastructure, enhances adaptability to unforeseen shocks.
Martin & Sunley 2014	Modularity	A modular system structure implies a network where subsystems or single elements are weekly connected so that they stay rather unaffected in the face of a disruption and cascading effects are contained.
Biggs et al. 2012	Modularity	"*Modularity refers to the extent to which there are subsets of densely connected nodes that are loosely connected to other sub- sets of nodes.*" (Biggs et al. 2012, p.428) This facilitates functionally autonomous subsystems or elements that can prevent the cascading of disturbances across scales
Resilience Alliance 2010	Modularity	A well-connected system can rapidly transmit disturbances and is prone producing cascading effects in the whole system. In a modular system where subcomponents are loosely connected single elements can better reorganize and absorb disturbances.

Tyler & Moench	Modularity & safe failure	Despite interdependence of systems, failures in one system should not lead to cascading effects in others.

Flatness

Author(s)	**Concept / Principle**	**Description**
Wardekker et al. 2010, n.a.	Flatness	Systems with non-hierarchical structure with distributed formal competences that allow for bottom-up approaches and prevent lengthy decision-making and bureaucracy processes that make a system inflexible and slow, and thus ineffective in responses and recovery.
Barnett 2001	Flatness	The number of hierarchical levels in regards of an organization, the more top-heavy a system is the less resilient.

Institutional decentralization & autonomy		
Author(s)	**Concept / Principle**	**Description**
Tanner et al. 2009	Decentralization / Autonomy	Decentralization is defined as the "*ability and capacity of municipal governments to make decisions and implement across a range of responsibilities and services*." (Tanner et al. 2009, p.21) Autonomy stresses relationships with other levels of government and stakeholders and capacities of lower governance levels (e.g. municipal level) to make autonomous decision and implement them (e.g. climate adaptation programs).
Lebel et al. 2006	Poly-centric multilayered institutions and decentralization	Poly-centric multilayered institutions have relatively independent governance units which allow for locally-informed actions and strategies due to tightened and monitoring activities. That way actions can better match social-ecological contexts and actors can respond more adaptively at appropriate levels.
Biggs et al. 2012 Folke et al. 2005	Polycentric governance systems / systems of adaptive governance	These have multiple governing authorities at different scales promotes redundancy, enhance learning and experimentation, and the employment of scale-specific knowledge
Lebel et al. 2006	Polycentric and multilayered institutions	Polycentric and multilayered institutions improve the fit between knowledge, action, and social-ecological contexts in ways that allow societies to respond more adaptively at appropriate levels.

Broad participation, stakeholder engagement & inclusiveness		
Author(s)	**Concept / Principle**	**Description**
Biggs et al. 2012, 2014	Participation	Broadening participation aims at the active engagement of relevant stakeholders in the management and governance process
Tyler & Moench 2012	Participation	Especially resilience-building targeting vulnerable groups strives for participatory and inclusive decision-making processes in urban development and systems

		management, allowing for an active role of those individuals and groups most affected by climate hazards.
Lebel et al. 2006	Participation	Public participation builds trust and subsequent joint deliberation of issues promotes the development of a shared understanding through repeated exchange with stakeholders which is required to self-organize and mobilize (base for social learning)
da Silva & Morera 2014	Inclusive / inclusion	Inclusion emphasizes the need for broad consultation and engagement of communities, including the most vulnerable groups. Shocks or stresses face by one sector, location, or community cannot be addressed in isolation. An inclusive approach contributes to a sense of shared ownership or a joint vision to build city resilience.
Norris et al. 2008	inclusive	Citizens should be involved in every step of the mitigation process in order to be able to access social capital. Communities should be able to address their own vulnerabilities to hazards, invest in their assistance and information networks, and enhance their problem sovling capacity while supported by professional practitioners.
Resilience Alliance 2010	Inclusiveness	Adaptive governance can enhance resilience by inclusiveness
W. N. Adger et al. 2005	inclusive	Inclusive governance structures can enhance adaptive capacity
Godschalk 2003	collaborative	Multiple opportunities for broad stakeholder participation

Room for autonomous change		
Author(s)	**Concept / Principle**	**Description**
van den Brink et al. 2013 Gupta et al. 2010	Room for autonomous change	The ability of actors to improvise during crisis, accommodate disturbances and experiment with contingencies. It is facilitated by institutions. The degree of autonomous space provided is indicated by the access to information for the population, the ability of actors to act according to plan and their capacity to improvise
Wardekker et al. 2010	Self-reliant, self-sufficient, self-regulating population	To confer public competence and power to respond in a self-directed way to disturbances, the government should leave room for residents to modify the area.
Godschalk 2003	autonomous	Ability to work independently of outside control
Tyler & Moench 2012	Resourcefulness	Capacity to mobilize assets and resources for action among others depends on access to information: households, enterprises, community organizations and other decision-making agents should have ready access to credible and meaningful information to enable judgments about risk and vulnerability, and to assess adaptation options

High Flux

Rapidity		
Author(s)	**Concept / Principle**	**Description**
Da Silva & Kernaghan 2012	Rapidity / Responsiveness	In general is referred to as the ability to reorganize and retain function after a disturbance. Rapidity forms a crucial dimension of responsiveness for preventing further losses and disruption.
Norris et al. 2008	Rapidity	Refers to one of the three dynamic attributes of a system (alongside robustness and redundancy), also termed adaptive capacities, and represents how quickly a resource can be accessed and used
Folke 2006	Rapidity	In engineering resilience, rapidity, understood as the return time of a system ("bouncing back"), is a measure of its recovery (Folke 2006)

Connectivity		
Author(s)	**Concept / Principle**	**Description**
Tasan-Kok et al. 2013	Connectivity	Degree to which the nodes of a networks are directly linked to each other, both physically and in terms of relationships between people and organizations
Godschalk et al. 2003	Interdependent	System components are connected so that they support each other
Biggs et al. 2012, 2014	Connectivity	Extent to which resources, species, or social actors disperse, migrate, or interact across ecological and social landscapes. These landscapes can be patches, habitats or social groupings; Specifically it describes the nature and strength of interactions between components; nodes and connections between them (links) facilitate the exchange of material and information
Janssen et al. 2006	Connectivity	Characteristic of networks structure, identified by the density of links in a network and reachability as the extent to which all the nodes in a network are accessible to each other
Davoudi et al. 2013	Connectivity	In SES it refers to connections between critical sectors (e.g. transport networks) and cooperation between different levels of governance; plays an important role in post-disaster recovery
Zevenbergen et al. 2008	Connectivity	Critical linkages between spatial layers of a system potentially impacted by a disaster

Networks and social capital		
Author(s)	**Concept / Principle**	**Description**
Davoudi et al. 2013	Networks	Presence of networks, cooperation and interlinkages are described as pathways to resilience because they facilitate the flow of ideas and resources, ant enable connections between people and institutions (Janssen et al. 2006)
Carpenter et al. 2001	Social networks	Self-organization is *inter alia* enhanced by social networks that enable problem-solving (→ flexibility)

Folke et al. 2005	Social capital	Social source of resilience are paramount for the capacity of a system to adapt and shape change; it is a building block in adaptive management (focusing on network, leadership and trust) and bridging and bonding links between people in social networks
Tasan-Kok et al. 2013	Social capital	Social capital building refers to the quality and quantity of a society's social interactions that are shaped by institutions, relationships, and societal norms; social capital building , (e.g. access to information and communication networks in times of difficulty), can help the quick recovery from socioeconomic or environmental change)
Gunderson 2009	Social capital	As natural capital is critical in ecological system for post-disturbance recovery, social capital is paramount in SES
Nelson et al. 2007	Social capital	Resources, such as technology, infrastructure, information, institutions or social capital, determine the adaptive capacity of a system
Norris et al. 2008	Network structures and linkages / social capital	Uncertainty bring the necessity to form multiple relationships that act as supportive interactions in the face of a disturbance, this is closely linked to the idea of participatory instead of highly hierarchical systems and the redundancy in social networks
Norris et al. 2008	Redundancy	In the social sphere, redundancy refers to having larger social networks, several means for problem-solving; it is represented by "resource diversity" for communities which makes them better able to cope with a disturbance that possibly eradicates a resources they heavily depend on

Having options for flexibility in response		
Author(s)	**Concept / Principle**	**Description**
Tyler & Moench 2012	Resourcefulness	Capacity to mobilize assets and resources for action. For instance, they can mobilize monetary resources for shifting livelihoods, or modifying social or physical structures. This is among others depending on access to credible information for all parties involved.
Tyler & Moench 2012	Flexibility / diversity	"*The ability to perform essential tasks under a wide range of [climatic] conditions, and to convert assets or modify structures to introduce new ways of doing so*" (Tyler & Moench 2012, p.313)
Bruneau et al. 2003	Resourcefulness	The capacity to identify problems, establish priorities, and mobilize resources when condition require it; the ability to apply material (monetary, physical, technological, and informational) and human resources to meet established goals
Martin & Sunley 2014	Economic diversity	Structural diversity: Regional economic diversity is considered to enhance robustness, and the scope for adaptive reorganization, whereas sectoral

		specialization reduces robustness by increasing vulnerability and limiting scope for recovery. “Rivet” effect opts against the economic dominance of and dependence on one particular sector or firm since these can drive the whole economy down.
Adger et al. 2005	Economic diversity	Diversity of economic livelihood options
Gunderson 2009	Economic diversity	Diverse economy enhances community resilience recover quicker following disturbance
Davoudi et al. 2013	Economic diversity	Diversity as part of resourcefulness (along with efficiency and rapidity): biological, economic diversity
Norris et al. 2008	Economic Diversity	Level and diversity of economic resources, studies have shown that social class can act as a buffer for disaster impacts

Managing connectivity of critical infrastructure, services and natural habitats		
Author(s)	**Concept / Principle**	**Description**
Tasan-Kok et al. 2013	Connectivity	Degree to which the nodes of a networks are directly linked to each other, both physically and in terms of relationships between people and organizations
da Silva & Morera 2014	Connectivity	Mainly physical aspect of connectivity in cities, facilitated by a combination of transport links and ICT encompassing a wide range of technologies
Davoudi et al. 2013	Connectivity	In SES it refers to connections between critical sectors (e.g. transport networks) and cooperation between different levels of governance; plays an important role in post-disaster recovery
Zevenbergen et al. 2008	Connectivity	Critical linkages between spatial layers of a system potentially impacted by a disaster
Davoudi et al. 2013	Biological diversity	Diversity as part of resourcefulness (along with efficiency and rapidity): biological, economic diversity
Folke 2006	Biological diversity	Biological diversity plays a paramount role in complex adaptive system for self-organizing ability, in the two ways of absorbing disturbance and re-organize following disturbance

Learning & Reflectivity

Author(s)	**Concept / Principle**	**Description**
Biggs et al. 2012	Learning & experimentation	Since SES are not stable but subject to change and surprise and the knowledge of SES incomplete, learning and experimentation are the key to enhancing resilience.
Folke et al. 2005	Learning & experimentation	Learning is understood as a continuous process of updating and adjusting understanding; it helps the individual to develop their ability to deal with new situations (adaptive expertise), and thus prepared for uncertainty and surprise.
Cutter et al. 2008	Learning	Learning contributes to the adaptive resilience of a system and is especially salient when the buffer capacity of the system (absorptive capacity) is

		exceeded. It manifests in "*beneficial impromptu actions are formalized into institutional policy for handling future events and is particularly important because individual memory is subject to decay over time*" (Cutter et al. 2008, p.603)
Godschalk 2003	adaptable	The capacity to learn from experience and the flexibility to change
Carpenter et al. 2001	Adaptive capacity	Relates to the presence of mechanisms for creating novelty and learning in human systems. Its prerequisite are institutions that facilitate experimentation, discovery and innovation.
Gupta et al. 2010	Learning capacity	Defined by the four criteria of trust, single loop learning, double loop learning and the creation of institutional memory.
Nelson et al. 2007	Capacity for learning	Crucial component of adaptive capacity and adaptive governance; learning in terms of institutional learning and arrangements and continuous testing and revision of ecological knowledge
Liao 2012	Learning	Learning is the ability to adjust to changing internal demands and outside pressures and forms part of adaptive capacity; it is facilitated by a learning-by-doing approach generating novelty; Periodic floods can be used as learning opportunities for developing a better fit
Da Silva & Morera 2014	Reflective	Reflective people and institutions accept conditions of uncertainty and change and, based on emerging information, develop mechanisms to constantly adapt to change instead of employing permanent solutions. They reflect on and learn from their past experiences to inform future decision-making.

Appendix 3: Operationalization of principles

Phase Plan/Prepare

Anticipation & Foresight

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Anticipation & Foresight	Building knowledge	Existence of (regional and city-wide) climate change-related projections, forecasts and scenarios (Lu & Stead 2013; Arup 2014; Godschalk 2003, Gunderson 2009) Identification and assessment of climate-related hazards, probability of occurrence, system's exposure, city-wide impacts and associated risks (Tyler & Moench 2012; Lu & Stead 2013; Linkov et al. 2014; Cutter et al. 2008; Davoudi et al. 2013; Godschalk 2003) Mapping of economic assets, critical functions (hospitals, police stations etc.), commercial and manufacturing establishments in flood-prone areas (Godschalk 2003)	Performance of city-wide vulnerability assessments which describe and map potential flood hazards and impacts on neighborhoods (Cutter et al. 2008; Lu & Stead 2013; Gersonius et al. 2011; Linkov et al. 2014; McBain et al. 2010; Tyler & Moench 2012; Godschalk 2003; Zevenbergen et al. 2008)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Anticipation & Foresight	Monitoring of slow variables	Real-time data collection; monitoring of natural (geological, atmospheric, oceanic) phenomena (National Academy of Sciences 2012) Periodic analysis and inspection of crucial infrastructure (transport, electricity networks, telephone lines, water supply, drainage systems) (de Bruijn 2004b)	Flood risk monitoring systems are in place (Biggs et al. 2012; Lu & Stead 2013) Continuous monitoring of factors that affect sea level, river, canal and polder water levels (Carpenter et al. 2001) Continuous monitoring, control and evaluation of dikes safety and of flood-protective facilities (Chelleri et al. 2015; Davoudi et al. 2013; Lu & Stead 2013)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Anticipation & Foresight	Information management & sharing	Access of government agencies and research institutions to global scientific information and important (scientific	

		data) (Pahl-Wostl 2007; Tyler & Moench 2012) Tools and mechanisms for information storage and sharing (i.e. data archives, open access, reports, policy documents) accessible for all employees over time, across institutional borders and between public and private entities (Tyler & Moench 2012; Cutter et al. 2013; Tasan-Kok et al. 2013, Pahl-Wostl 2007, van den Brink et al. 2013) Presence of platforms of exchange among actors across institutional boundaries (e.g. policy officials, municipality representatives, project coordinators), such as workshops, brainstorming sessions (van den Brink et al. 2013; Moench 2014)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Anticipation & Foresight	Capacity to learn from past experience	Keeping track records and data archives on hazards (over time), disaster losses (National Academy of Sciences 2012; Tasan-Kok et al. 2013; Cutter et al. 2013) Lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms (Folke et al. 2005; Tyler & Moench 2012; Cutter et al. 2008; Davoudi et al. 2013; Adger et al. 2005; da Silva & Morera 2014; Schipper & Langston 2015)	Presence of accessible long-term track records of previous flooding events and disturbances (National Academy of Sciences 2012; Tasan-Kok et al. 2013) Lessons learnt from previous flooding events are formulated into tangible, accessible, evaluative reports

Preparedness & Planning ahead

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Preparedness & Planning ahead	Public awareness, risk communication education & training	Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action during disasters (e.g. guidance for preparation and appropriate response)	Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations (da Silva & Morera 2014; Eraydin & Taşan-Kok 2013; Lu & Stead

		(Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004; Gupta et al. 2010; Raadgever et al. 2015) Applying risk communication strategies for affected residents, e.g. flyers, targeted campaigns (van den Brink et al. 2013) Hazard awareness, (water) safety education programs and response trainings to neighborhood and community organizations (Godschalk 2003; Schelfaut et al. 2011; Pahl-Wostl 2007)	2013; Tyler & Moench 2012; Schelfaut et al. 2011; Norris et al. 2008)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Preparedness & Planning ahead	Response & Emergency Management	Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies (da Silva & Morera 2014; Schelfaut et al. 2011; Norris et al. 2008) Prevalence of hazard management plans, hazard mitigation plans, emergency response plans and contingency protocols (Schelfaut et al. 2011; Cutter et al. 2008; Linkov et al. 2013) Prevalence of evacuation plans, designation of evacuation routes and presence of shelter capacity (Cutter et al. 2013; da Silva & Morera 2014; van den Brink et al. 2013; de Bruijn 2004b) Training and capacity building on risk communication for responsible authorities (Schelfaut et al. 2011)	Presence of a flood forecasting and early flood warning system (Raadgever et al. 2015; Schelfaut et al. 2011)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Preparedness & Planning ahead	Preparedness of businesses for adverse events	Information provision of climate scenarios, climate-related impacts and threats (Godschalk 2003; Lonsdale et al. 2010) Presence of issue-specific formal or informal networks for exchange of best practice and knowledge generation (Lonsdale et al. 2010)	

		Businesses have an understanding of potential climate change related threats, associated risks and vulnerabilities in the business operation as well as opportunities (Lonsdale et al. 2010) Companies factor the impacts of climate change into their business practice (for instance by having business continuity and contingency plans in place) (Rose 2004; Lonsdale et al. 2010)	

Homeostasis

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Homeostasis	Preservation & restoration of regulating ecosystem services		Policies and plans for natural areas and ecosystem restoration (Tompkins & Adger 2004; Godschalk 2003) Increasing / creating urban green spaces and restoration of urban floodplain wetlands (Biggs et al. 2012; Wardekker et al. 2010; da Silva & Morera 2014) Wetlands acreage and loss (Godschalk 2003) Percentage of impervious surface area (Godschalk 2003)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Homeostasis	Integrated planning, coordination & collaboration	Presence of bridging mechanisms (e.g. actors, policies, laws, tools and instruments) that link and align strategies (Raadgever et al. 2015) Presence of a formalized, cross-sectoral, common vision underlying planning and implementation of projects (da Silva & Morera 2014; Rockefeller Foundation 2015; Rockefeller Foundation & ARUP 2015)	Linking urban (re-) development, planning processes, maintenance programs and other ongoing projects (road maintenance and public area development) (Wardekker et al. 2010; Smit & Wandel 2006) Cross-sector collaboration, mainstreaming of water policies with other sectorial policies (drainage, land use, urban development) (Runhaar et al. 2009; Uittenbroek et al. 2013)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**

Homeostasis	Inclusiveness & Equity standards	Legally enshrined equal rights and entitlements of citizens to use resources, urban systems and services (Tyler & Moench 2012) Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs) (Godschalk 2003) Collaboration between municipalities and residents in neighborhoods to determine their needs and set appropriate vulnerability-reducing measures (Godschalk 2003) Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits (Lebel et al. 2006) Assessments of distributional consequences and who wins and loses from the implementation of particular climate adaptation measures and impacts (Adger et al. 2005)	

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Homeostasis	Clearly defined responsibility of actors and institutions	Presence of specific divisions of accepted responsibilities (Raadgever et al. 2015) Transparency on responsibilities, tasks and roles of governing authorities and stakeholders (de Bruin et al. 2009) Intergovernmental division of labor for performing emergency response activities (e.g. search and rescue) (Bruneau et al. 2003)	Responsibilities are clearly defined and allocated for causing and solving water-problems, sewage systems (Gupta et al. 2010) Statutory responsibility for flood prevention and protection is defined and determined in policy documents (Wardekker et al. 2010) Legal responsibilities for property damage caused by flooding events are clearly defined and known by involved parties (Wardekker et al. 2010; de Bruijn 2004; Schelfaut et al. 2011) Insurability of private property against flood loss (Van den Brink et al. 2013; Godschalk 2003)

			Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery (Raadgever et al. 2015; de Bruijn 2004)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Homeostasis	Quick notification of disturbances	Multiple, reliable communication and broadcast technologies (internet, mobile phone, telephone, newspaper, TV etc.) to be harnessed for communicating flood warnings (da Silva & Morera 2014; Schelfaut et al. 2011; Norris et al. 2008)	Presence of a flood and weather forecasting, monitoring and early warning system to generate timely information that facilitates anticipation (Raadgever et al. 2015; Schelfaut et al. 2011; Linkov et al. 2013)

Phase Absorb

Robustness & Buffering

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Robustness & Buffering	Robustness through flood-protective infrastructure		Presence of flood-protective structural measures and installations (Godschalk 2003) Presence of formalized water safety / dike standards that are regularly monitored (da Silva & Morera 2014; Raadgever et al. 2015) Periodic assessment, optimization and improvement of flood-protective infrastructure (Cutter et al. 2013)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Robustness & Buffering	Creating buffer capacities		Implementation of additional levees, canals and water arms (Gunderson 2009) Increasing above and under-ground (rain)water storage and capture mechanisms (Wardekker et al. 2010; McBain et al. 2010; Zevenbergen et al. 2008) (Re)creating open space as urban floodplain wetlands and as urban green spaces (parks) (Godschalk 2003; da Silva & Morera 2014; van den Brink et al. 2013)

			Increasing the percentage of floodable areas (Liao 2012) Increasing the drainage capacity of the urban water system by designing drainage networks for exceedance (McBain et al. 2010)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Robustness & Buffering	Impact- and risk-reducing planning & planning practice		Limiting development rights in flood plains and areas at risk from flooding (flood zoning) (Raadgever et al. 2015; Tyler & Moench 2012) Prohibiting (property) development in flood-prone areas (Raadgever et al. 2015) Introduction of permits in flood-prone areas (Schelfaut et al. 2011) Relocating property from flood-prone areas and inhibiting new development (Godschalk 2003; Zevenbergen et al. 2008; van den Brink et al. 2013) Flood-proofing and flood-resilient design and construction standards for buildings, public facilities and assets (da Silva & Morera 2014; Godschalk 2003; Zevenbergen et al. 2008; van den Brink et al. 2013; Liao 2012) Elevation of ground level in urban flood-prone areas (Wardekker et al. 2010; Liao 2012) Flood-risk conscious interior design and appropriate planning (Wardekker et al. 2010; Zevenbergen et al. 2008)

Diversity

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Diversity	Functional & response diversity	Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people) (Liao 2012;	A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization (Liao 2012)

		Wardekker et al. 2010; Resilience Alliance 2010) Variety in energy systems using different energy sources which can be generated at different scales (local, regional, global) (SheltAir Group 2003) Variety in food provision: maintain local capacity to produce food, while strengthening transnational trade networks (SheltAir Group 2003) The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated (Martin & Sunley 2014) Heterogeneous population covering a wide range of different expertise, occupations and education (Walker et al. 2004; Martin & Sunley 2014; Rockefeller Foundation & ARUP 2015) Parallel existence of different land-use types in cities (Gunderson 2009) Implementing measures for crop diversification (i.e. urban farming, home gardens (Moench 2014)	Diverse sources of design for flooding protection infrastructure (Pahl-Wostl 2007; Cutter et al. 2008; Cutter et al. 2010)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Diversity	Spatial diversity	Financial institutions, economic activities, hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city (Tyler & Moench 2012) Various, geographically and spatially distributed (drinking) water sources and reservoirs around the city (Sheltair Group 2003; Tyler & Moench 2012) Food supplies are sourced from different geographic areas (Tyler & Moench 2012)	Decentralized flood-protective infrastructure (Pahl-Wostl 2007)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**

Diversity	Actor & stakeholder diversty	Variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process (Gupta et al. 2010; van den Brink et al. 2013; Biggs et al. 2012; da Silva & Morera 2014) (Biggs et al. 2012; Da Silva & Morera 2014) Actors and stakeholders involved in decision- and policy-making have differing professional and knowledge backgrounds (Biggs et al. 2012; Folke et al. 2005; Berkes & Ross 2013) Different government and non-governmental stakeholders are involved in setting the TOR and/or consulted (Huntjens et al. 2010)	Different problem frames and policy solutions for urban flooding (van den Brink et al. 2013)

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Diversity	Institutional diversity, multi-level governance systems & linkages	Organizations with different sizes, cultures, funding mechanisms, internal structures (Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Tyler & Moench 2012; Kernaghan & da Silva 2014; van den Brink et al. 2013; Resilience Alliance 2010; Walker et al. 2004) Various governing authorities at different scales made up by a diverse group of actors with different roles and overlapping functions (Biggs et al. 2012; Biggs et al. 2014; Gupta et al. 2010; Folke et al. 2005) Presence of formal and informal partnerships between governing authorities, academia, firms and NGOs (da Silva & Morera 2014) Presence of platforms of exchange among actors, such as workshops, brainstorming sessions (van den Brink et al. 2013)	Governing authorities involved in flood risk management differ in size, culture, internal structure (Adger et al. 2005; Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Tyler & Moench 2012) Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level) (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006) Distributed flood-response capacity across levels (households, communities, municipalities) (Liao 2012)

Redundancy

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Redundancy	Overlapping functions & roles	Shared responsibilities, rights and management authorities among actors and responsible institutions across scales (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005) Redundancy of actors and actors roles (Folke et al. 2005) Different organizational forms that share the same issues areas (Biggs et al. 2012) Polycentric, multi-level governance systems with decentralized decision-making structures (Biggs et al. 2012; Norris et al. 2008)	Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level) (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Redundancy	Functional redundancy in important functions & services	Multiple access / evacuation routes, multiple routes of supply, electricity, sewage removal (Cutter et al. 2010; Cutter et al. 2008; Wardekker et al. 2010) Several transmission towers to sustain communication (Tyler & Moench 2012) Multiple counterparts for vital functions (Wardekker et al. 2010)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Redundancy	Spare capacities & back-up resources	Alternative power supplies and energy back-up generators for key businesses, critical infrastructure and services (Bruneau et al. 2003; Tyler & Moench 2012) Alternative water supplies for all key businesses and critical infrastructure (Bruneau et al. 2003) Maintaining stocks of food, medicine, water supplies in case of disruption (Tyler & Moench 2012)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Redundancy	Compartmentalization & modularity	Presence of polycentric, multi-level governance systems (Biggs et al. 2012) Communication, transport networks, infrastructure grids and other vital functions and services in cities are based on a modular network structure (SheltAir Group 2003) Sectorial and organizational components of an economy are based on a modular network structure (Martin & Sunley 2014)	Presence of compartmentalization dikes, dike rings, compartmentalized polders, temporary dams or flood defences that prevent floodings from spreading to other regions or locally retain substances (Gersonius et al. 2011; Wardekker et al. 2010)

Phase Recover

Flatness

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Flatness	Institutional decentralization & autonomy	Shared responsibilities, rights and management authorities among responsible institutions across scales (Nelson et al. 2007; Tanner et al. 2009; Adger et al. 2005) Financial independence of governing bodies (Lebel et al. 2006) Municipal authorities have the autonomy to authorize plans and legislate policy (Tanner et al. 2009) Autonomous management capacity and ability to autonomously develop own strategic goals, tailor-made policies and measures (Lebel et al. 2006; Pahl-Wostl & Knüppe 2013) Independent governance units with a particular domain of authority within a designated geographic area (Folke et al. 2005; Biggs et al. 2012)	Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level) (Biggs et al. 2012; Biggs et al. 2014; Folke et al. 2005; Lebel et al. 2006)

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators

Flatness	Broad participation, stakeholder engagement & inclusiveness	Presence of mechanisms for providing stakeholder and public input to decisions, programs and strategies (e.g. hearings, meetings, local consultations) (Davoudi et al. 2013; Tyler & Moench 2012) Non-governmental stakeholders contribute to agenda setting, analyzing problems, developing solutions (''coproduction'') (Biggs et al. 2012, 2014; Huntjens et al. 2010) Presence of open, deliberative forums or platforms of exchange between actors (policy officials, municipality representative, project coordinators, local population) before and during the implementation of projects (i.e. workshops, brainstorming sessions) (van den Brink et al. 2013; Mees et al. 2014) Designing varied local and context-specific mitigation approaches based on neighborhoods consultation and collaboration and needs assessment (Godschalk 2003; Norris et al. 2008) Legal provisions concerning access to information, participation in decision-making (e.g. consultation requirements before decision-making) and access to courts (Huntjens et al. 2010) Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits (Lebel et al. 2006) Decision-making processes are transparent and aim at including and equally representing all interests at stake (Mees et al. 2014; Tyler & Moench 2012)	

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**

Flatness	Room for autonomous change	**Continuous access to information (institutions)** Access of government agencies and research institutions to global scientific information and important scientific data (Pahl-Wostl 2007; Tyler & Moench 2012) Tools and mechanisms for information storage and sharing (i.e. data archives, open access, reports, policy documents) accessible for all employees over time, across institutional borders and between public and private entities (Tyler & Moench 2012; Cutter et al. 2013; Tasan-Kok et al. 2013, Pahl-Wostl 2007, van den Brink et al. 2013) **Continuous access to information (public)** Applying risk communication strategies for affected residents, e.g. flyers, targeted campaigns (van den Brink et al. 2013) **Capacity to act according to plan** Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action during disasters (e.g. guidance for preparation and appropriate response) (Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004; Gupta et al. 2010; Raadgever et al. 2015) **General** Procedures that enable groups to form legal voluntary organizations, raise funds and undertake activities in	**Continuous access to information (public)** Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations (da Silva & Morera 2014; Eraydin & Taşan-Kok 2013; Lu & Stead 2013; Tyler & Moench 2012; Schelfaut et al. 2011; Norris et al. 2008) **Capacity to act according to plan** Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action for flooding events (e.g. guidance for preparation and appropriate response) (Schelfaut et al. 2011; Norris et al. 2008; de Bruijn 2004; Gupta et al. 2010; Raadgever et al. 2015) Hazard awareness, (water) safety education programs and response trainings to neighborhood and community organizations (Godschalk 2003; Schelfaut et al. 2011; Pahl-Wostl 2007) Affected population is provided guidance on flood-resilient construction and how to

		relation to emerging needs (Tyler & Moench 2012)	prepare their homes for flooding (Schelfaut et al. 2011)

High Flux

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
High Flux	Availability of & access to resources	Pre-event arrangements for governmental reimbursement, such as national continency funds or damage compensation payments out of national, regional or municipal funds (Bruneau et al. 2003; da Silva & Morera 2014; van den Brink et al. 2013) Institutions withhold financial resources for required public hazard-related expenditures concerning roads, drainage and sewage systems (Godschalk 2003) Reduction of irreversible commitment of resources (Wardekker et al. 2010) Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock (Arup 2014b; de Bruijn 2004; Bruneau et al. 2003) Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs) (Godschalk 2003)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
High Flux	Social & institutional networks	Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs (Davoudi et al. 2013; Folke et al. 2005; Huntjens et al. 2010) Prevalence of platforms of exchange among actors such as workshops, congresses, city labs (van den Brink et al. 2013; Moench 2014)	

		Level of social cohesion and inter-group contacts among population groups (de Bruijn 2004)	

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
High Flux	Having options for flexibility in response	Citizens have the monetary resources to shift livelihoods (i.e. find new income sources), modify physical structures or change physical location if required (Schipper & Langston 2015; Tyler & Moench 2012) Citizens have convertible assets and skills so that they are capable of temporarily repurposing resources, means and spaces when changing conditions require it (Moench 2014; Tyler & Moench 2012; Rockefeller Foundation 2015) Financial mechanisms for fostering (local) business development and innovation (Rockefeller Foundation & ARUP 2015) Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes (Martin & Sunley 2014) Communities' livelihood strategies are not confined to a single economic resource (Norris et al. 2008; Schipper & Langston 2015)	

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
High Flux	Managing connectivity of critical infrastructure, services and natural habitats	Identification of critical linkages between different spatial layers, critical physical and spatial links between transport networks, ICT networks and vital infrastructure that might be affected by a disaster (Davoudi et al. 2013; Zevenbergen et al. 2008) Investigating into factors that contribute to failure of water, sewerage, transport and food system infrastructure that causes major	

		disruptions, and locating where system failure have major impacts (Moench 2014) Connecting webs of green and ribbons of blue (Sheltair Group 2003) Preserving and implementing well-connected habitat patches (Biggs et al. 2012) Improve spatial heterogeneity in landscapes by implementing spatially alternating land use (Biggs et al. 2012)	

Phase Adapt

Learning & Reflectivity

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Learning & Reflectivity	Institutional learning capacity	Institutions are monitoring their activities and performance and critically evaluate implemented policies (Cutter et al. 2013; Gupta et al. 2010; Huntjens et al. 2010) Iterative revision and updating of plans, strategies and standards based on emerging information and research (Tyler & Moench 2012; Lonsdale et al. 2010; Moench 2014) Participatory co-learning approaches by providing spaces for joint learning (Lonsdale et al. 2010) Institutions adopt new procedures, patterns of collaboration or management decisions (Linkov et al. 2013; Gunderson 2009; Schmitt et al. 2013; Nelson et al. 2007; Gupta et al. 2010) Learning outputs (i.e. changing insights and circumstances) inform policy changes and amendments (Nelson et al. 2007; Liao 2012; Gunderson 2009)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Learning & Reflectivity	Experimentation & innovation	Creation of testing grounds and support for 'informal space' to experiment and innovate (Lonsdale et al. 2010) Small- and large scale experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts which are financially supported (Resilience Alliance 2010; Folke et al. 2005; Biggs et al. 2012; Huntjens et al. 2010; Zevenbergen et al. 2013)	

Flexibility

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Flexibility	Institutional flexibility	Decision-making processes allow for a change in speed and actor composition (Buuren et al. 2015) Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon and goals of strategies and activities (Buuren et al. 2015) Institutions offer room for changing the procedures and cooperation arrangements if required (Buuren et al. 2015)	

Principle	Intermediate Principle	General indicators	Flood resilience-specific indicators
Flexibility	Flexibility in spatial planning	Development of multi-use spaces or convertible structures that allow for short-term and long-term shifts in the use of space, parcels, buildings (Sheltair Group 2003; Wardekker et al. 2010; Zevenbergen et al. 2008) Employing modular elements in buildings (Wardekker et al. 2010); Spatial design allows for additions or deletions to the quantity of space and	

		land dedicated to particular uses (Sheltair Group 2003) Leaving spaces without development so that they can be used for other purposes (Wardekker et al. 2010; van den Brink et al. 2013; Raadgever et al. 2015; Tyler & Moench 2012) Reducing life-cycles of buildings and infrastructure (Wardekker et al. 2010; Zevenbergen et al. 2008)	

Principle	**Intermediate Principle**	**General indicators**	**Flood resilience-specific indicators**
Flexibility	Flexibility in measures	Employing no-regret measures in climate adaptation apt for a broad range of possible future scenarios (de Bruin et al. 2009; Raadgever et al. 2015; Stead & Tasan-Kok 2013; Wardekker et al. 2010) Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: designing measures for reversibility (Huntjens et al. 2010) No one-fits all solution but consideration of alternatives which include small- and large-scale structural and non-structural measures (Huntjens et al. 2010) Reducing irreversible commitment of financial resources by broadening measures (Wardekker et al. 2010) Urban planning, disaster risk management, climate adaptation strategies and respective policy development account for a long-term planning horizon (Zevenbergen et al. 2008; Lu & Stead 2013; S. Cutter et al. 2013; Godschalk 2003)	

Appendix 4: Illustration application valuation / Matrix system

Example: Performance of city-wide vulnerability assessments which describe and map potential flood hazards and impacts on neighborhoods

The development of tools for vulnerability assessments rank high on the Dutch agenda with the purpose to support professionals and policy makers in creating appropriate measures.
For instance, based on the KNMI data, in a multi-actor and multi-sector collaboration of universities, knowledge institutes and consultancies a Climate Change Atlas was developed for each user to explore area-specific vulnerabilities along the projected future threats of coastal, riverine, urban flooding, heat and drought (Kennisportaal Ruimtelijke Adaptatie 2015). Likewise, the Province of South Holland created a risk assessment tool for developments in outer dike areas (Interview Sandra R6). Furthermore, safety regions create risk profiles for each type of disturbance by drawing on specialized knowledge about changing (flood) risk due to updated climate change projections (Interview R11). Prominent ways to assess vulnerabilities with regards to flood risk, heat stress and drought risk on a regional or city-scale are stress tests (so-called Klimaatscan) which have been adopted by several municipalities that signed commitment agreements to the Delta Decision Spatial Planning (Interview R5 and R12).
Furthermore, water modelling tools developed by Deltares, such as the Delft 3D Coastal and River System Modeling are widely used for problem analysis, producing flood risk maps and risk profiles For Rotterdam, these flood simulations have been used to show the temporal sequence of water spreading across the Rotterdam area after a dike breach, or flooding in unembanked areas due to high river levels. By doing so, vulnerable spots in outer-dike areas, such as Noordereiland or Kop van Feijenoord or businesses in the former port area with possible cascading effects across the whole supply chain of port activities and inner dike areas, such as roads, tunnels and electricity hubs were identified (Interview R7).

Appendix 5: List of interviewees

Rotterdam

R1. Senior policy researcher, Department of Water, Agriculture and Food, PBL Netherlands Environmental Assessment Agency, 22 February 2016
R2. Strategic advisor water, Department of Public Works, Municipality of Rotterdam, 24 February 2016
R3. Senior policy advisor, Department of Water Management, Water Authority Delfland, 24 March 2016
R4. Strategic policy advisor, Water Authority Delfland, 16 April, 2016
R5. Lector water management, University of Applied Sciences Amsterdam, 19 April 2016
R6. Senior policy advisor (second interview), Department of Water Management, Water Authority Delfland, 21 April 2016
R7. Senior Advisor Integral Water Management and Climate Adaptation, Department Public Works, Municipality of Rotterdam, 22 April 2016
R8. Hoogheemraad, Water Authority Schieland and Krimpenerwaard, 25 April 2016
R9. Strategic consultant, Water Authority Hollandse Delta, 26 April 2016
R10. Senior advisor Flood, Rijkswaterstaat, 28 April 2016
R11. Senior policy advisor, Information Manager CoPI/ROT, Department Crisis Management, Safety Region Rotterdam-Rijnmond, 4 May 2016
R12. Senior policy advisor, DP Spatial Adaptation, IenM, 4 May 2016
R13. Senior advisor Sustainability, Municipality of Rotterdam, 10 May 2016 (Presentation Adaptation Futures Conference in Rotterdam, 10 – 13 May, 2016)
R14. Strategic advisor and project management city development at Urban Impact (owner), program manager Rotterdam Centre for Climate Resilient Delta Cities, 11 May 2016
R15. Senior policy advisor, DP Spatial Adaptation, IenM, 12 May 2016
R16. Senior planner and senior landscape architect (2 interviewees), Department Urban Development, Municipality of Rotterdam, 17 May 2016
R17. Advisor Environment, Spatial Development and Sustainability, Department Urban Development, Municipality of Rotterdam, 18 May 2016
R18. Senior policy advisor water safety, project management EU Interreg FRAMES, Department for Water, Province of South Holland, 18 May 2016
R19. Policy advisor, Department of Safety, Municipality of Rotterdam, 19 May 2016
R20. Senior policy advisor, Water Authority Delfland, director of the Water Buffer Foundation, 20 May 2016

London

L1. Program Manager Joint DEFRA / EA Flood and Coastal Erosion Research and Development Program, Evidence Directorate, Environment Agency, 29 April, 2016
L2. Strategy and Program Manager Climate Adaptation, GLA, 12 May, 2016 (including parts of the presentation he gave at the Adaptation Futures Conference in Rotterdam, 10 – 13 May, 2016)
L3. Owner John Dora Consulting Limited and Member of the Thames Regional Flood and Coastal Committee, Environment Agency, 11 May 2016 (Presentation Adaptation Futures Conference in Rotterdam, 10 – 13 May, 2016)
L4. Project Manager London Climate Change Partnership, 12 May 2016
L5. Principal Program Manager, GLA, 31 May 2016

L6. London Resilience Officer, London Resilience Team, 31 May 2016

L7. Sustainability Coordinator, Transport for London, 1 June, 2016

L8. Principal Policy Officer, Transport, Infrastructure & Environment and Resilience Policy and Public Affairs Division, London Councils, 8 June 2016

L9. Deputy Chief Executive, Team London Bridge Business Improvement District, 10 June, 2016

L10. Flood Expert, Thames Estuary Partnership, 14 June, 2016

L11. Climate Change Senior Advisor, Environment Agency, 15 June, 2016

L12. Team Leader Planning Policy and Planning Policy Officer (2 interviewees), Southwark Council, 17 June, 2016

L13. Flood risk manager, Department Highways, Southwark Council, 21 June, 2016

Appendix 6: Interview questions

BUILDING KNOWLEDGE ABOUT DISTURBANCE, EXPOSURE AND VULNERABILITY

- Which sources of knowledge about climate change-related effects, flood risks (riverine, tidal, surface, and coastal) and vulnerabilities do you use for your work (i.e. climate change projections & scenarios, weather projections, water / drainage system)?
- Do you as an organization actively contribute to generating this knowledge? If yes, in what ways?
- In what ways do you assess the vulnerability of your area to climate change effects, their consequences and related risk, specifically in regards of flooding and extreme rainfall?

INFORMATION MANAGEMENT AND SHARING

- Are disciplinary backgrounds of the employees of your organization varied? To what extent is there specialized knowledge in your organization on topics relevant to flooding and climate adaptation?
- How is relevant information (reports, documents etc.) stored in your organization?
- Do you have access to climate scenarios and do you make use of them to inform decision-making? Which ones do you use?
- To what extent does information exchange take place, both internally and externally (with the public, boroughs, with other organizations, cities etc.)?

MONITORING OF SLOW VARIABLES

It is usually the combination of a shock (e.g. cloudburst, rainstorm, storm surge) with slow variables which makes the system approach potential thresholds where disturbances can turn into disasters. These slow variables can be of socio-economic, governance-related or ecological nature. For short-term shocks like cloudburst events or riverine flooding, variables like rainfall patterns, soil type, the extent of impermeable surfaces in the city. For long-term gradual changes like sea level rise, land elevation and subsidence or coastal welands deterioration are among these slow variable.

- Could you name the most important factors that give rise to flooding events in your city (i.e. surface water, riverine, coastal flooding)? Are these factors being monitored? How?

HOMEOSTASIS

A system consists of feedbacks between its components that direct the system by triggering changes and driving responses. In a resilient system these feedbacks are known and geared accordingly. That means that multiple feedback loops are implemented that counteract disturbances (dampening feedback) and stabilize the system. Examples are for instance monitoring, that provides information about the state of an SES to actors, so that they can adjust behavior or act upfront to alarming conditions; in regards of emergency management it could also be the quick provision of information that enhance citizens' response during emergencies but also the preservation of regulating ecosystem services (flooding buffer).

- Can you think of any example for such a mechanisms based on your experience, in relation to short-term shocks (riverine, surface water, cloudbursts flooding) and long-term gradual trends (sea level rise)?

INTEGRATION

- How would you consider the level of integration of flood risk/water management/water safety into other (sectorial) policy areas (emergency management, drainage, land use, urban planning, and climate adaptation)?
- Which mechanisms are used for integration and coordination?[19]

[19] These questions were formulated based on the interview questions used in Mees (2010).

PREPAREDNESS

- Is there an early flood warning system in place? How do you warn people in the case of a flooding event? Which channels do you use for doing so?
- Which tools are applied to inform and educate the public about flood risk (i.e. information provided to households, community organizations, trainings, guidance for preparation and response etc.)?
- Does the public have access to flood risk information and early warning systems?
- Are plans and scripts for action in case of flooding events provided?
- Are there emergency plans, contingency plans, recovery plans and evacuation plans and routes in place?
- What about shelter capacities?

- Is there anything specifically being done to prepare businesses for such events (i.e. provide info on climate scenarios, educating them about hazard mitigation etc.)?

ROBUSTNESS AND BUFFERING

- What are the major structural measures taken to prevent flooding events, please refer to several types of flood risk prevalent for this area (e.g. cloudbursts, tidal, surface water, riverine, groundwater etc.)?
- Are there additional buffer capacities installed for absorbing flooding events to a certain extent (for instance by over-dimensioning water capture/storage capacities, increasing natural absorption mechanisms etc.)? Which ones?
- What other planning or policy mechanisms are used to reduce vulnerability, risks of the city towards flooding events and potential flooding impacts (again please consider the different types of flooding London is vulnerable to) (e.g. construction and building codes, legislation, spatial development etc.)?

DIVERSITY

A system with many different components is less vulnerable to disturbance and can better absorb events since it has the advantage of different response to threats and different ways of absorbing incidents (response diversity). The prevalence of many different ways of needs fulfillment under a broad range of different circumstances also helps it with quicker recovery, since a shift to alternative service provision is possible (i.e. diversified economy). This is closely connected with the idea that people can adopt alternative strategies in response to disruption and have options to modify behavior if required (e.g. changing physical location, finding new income sources).

Indicating some examples of the following categories:

<u>Functional diversity</u>

- Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people)
- Diverse education, expertise, occupations of people living in a district
- Diverse economy (recovery)

<u>Spatial diversity</u>

- Financial institutions, economic activities hospitals, crisis centers, refugee centers, water pumping facilities etc. are physically distributed across the city to spread risk

<u>Diversity in governance systems</u>

- Size, culture, internal structure of governing authorities involved in flood management

- Is diversity in one of the described ways considered, implemented or specifically aimed at with your activities?

COLLABORATION & PARTNERSHIPS

- Which are the major agencies you are working with concerning water and flood risk management?

- How would you best describe collaboration with these parties (i.e. mere exchange of information, meetings, to active exchange)? Do you have specific platforms of exchange?
- Are there partnerships, formal/informal networks?

REDUNDANCY
Plays a major role for absorbing disturbances. It means engineering a system in a way that there are multiple components that perform the same function and therefore compensate for failure of other parts, like safe failure mechanisms.

- Can you think of anything where this is being implemented?

It is also prevalent in back-up systems (e.g. electricity, gas, transport), or keeping buffer stocks (e.g. food, water) that help maintain service delivery in times of crisis.

- Is that something being provided?

FLATNESS / ROOM FOR AUTONOMOUS RESPONSE
From a resilience perspective a system should not be governed in a hierarchical, top-down mode but rather equip lower local levels of governance and the population with formal competence to act (autonomously). The capacity to self-organize is an important resilience feature.

- Are there any measures in place that equip the public with the capacity to act/react autonomously and self-sufficiently to flooding events?
- Is there room for action and reaction and can they intervene into the current system?

PARTICIPATION / STAKEHOLDER ENGAGEMENT
- How would you describe the level of involvement of non-governmental stakeholders in the different phases: 1) developing solutions 2) planning 3) decision-making 4) implementation of projects and measures?
- Are there any means and tools provided to facilitate the input of citizens in the different phases of designing the strategies / decision-making, planning and implementation (i.e. stakeholder consultation, platforms of exchange such a joint workshops, brainstorming sessions?

RESPONSIBILITIES / AUTONOMY
- Who are the relevant agencies involved in flood risk, water and drainage management and what are their roles and responsibilities specifically with regards to flood prevention and adaptation measures?
- Are these responsibilities clearly defined and is every agency aware of their particular responsibility?
- Are there shared responsibilities/functions/roles among responsible institutions?
- What is the level of autonomy of these institutions? Would you describe the system as centralized or decentralized?

HIGH FLUX
A quick response requires access to resources (financial, human, technology, material) and their quick mobilization. Here it is mainly about which resources organizations have at hand to quickly mobilize and move information, knowledge, assets etc. through the system and thereby facilitate quick recovery (in terms of swiftly resuming function) and response.

- Which resources do you have available in your organizations for flood response?
- How quickly can you access them / how quickly can you mobilize them?

- What other relevant factors can you think of for a quick emergency response and recovery?
- Are there any particular mechanisms or supportive services to help people with recovery?
- Do they have access to financial resources (contingency funds, insurance schemes etc.) that can help them 1) make flood proofing installations / adjustments in their own homes and 2) restore damaged property after a flooding?
- Are there any specific services/resources provided to vulnerable groups?

CONNECTIVITY

For a fast response and recovery relevant agencies, critical sectors and vital functions (ICT, electricity, gas, drinking water) should be well connected to facilitate a quick flow of resources. The idea is that everything should be connected in a network structure with multiple nodes that are easily accessible by everybody (i.e. services, food provision, information, drinking water, recovery services)

- Are you aware of the critical linkages between spatial layers that could be affected by adverse events?
- Do you investigate cascading effects of flooding events with other sectors?
- Are there any measures set to prevent these cascading effects?
- Is connectivity a factor being considered in linking green spaces and water ways?

SOCIAL NETWORKS

- Are there any actions taken to improve community cohesion, in order to improve the capacity of citizens to self-organize and respond autonomously?
- Presence of neighborhood and community initiatives such as urban greening or the creation of green spaces?
- In general, how would you consider the level of social cohesion, inter-group contacts among communities? Are there social networks that are well connected and people can build on for accessing resources of others if required (e.g. contingency situations)?

CAPACITY TO LEARN

- Does your organization monitor its performance? In what ways? Are there specific (performance) indicators used?
- Are former policies being evaluated after their implementation?
- Are lessons learnt from previous actions and (flooding) events translated into tangible reports, evaluations etc.? Can you give me an example for flooding?
- Is there sufficient room for experiments such as pilot projects, or testing alternative strategies and management approaches?
- How would you describe the extent of innovation concerning flood risk / water management?
- Is there room for participatory, continuous learning in your organization and beyond? In what ways?
- Do uncertainties in climate change and projections play a role for your organization and its activities? If yes, how do you deal with them? [20]

FLEXIBILITY

- How would you consider the flexibility in decision-making processes in your agency?
    - Is a change in speed of the process possible, are there many formal rules that guide interaction between participants?
    - Is there room in your agency for changing scope, goals of strategies and activities, time horizons?
- To what extent does current spatial planning allow for flexibility with regards to flood risk / impact reducing measures?

[20] Questions 4, 5, 6 and 7 were formulated based on the interview questions used in Mees (2010).

    - Are shifts in use of space, parcels or buildings possible, both minor shifts (multi-functional use of spaces, modular elements in buildings) as well as larger, long-term shifts (legal provisions for repurposing of space and spatial functions; short life-cycles of buildings / infrastructure)?
    - Are future adjustments, such as retrofitting, spatial expandability or deletions possible (e.g. leaving space around dikes for broadening their base)?
- How flexible are the measures taken to prevent or buffer flood risk in general?
    - Do they limit the range of possible measures that can be taken in the future?
    - Are they reversible?
    - Do they lend themselves to combination with other measures (e.g. small-, large scale, structural and non-structural measures)?

Appendix 7: Diagnostic Tool

PHASE / POLICY DIRECTION	PRINCIPLE	OPERATIONALIZATION	FINAL SET OF INDICATORS
PLAN / PREPARE	**Anticipation & Foresight** Planning ahead and foresight are essential tools for anticipatory adaptation. They originate from the human capacity to anticipate disturbances to a certain degree, imagine different futures and thus, consider possible outcomes and to implement preparatory interventions. In regards of climate hazards, anticipation is mainly concerned with creating relevant knowledge about disturbances, their probabilities, potential risks, impacts and resulting vulnerabilities. But the resulting knowledge should also be shared among organizations and made accessible for the wider population to create awareness.	**Building knowledge about disturbance, exposure, vulnerability**	**GENERAL** Existence of (regional and city-wide) climate change-related projections, forecasts and scenarios Identification and assessment of climate-related hazards, probability of occurrence, system's exposure, city-wide impacts and associated risks Mapping of economic assets, critical functions (hospitals, police stations etc.), commercial and manufacturing establishments in flood-prone areas **FLOOD-RESILIENCE SPECIFIC** Performance of city-wide vulnerability assessments which describe and map potential flood hazards and impacts on neighborhoods
		Monitoring of critical slow variables	**GENERAL** Real-time data collection; monitoring of natural (geological, atmospheric, oceanic) phenomena Periodic analysis and inspection of crucial infrastructure (i.e. transport, electricity networks, telephone lines, drainage systems **FLOOD-RESILIENCE SPECIFIC** Flood risk monitoring systems are in place Continuous monitoring, control and evaluation of dikes safety and of flood-protective facilities Water storage capacity and volume of the sewer system / water system Amount of permeable, impermeable, semi-permeable surfaces in city Population density and growth Soil type and subsidence Coastal erosion Sea level rise Peak river (fluvial) flood flows Public and institutional attitudes to flood risk
		Information management & sharing	**GENERAL / FLOOD-RESILIENCE SPECIFIC** Access of government agencies and research institutions to global scientific information and important (scientific data) Tools and mechanisms for information storage and sharing (i.e. data archives, open access, reports, policy documents) accessible for all employees over time, across institutional borders and between public and private entities Presence of platforms of exchange among actors (e.g. policy officials, municipality representatives, project coordinators), such as workshops, brainstorming sessions
		Capacity to learn (from past experience)	**GENERAL** Keeping track records and data archives on hazards (over time), disaster losses Lessons learnt are continuously incorporated into planning, implementation activities, preparedness and recovery mechanisms **FLOOD-RESILIENCE SPECIFIC** Presence of accessible long-term track records of previous flooding events and disturbances Lessons learnt from previous flooding events are formulated into tangible, accessible reports
	Preparedness & Planning ahead Preparedness is strengthening a city's coping responses before a disaster occurs. Being better prepared enhances the chances of absorbing impacts and quicker recovery. Apart from building and implementing adequate emergency & response management and mechanisms, this also entails providing the required resources for communities and businesses to plan and prepare for adverse events, such as the provision of adequate information, training and educational measures or the adoption of community flood plans.	**Public Awareness, Risk Communication, Education & Training**	**GENERAL** Presence and public disclosure of emergency procedures, evacuation routes, plans and scripts for action during disasters (e.g. guidance for preparation and appropriate response) Applying risk communication strategies for affected residents, e.g. flyers, targeted campaigns Hazard awareness, (water) safety education programs and response trainings to neighborhood and community organizations **FLOOD-RESILIENCE SPECIFIC** Disclosure of credible and correct information on flood risk via various channels by respective governance institutions to households, and community organizations Making flood risk comprehensive for the public
		Response & Emergency Management	**GENERAL** Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies Prevalence of regional hazard management plans, hazard mitigation plans, emergency response plans and contingency protocols Prevalence of regional evacuation plans, designation of evacuation routes and presence of shelter capacity Training and capacity building on risk communication for responsible authorities **FLOOD-RESILIENCE SPECIFIC** Presence of a flood forecasting and early flood warning system
		Preparedness of businesses for adverse events	**GENERAL** Presence of issue-specific formal or informal networks for exchange of best practice and knowledge generation (Lonsdale et al. 2010) Businesses have an understanding of potential climate change related threats, associated risks and vulnerabilities in the business operation as well as opportunities Companies factor the impacts of climate change into their business practice (for instance by having business continuity and contingency plans in place) **FLOOD-RESILIENCE SPECIFIC** Governing authorities provide companies with (online) tools (i.e. climate scenarios, flood maps), timely and tailored flood warnings,(water-related) knowledge, workshops for climate adaptation, flood risk mitigation and preparation

Homeostasis Dynamics in a SES arise from interactions and feedbacks between fast variables responding to the conditions generated by slow variables. Strategic management of feedbacks to prevent regime shifts (caused by disasters or slow trends) is therefore crucial. One way to do so is through implementing multiple feedback loops that counteract disturbances (dampening feedback) and/or stabilize the system to maintain a particular SES regime.	**Preservation & restoration of regulating ecosystem services**	**FLOOD-RESILIENCE SPECIFIC** Policies and plans for natural areas and ecosystem conservation Increasing / creating urban green spaces, green roofs, urban tree canopy cover (Re) implementing urban floodplain wetlands, coastal wetlands Wetlands acreage and loss Percentage of impervious surface area
	Integrated planning, coordination & collaboration	**GENERAL** Creating institutional and organizational structures that promote integrated knowledge sharing between departments, management authorities and across different scales Provide for flexible budget investment mechanisms in organizations and municipal departments Promote cross-sector collaboration and arrangements for sharing of (confidential) knowledge and information between sectors Presence of bridging mechanisms (e.g. actors, policies, laws, tools and instruments) that link and align strategies Presence of leadership driving cross-departmental collaboration and projects forward Creating co-benefits to connect agendas of different policy domains Presence of a formalized, common vision underlying planning and implementation of projects **FLOOD-RESILIENCE SPECIFIC** Integration of climate adaptation (and water safety) into other sectorial policies via anchoring in standards or (national) laws or by harmonizing regulations / policies across sectors and policy areas or creating control mechanisms for spatial planning along the lines of flood protection Linking urban (re-) development, planning processes, maintenance programs and other ongoing projects (road maintenance and public area development)
	Inclusivness & equity standards	**GENERAL** Legally enshrined rights and entitlements of citizens to use resources, urban systems and services (e.g. legal registration of residence coupled to receiving services) Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas (e.g. relocation housing programs) Setting aside financial resources to make poor neighbourhoods safer from disturbances Collaboration between municipalities and residents in neighbourhoods to determine their needs and set appropriate vulnerability-reducing measures Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits Assessments of distributional consequences and who wins and loses from the implementation of particular climate adaptation measures and impacts
	Clearly defined responsibilities of actors / institutions	**GENERAL** Presence of specific divisions of accepted responsibilities Formal mechanisms of oversight and /or cooperation such as an agreed coordinating responsibility where there are more than one risk owners Transparency on responsibilities, tasks and rolse of governing authorities and stakeholders **FLOOD-RESILIENCE SPECIFIC** Responsibilities are clearly defined and allocated for causing and solving water-problems, sewage systems Statutorily defined risk owner with clear line of oversight and responsibility Legal responsibilities for property damage caused by flooding events are clearly defined and known by involved parties Insurability of private property against flood loss Citizens are aware of their responsibilities and roles in flood protection, prevention, response and recovery
	Quick notification of disturbances	**GENERAL** Multiple, reliable communication technologies (ICT) to be harnessed for disseminating information during emergencies Variety of broadcast technologies (internet, mobile phone, telephone, newspaper, TV, radio, public broadcasts in the street) used for communicating flood warnings **FLOOD-RESILIENCE SPECIFIC** Presence of a flood and weather forecasting, monitoring and early warning system to generate timely information that facilitates anticipation Use of centering and remote sensing techniques in dikes to observe system behaviour

ABSORB DISTURBANCE

Robustness & Buffering

The inherent strength of a city, referred to as robustness and the existence of buffering mechanisms based on over-dimensioning systems (i.e. water storage capacity) determine whether a city can endure, cope with a hazard and maintain function during adverse circumstances. Solid flood-protective infrastructure coupled with pre-emptive planning practices, such as flood-sensitive building codes and event buffering capacity can enhance the robustness of a system.

Robustness through infrastructure

FLOOD-RESILIENCE SPECIFIC
- Presence of flood-protective structural measures and installations
- Presence of formalized water safety / dike standards that are regularly monitored
- Periodic assessment, optimization and improvement of flood-protective infrastructure
- Impacts of flooding events on critical infrastructure and urban public utility networks are assessed (i.e. water system, flood defences, drinking water, transport systems, gas, ICT, port), vulnerabilities and system failure factors identified and pre-emptive measures and response strategies for maintaining functions developed

Creating buffer capacities

FLOOD-RESILIENCE SPECIFIC
- Implementation of levees, canals and water arms
- Improving (natural) water infiltration and storage capacity, for instance by increasing above and under-ground (rain)water storage and capture mechanisms, (re)creating urban floodplain wetlands and green spaces or using permeable paving
- Increasing the percentage of floodable areas, for instance by widening river and polder beds, deepening basins, installing emergency basins or temporarily inundating agricultural and nature areas
- Increasing the drainage capacity of the urban water system, for instance by enlarging sewerage pipes, installing larger pumping stations or higher capacity pumping stations in the water system, enlarging precipitation channels, implementing design standards for shorter return periods of storm water events

Impact- and risk-reducing planning & planning practice

FLOOD-RESILIENCE SPECIFIC
- Limiting development rights in flood plains and areas at risk from flooding (flood zoning)
- Introduction of permits in flood-prone areas
- Flood-proofing and flood-resilient construction codes and standards for buildings and public facilities
- Elevation of ground level of urban flood-prone areas
- Flood-risk conscious interior design and appropriate planning

Redundancy

Describes the presence of multiple elements or replication of components or pathways in order to have multiple instances available that perform the same function. These can fully substitute each other and therefore prevent system failure in case one component fails. From a resilience-building perspective it implies the strategic creation of systems that have multiple nodes, connected components and spare capacities that prevent failure in the face of extreme pressures or disruption, and maintain service delivery. It applies both to technological (power grid, infrastructure) as well as to social systems (large social networks that offer different problem-solving options).

Overlapping functions and roles

GENERAL
- Shared responsibilities, rights and management authorities among responsible institutions across scales
- Polycentric, multi-level governance systems with decentralized decision-making structures
- Constant group of people participating in projects and the creation of policy documents; Working groups / project groups integrate multiple actors (shared knowledge)

FLOOD-RESILIENCE SPECIFIC
- Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)
- Flood risk mitigation measures are taken by public and private organizations and actors

Functional redundancy in important functions & services

GENERAL / FLOOD-RESILIENCE SPECIFIC
- Provision of redundancy mechanisms in critical infrastructure (i.e. water system, electricity, ICT sector, transport networks)

Spare capacities & back-up resources

GENERAL / FLOOD-RESILIENCE SPECIFIC
- Alternative power supplies and energy back-up generators for key businesses, critical infrastructure and services
- Alternative water supplies for all key businesses and critical infrastructure

Compartmenalization & modularity

GENERAL
- Presence of polycentric, multi-level governance systems
- Communication, transport networks, infrastructure grids and other vital functions and services in cities are based on a modular network structure
- Sectorial and organizational components of an economy are based on a modular network structure

FLOOD-RESILIENCE SPECIFIC
- Presence of compartmentalization dikes, dike rings, compartmentalized polders, temporary dams or flood defences that prevent floodings from spreading to other regions or locally retain substances

ABSORB DISTURBANCE

Diversity

Systems with many different components are more resilient than their counterparts with only a few. Diversification of resources and means can reduce a system's vulnerability by generating heterogeneous components performing different functions and thus facilitating a diversity of responses to threats. Furthermore, the prevalence of multiple ways of needs fulfillment (also called functional diversity) facilitates performing essential tasks and maintaining functions under a wider range of climate conditions and thus, enhances a system's flexibility.

Functional & response diversity

GENERAL
Diversification of energy supply, food supply, transport options (multiple modes and capacities for transporting key goods and people)
Enhancing the variety in energy systems by promoting the generation of different energy sources at different scales (local, regional, global), for instance via creating incentives for decentralized heat or energy networks
Variety in food provision: maintain local capacity to produce food, while strengthening transnational trade networks
The economic landscape consists of a variety of different companies varying in size, sector and industry accommodated
Parallel existence of different land-use types in cities
Strengthening mixed use developments by creating incentives for small- and medium-sized enterprises, promoting clusters of research and innovation, supporting changes of office surplus use to other uses and/or identifying opportunities for new workspace development
Implementing measures for crop diversification (i.e. urban farming, homegardens)
FLOOD-RESILIENCE SPECIFIC
A flood hazard management system entails a diversity of measures for mitigation, preparedness, response, and reorganization
Diversity in types of flood protection interventions (preventive alongside adaptive measures) and water absorption mechanisms (i.e. sewer, water storage, permeable paving, public and private green spaces)

Actor & stakeholder diversity

GENERAL
Variety of governmental and non-governmental stakeholders from differing sectors (i.e. politicians, academia, firms, NGOs) and administrative levels are involved in decision-making, planning and implementation process
Actors and stakeholders involved in decision- and policy-making have differing professional and knowledge backgrounds
Different government and non-governmental stakeholders are involved in setting the TOR and/or consulted
FLOOD-RESILIENCE SPECIFIC
Different problem frames and policy solutions for urban flooding

Institutional diversity, multi-level governance systems and linkages

GENERAL
Organizations with different sizes, cultures, funding mechanisms, internal structures
Various governing authorities at different scales made up by a diverse group of actors with different roles and overlapping functions
Presence of formal and informal partnerships between governing authorities, academia, firms and NGOs
Presence of platforms of exchange among actors, such as workshops, brainstorming sessions
FLOOD-RESILIENCE SPECIFIC
Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)
Governing authorities involved in flood risk management differ in size, culture, internal structure
Distributed flood-response capacity across levels (households, communities, municipalities)

PHASE / POLICY DIRECTION	PRINCIPLE	OPERATIONALIZATION	FINAL SET OF INDICATORS
	Flatness Flatness refers to a non-hierarchical way of governing a system and is a means of enhancing self-organization. The absence of a local formal competence to act on behalf of the population, as well as on lower policy levels along with lengthy decision-making and bureaucracy processes make the system inflexible and too slow to cope with changes and thus, ineffective in responses. Flatness is represented by inclusive, participatory processes that include a wide range of stakeholders, and providing the public with the power, authority and competence to respond to disturbances on their behalf.	**Institutional decentralization & autonomy**	**GENERAL** Shared responsibilities, rights and management authorities among responsible institutions across scales Level of financial independence of governing bodies Municipal authorities have the autonomy to authorize plans and legislate policy Autonomous management capacity and ability to autonomously develop own strategic goals, tailor-made policies and measures Independent governance units with a particular domain of authority within a designated geographic area **FLOOD-RESILIENCE SPECIFIC** Governing authorities involved in water and flood risk management are distributed across scales (local, regional, national level)
		Broad participation, stakeholder engagement & inclusiveness	**GENERAL** Non-governmental stakeholders are involved at an early stage in the planning and design process and contribute to problem analysis and developing solutions ("coproduction"), for instance by means of co-creation spaces or public contests that facilitate individual inputs of ideas or the presence of small-scale adaptive measures in public space which offer room for broad participation Presence of mechanisms for providing stakeholder and public input to decisions, programs and strategies (e.g. hearings, meetings, local consultations) Presence of open, deliberative forums or platforms of exchange between actors (policy officials, municipality representative, project coordinators, local population) before and during the implementation of projects (i.e. workshops, brainstorming sessions) Legal provisions concerning access to information, participation in decision- making (e.g. consultation requirements before decision-making) and access to courts Policy-making processes and financial expenditures of governing authorities are transparent to the public and have sanctioning mechanisms in place for groups to challenge poor performance and perceived unjust distribution of risks and benefits Decision-making processes are transparent and aim at including and equally representing all interests at stake **FLOOD-RESILIENCE SPECIFIC** Designing varied local and context-specific mitigation approaches based on neighborhoods consultation and collaboration and needs assessment
		Room for autonomous change	**GENERAL** All indicators in "Information management & sharing" and "Public Awareness, Risk Communication, Education & Training" **FLOOD-RESILIENCE SPECIFIC** All indicators in "Public Awareness, Risk Communication, Education & Training" **+** Public awareness, education programs, and hands-on showcases concerning water management approaches with respect to climate change impacts Providing funding and guidance on flood-resistance measures, flood-resilient construction and property retrofitting Providing solutions, tools and guidance for small-scale (storm-water-related) measures on private property (i.e. urban wetland, storage facilities for rainwater) Procedures that enable groups to form legal voluntary organizations, raise funds or subsidies for residents' or community-led initiatives and autonomous small-scale projects and provide required venues and space for developing them

Phase	Principle	Attribute	Indicators
RECOVER	**High Flux** The principle of High Flux is rooted in the concept of perceiving urban processes to happen in "systems of cities", consisting of social and ecological networks with dynamic interlinkages (panarchies). High Flux represents a fast rate of movement of resources through the system that ensures a fast mobilization of these resources to quickly respond to threats and changes. This mechanism addresses rapidity by seeking ways and implementing conditions to maximize promptness in response. The underlying idea is that the faster the rate of movement of resources, the more resources are available at a given point in time to deal with disturbance.	**Availability of and access to resources**	**GENERAL** Pre-event arrangements for governmental reimbursement, such as national continency funds or damage compensation payments out of national, regional or municipal funds Quick provision mechanisms of financial support (i.e. funds to restore assets, insurance payouts) after a shock Municipalities provide supportive resources and assistance to vulnerable population in high-risk areas Presence of fixed protocols (in calamity, continuation, recovery plans) with clearly defined tasks in the chain of emergency responders including for citizens on local levels (i.e. through community flood plans) which are regularly enacted Quick mobilization of human resources for disaster response (due to standby mode and rapid operational readiness) **FLOOD-RESILIENCE SPECIFIC** Tools for swift visualization of flooding scenario and impacts and accessible knowledge base about the affected area, the water system and its reaction to hazards
		Social & institutional networks	**GENERAL** Presence of formal or informal cross-sector partnerships and networks among municipal institutions and departments and beyond as well as between governing authorities, academia, firms and NGOs Prevalence of platforms of exchange among actors such as workshops, congresses, city labs Formal and informal partnerships and networks between emergency responders and citizens that advance the speed of recovery (i.e. flood groups, flood forums, mutual aid agreements, church groups) Presence of local, community-level projects that improve social cohesion and maintain connections between different groups of people Integrative, participatory measures, physical and virtual places that link citizens Governing authorities connect, strengthen existing networks, community-led initiatives and contribute to the emergence of new ones Partnering with community leaders with broad social networks and existing initiatives to improve stakeholder engagement
		Having options for flexibility in response	**GENERAL** Presence of a diverse economy accommodating a variety of sectors, industries and enterprise types and sizes Communities' livelihood strategies are not confined to a single economic resource Financial mechanisms for fostering (local) business development and innovation Developing education, leadership, entrepreneurship programs and curricula aiming at skills development in rapidly changing contexts **FLOOD-RESILIENCE SPECIFIC** Vulnerable groups in areas exposed to flooding (i.e. low-income occupations, unemployment, pensioner households, social renters) have access to funding mechanisms to reduce flood risk to physical structures (property protection), to flood insurance for compensation payments in case of flood damage and loss and other support services required for their safety and resuming livelihoods after a flooding event; Authorities involved in flood-risk management and response have mobile resources for flood mitigation at their disposal (i.e. pumps, removable secondary defences)
		Managing connectivity of critical sectors, infrastructure, natural habitats	**GENERAL** Measures to calculate and improve accessibility to urban areas and connectivity of (public) transport options Critical points for accessibility to critical infrastructure during adverse events are identified and pre-emptive measures and response strategies for maintaining functions are developed Spatial intersections of networks with other infrastructure systems and potential cascading effects to other systems are identified and response mechanisms developed or in development Connecting habitat patches (i.e. green grid) and creating blue corridors (i.e. new water networks from existing and new canals)

ADAPT	**Learning & Reflectivity** Under conditions of uncertainty and unexpected changes, learning becomes pivotal for affecting actual change. It is the most important driver for strategic adjustments in part of the system and new strategies to cope with change. It depends on the capacity and willigness of organizations and individuals to apply new knowledge, adopt novel, alternatives strategies in response to changing circumstances and change set goals if a new context requires it.	**Institutional learning capacity & reflectivity**	**GENERAL** Institutions are monitoring their activities and performance Integration of long-term resilience thinking into processes and procedures and recognizing when changes to standard practice are required Iterative revision and updating of plans, strategies and standards based on emerging information and research Participatory co-learning approaches by providing spaces for joint learning, such as information netowkrs, workshops, webinars Learning outputs (i.e. changing insights and circumstances) inform policy changes and amendments
		Experimentation & innovation	**GENERAL** Creation of testing grounds and support for 'informal space' to experiment and innovate Small- and large scale experiments to test alternative approaches and designs, inform policy recommendations and explore new ways to live with climate change impacts which are financially supported
	Flexibility Uncertainty requires flexible planning, spontaneous responses and adopting flexible elements that are apt for several scenarios to come. From an institutional perspective, flexibility in structure and processes is crucial to be operational under fast-changing conditions. Flexibility in spatial means refers to creating anticipatory physical "structural elbowroom" for future adjustments, extensions or retrofitting. Flexibility can also be perceived as a design principle for adaptation measures according to reversibility, and avoiding limitations on the range of possible future mesaures.	**Institutional flexibility**	**GENERAL** Institutions offer room for changing the procedures and cooperation arrangements if required Institutional conditions allow for adjustment in the agenda in terms of changes in scope, direction, time horizon and goals of strategies Decision-making processes allow for a change in speed and actor composition if required
		Flexibility in spatial planning	**GENERAL** Development of multi-use spaces or convertible structures that allow for short-term and long-term shifts in the use of space, parcels, buildings Respective policies and provisions are in place that safeguard additions or deletions to the quantity of space dedicated to particular uses at a later stage or interventions into land-use if required
		Flexibility in measures	**GENERAL** Employing no-regret measures in climate adaptation apt for a broad range of possible future scenarios Building in allowances according to future climate projections Urban planning, disaster risk management, climate adaptation strategies and respective policy development account for a long-term planning horizon Measures taken now or proposed for the near future do not limit the range of possible measures that can be taken in the far future: designing measures for reversibility, sequencing of planning decisions and required sets of interventions according to key thresholds in the current flood risk management system Reducing irreversible commitment of financial resources by broadening measures Implementing policies that allow for a strategy change and amendments in agreements rather than legislative acts No one-fits all solution but consideration of alternatives which include small- and large-scale structural and non-strutural measures based on local context