Master's thesis - Water Science and Management

Developing a method to quantify drought via multiple indicators to analyze the freshwater goal of the Netherlands

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Deltares

Enabling Delta Life

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Table of content

Contents

Summary

Water management in the Netherlands is extensive due to the history the country has with both extremes, droughts and especially floods. Droughts occur in the Netherlands in situations where a combination of severe cumulative precipitation deficit and a low discharge of the Rhine are present. A severe drought can jeopardize the freshwater availability which is crucial for many sectors in the Netherlands. The 'Delta Program Freshwater' is initiated with the objective to prepare the Netherlands for future changes in water availability. A freshwater goal has been set up which consists of 'being resilient against a freshwater shortage in 2050'. In this research the region 'Noord-Nederland', which defines the freshwater goal as being resilient against a 1:20 drought and the region 'West-Nederland', which defines the freshwater goal as being resilient against a 1:30 drought will be examined. The regions differ quite substantially: region North largest thread is salinization which deteriorates agricultural irrigation, the largest thread for region West is the absence of water supply towards the region since it is highly dependent on water transport from upstream rivers and canals.

The research aim is to develop a method to quantify the effectiveness of multiple measures (strategies) that could be implemented to cope with drought consequences in both regions. Through various drought indicators the freshwater goal will be translated towards a quantitative described goal. The problem definition originates from the fact that being resilient against a freshwater shortage is a complex concept, since several types of drought exist, and drought can be quantified with many different variables. Three drought indicators are set up during this research: cumulative precipitation deficit, discharge below a certain level and water shortage. By using data sets from the KNMI, calculations that were performed in a quick scan instruments (Qwast model) and by interviewing stakeholders of the regions, thresholds were identified for the drought indicators to display the 1:20 and 1:30 droughts.

In the discussion the drought indicators are compared in both the current scenario and a future scenario with significant climate change and significant socio-economic growth. Furthermore, an analysis is made on the impact of various strategies that could be implemented to cope with the consequences of drought. Finally, the business analytics product Power BI is utilized to build a decision support system in a dashboard, which is examined on its suitability to support drought adaptation planning.

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1. Introduction

1.1 Water resources management in the Netherlands

Water resources management is crucial for many sectors in the Netherlands such as agriculture, industry, shipping and for the reliability of the drinking water supply and the electricity supply (Mostert, 2016). Especially since the demand for freshwater in the Netherlands is increasing, and studies suggest that due to the consequences of climate change and socio-economic developments the frequency and severity of water shortages could increase (van Duinen et al., 2015, Wanders et al., 2015, van der Wiel et al., 2019, Samaniego et al., 2018, Mens et al., 2019). The Netherlands can be divided in 5 different main freshwater regions, which are further divided in to 17 sub-regions (figure 1). A lot of similarities are present between the regions, however significant differences occur which originate from other water allocation systems. In certain regions the amount of precipitation is crucial to sustain the freshwater supply, while other regions are heavily dependent on water supply from rivers. The 'Delta Program Freshwater' is initiated with the objective to prepare the Netherlands for future changes in water availability. A collaboration between the government, entrepreneurial associations (e.g. LTO, an agricultural and horticultural association) and waterboards from the freshwater regions is set up to prepare a strategy that reduces the consequences of droughts in the present-day and for the future. These measures should enhance the water system to being more robust against droughts, hereby reducing the potential risk, the probability and occurrence of water shortages. The program is currently in its first phase (2015-2021), while many preparations are being performed to successfully prepare for the second phase (2022-2028). This preparation occurs via work sessions where involved stakeholders discuss on the costs and benefits of specific measures. In 2021 a government decision has to be made on the preferred strategy and how this program will be carried out during the period 2022-2028.

Figure 1 sub-region division of the Netherlands (Mens et al., 2019)

Due to the large number of stakeholders involved, the different interests of the stakeholders and the prioritization of measures to reduce drought risk, the decision-making is complex. Currently, there is a lot of research being conducted on the effects of multiple combinations of measures from a hydrologic, ecologic and economic perspective. Multiple criteria are used to rate the different measures to look for the optimal solution by weighing factors like costs, benefits and effectiveness. Due to the large number of involved stakeholders, it is crucial that the criteria are clearly defined to have a uniform understanding, and consequently a fair/correct rating of the measures. A criterion which is not well-defined and could therefore be problematic is the effectiveness of an adaptive measure. The moment at which a measure is labeled as effective could differ significantly per stakeholder. According to business dictionary the definition of effectiveness is 'the degree to which objectives are achieved and the extent to which targeted problems are solved'.

Multiple guidelines are constructed by the ministry of infrastructure and water management to obtain a vision and indicate what should be the main focus of the Delta Program Freshwater in the future under climate change, the freshwater goal: 'The Netherlands resilient against a freshwater shortage in 2050' (figure 2). However, these guidelines are not clearly defined and therefore at this moment the effectiveness of measures cannot be quantitatively measured:

1. Healthy and balanced water system
2. Protect crucial user functions
3. Improve competitive position of water dependent sectors
4. Effective and frugal usage of water
5. Develop water knowledge, water skill and water innovations

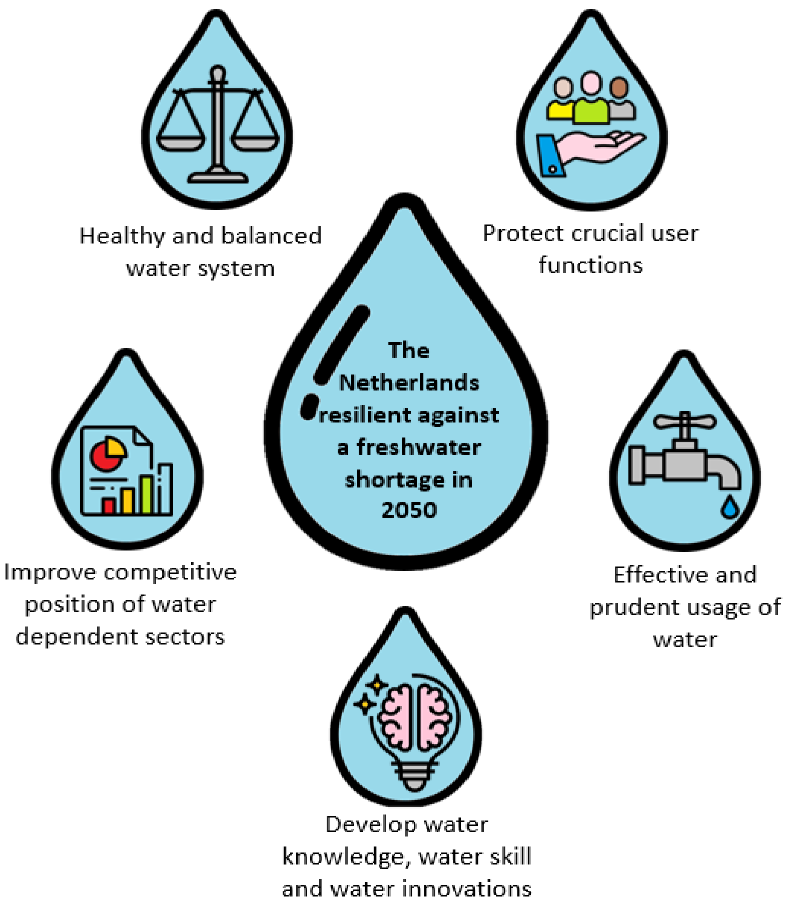

Figure 2 Freshwater goals (adapted from 'Diagram Freshwater Goals Ministry', Rijkswaterstaat (2020))

1.2 Problem description

Societal problem

Many different sectors that are affected by a water shortage due to droughts prefer specific measures to improve their situation in a changing climate. However, not all measures can be implemented due to a limited budget, and measures are not always improving the conditions for the majority of the stakeholders. Certain measures may even have negative effects on several stakeholders. Decisions have to be made on which measures should be prioritized. Some regions will benefit more from certain strategies than other regions. The decisions should be substantiated as to why they are chosen. Furthermore, due to the limited budget, some stakeholders should be prepared to accept freshwater shortage in certain regions in the future. There is always a remaining probability of water shortage due to drought.

Scientific problem

The scientific problem is the complexity of defining when The Netherlands is resilient against a freshwater shortage. The difficulties arise from the main cause of a freshwater shortage; a drought, since it can be quantified and measured with many different variables. Such variables include low river discharge, cumulative precipitation deficit, low groundwater level, low soil moisture, low reservoir or lake levels and many more (Van Loon et al, 2016). The occurrence of droughts in densely populated regions cannot be seen as solely natural hazards. Anthropogenic land surface alterations such as deforestation and urbanization have also influenced variables that contribute towards a drought such as surface runoff, evapotranspiration, infiltration and storage of water (Van Loon et al, 2016).

Besides the complexity of drought definition, a quantitative analysis of the response from the different stakeholders is also difficult to make. The definition of an effective measure or strategy will vary between the different stakeholders, making it difficult to perform an objectively measured criteria analysis. Besides the absence of a uniform definition, a quantitative method to assess the effectiveness is also lacking. The scientific relevance of this research is to fill this gap and therefore to develop a method to assess the different strategies on their effectiveness and by which progress towards the freshwater goal can be evaluated.

For Deltares, a rapport in which the stakeholder's perspective on effectiveness is missing, the models only look at effects on hydrology/ecology/economics aspects. The criteria effectiveness is qualitatively measured in reports, however an exact quantitative analysis is missing. There is a lot of uncertainty on how to correctly rate this criterion, while it provides a substantial portion in the multi criteria analysis from the ministry on the freshwater goal.

1.3 Available literature on the problem

Many reports that discuss and analyze the freshwater availability in the Netherlands are available. 'Werken aan zoet water in de Delta' (ministry of infrastructure and water management, 2019) looks at the provisional costs and benefits of applied measures in the Zoetwater Delta Program phase 1 on a hydrologic, ecologic and economic level. The severe drought of 2018 in Europe and its implications was a profound test for the freshwater availability in The Netherlands. Multiple sectors and regions were impacted differently by the high temperatures and the absence of precipitation (van Hussen et al., 2019). The areas located at a higher altitude experienced soil moisture shortage, while the coastal areas had to deal with increased salinization (Kramer et al., 2019).

Besides an analysis of the already applied measures, multiple studies have taken a closer look at the future of the freshwater availability in the Netherlands (Wolters et al., 2017, Thissen et al., 2017, Mens et al., 2019). Measures that could potentially be implemented to adapt to the predicted increase in demand of freshwater and decrease in supply of freshwater are discussed in Delsman et al., 2019 using quick scan instruments like the Quick Water Allocation Scan Tool (QWAST). Further in-depth analysis of the potential hindrances that could occur if we don't intervene are discussed in Mens et al., 2019: surface water shortages for irrigation, insufficient water level management, internal and external salinization.

In order to make such predictions and future analysis, plausible scenarios needed to be constructed to simulate potential future conditions. In 2011, the first version of 'Delta Scenarios' was developed, which have been further elaborated and described in to detail in 2016/2017. The Delta Scenarios have been set up by using two indicators: socio-economic growth or decline and degree of climate change (figure 3). Both indicators have a significant influence on the freshwater supply and demand. Various future scenarios could potentially unfold dependent on the rate of development of each indicator, in Wolters et al (2017) four scenarios are described and compared on their long-term outcomes, 2050 and 2100.

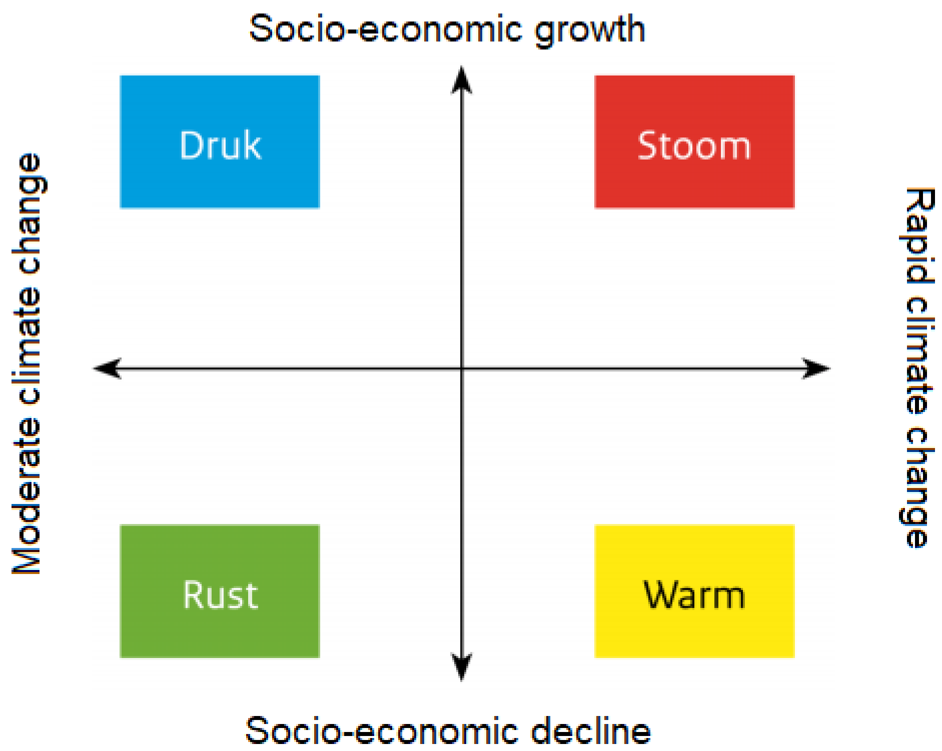

Figure 3 Positioning of the Delta Scenarios (adapted from Wolters et al (2017))

Since the ‘Stoom’ scenario is assuming both socio-economic growth and rapid climate change, the forthcoming conditions simulate the largest water shortages for most areas and most sectors. Some characteristics that stand out in this scenario are: highest relative change in urbanization (increase) and agricultural area (decrease), a temperature change of +2 degrees in 2050 and +4 degrees in 2100, a sea-level rise of +35 cm in 2050 and +85 cm in 2100 and a significant change in discharge patterns for the Rhine and Meuse, increasing discharge during the winter and decreasing discharge during the summer. Such conditions lead to an increased probability for extreme river discharges that could flood large parts of the Netherlands (Bruggeman et al., 2013). It could be argued that assuming the most extreme scenario is wise, since an underestimation of the conditions can lead to more devastating results than an overestimation.

A case study in Sicily (Rossi et al., 2005) implemented different courses of action to cope with drought. The different alternative sets of mitigation strategies were ranked by multiple criteria (economic, environmental and social aspects) for comparison. By using a Multi Criteria Decision Analysis (MCDA), preferred strategies were identified. The case study ends with an additional criterion of the preferences of the stakeholders, using a veto system for all the strategies. This system results in an overview of potential coalitions against certain strategies, indicating the strategy which is most probable to be accepted and at the same time scored high in the economic, environmental and social aspects.

Hansen (2010), used the method of Multi Criteria Mapping (MCM), which aims to identify the reasons why certain strategies are preferred by particular stakeholders. This is done by looking at the various factors that influence the decision making of the stakeholders.

To deal with the problem of quantifying the effectiveness of a measure, Takim & Adnan (2008) analyzed the success of a measure in terms of effectiveness performance. Various indicators that were compiled to measure effectiveness were set up in a survey and sent to four different stakeholder groups to be scored individually. The research found that the degree of effectiveness of a certain measure, differed between the various stakeholders due to distinct requirements and priorities.

Although some research has been conducted on multi criteria decision making, decision support systems are not utilized in these projects to our knowledge. For example, Power BI, a business analytics product from Microsoft, is rarely used. Power BI is able to operate as a decision support system, since it can provide a detailed overview of the available data, similar to software such as Tableau and Sisense (Brands & Holtzblatt, 2015). Multiple papers (Delen 2014, Familiar & Barnes 2017) discuss the possibilities of business analytics and its potential impact, but they don’t go into much detail regarding its usability as a decision support system. Hence, this application is still quite undiscovered in the available literature.

1.4 Research aim & research question

The aim of this research is to develop a method to quantify the effectiveness of multiple measures (strategies) that could be implemented to cope with drought consequences in freshwater regions ‘Noord-Nederland’ and ‘West-Nederland’. The results will add valuable knowledge by translating abstract management objectives towards quantitative described goals. To achieve this aim, the following research question is divided into several sub-questions:

‘’How effective are various strategies in reaching the freshwater goal of the Delta Program in the regions ‘Noord-Nederland’ and ‘West-Nederland’?’’

i. What does the freshwater goal entail in the regions ‘Noord-Nederland’ and ‘West-Nederland’?
ii. How can the freshwater goal be quantified by means of criteria?
iii. How do the strategies differ in their degree of effectiveness according to the various indicators of drought measurement?
iiii. To what extent is Power BI suitable as a decision support system for future drought adaptation planning?

2. Theory and Tools

2.1 Literature

The theory which will be used to identify and choose the stakeholders for the interviews is a combination of literature review and expert knowledge. The definition of a stakeholder is adopted from Downar (2018): 'a person (entity) involved in a project through a certain form of engagement, having a specific interest, measurable or not, but related to a benefit or loss'. As aforementioned, many reports regarding the hydrologic and economic effects from measures against droughts exist. Stakeholder identification can be partly performed from these reports. In Schasfoort at al., 2019, a calculation is made for the sectors that will experience the most significant effects due to droughts. The sectors include shipping, agriculture and many more, which can all be identified as stakeholders, since many measures will influence their hydrologic and economic conditions. It is therefore possible to choose from a range of stakeholders per region, which could have different opinions on policies or ambitions compared to each other.

Interviews can be set up in many different manners in order to achieve the desired type of answers. A structured interview uses the same set of predefined questions which is a convenient way to compare multiple opinions regarding measures and ambitions (Ellis et al, 2002). However, if it is desired that an interview is more a conversation and results in a source of insight, an unstructured interview should be performed. In this research a combination of the two interview styles was chosen to provide detail, depth and an insider's perspective via semi-structured interviews (Leech, 2002).

The theory behind a decision support system is that it can be of assistance by choosing between various options by comparing particular information. In this research a comparison will be made regarding the impact of strategies towards the water shortage per region.

2.2 QWAST

The strategies which display the most potential and/or are most interesting have been analyzed in the Quick Water Allocation Scan Tool (QWAST). The majority of the results in this research are based on data that is calculated via Qwast. The model is a simplified version of the 'National Water Model'. QWAST consists of a coarse network of the water allocation system in the Netherlands, containing water buffers, allocation paths and distribution points that include prioritization (figure 4a) (Gijsbers et al., 2017). This model can look into what-if scenarios and analyze how water allocation patterns are altered when particular conditions occur (figure 4b), or particular measures are taken. In doing so, an assessment can be made between different mitigation strategies and consequently what kind of trade-offs are present between each region and sector (Gijsbers et al., 2017).

2.3 Power BI

The decision support system will be constructed in Power BI, which will aim to provide a clear visualization of the chosen combination of measures (strategies).

Figure 4a Overview Qwast surface water network

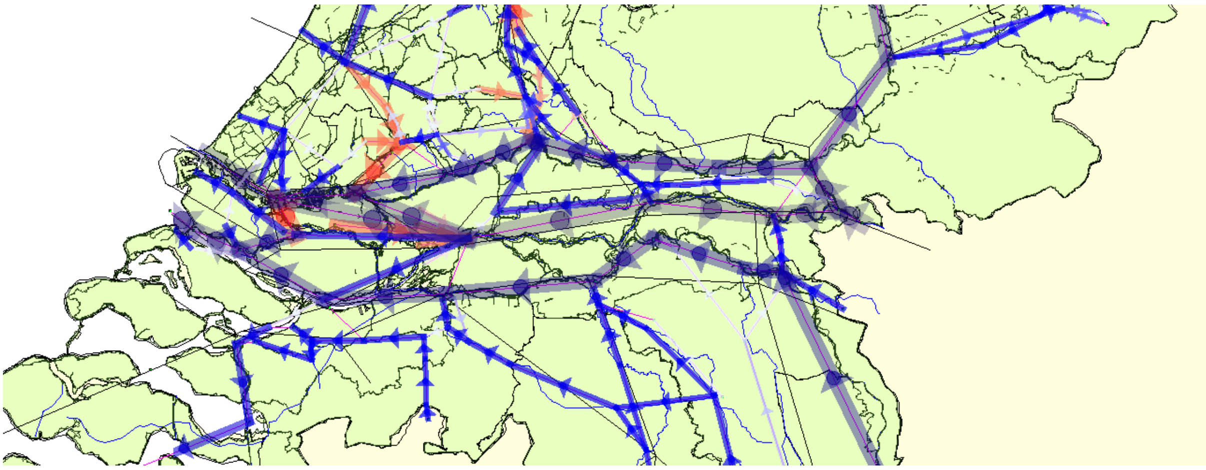

Figure 4b Example of water distribution in Qwast (Thickness of the lines represent the magnitude of the water transport, arrow indicates the direction of the transport)

2.4 Hypothesis

Due to the large amount of measures that are available and different perspectives between the stakeholders, no strategy which satisfies all involved parties is likely to exist. Furthermore, it is possible that the stakeholder point of view will not always align with the quantitative drought indicators point of view which displays which combination of measures is most effective to reach the freshwater goal. This could stem from individual priorities from the stakeholders which influences their judgement.

It is also expected that stakeholders from the Northern part of the Netherlands and Western part of the Netherlands will have different definitions on both the freshwater goal and as to what an 'effective' strategy entails. This is due to the fact that being resilient against a freshwater shortage can be significantly different because of the various variables that influence the water supply per region.

3. Materials and methods

3.1 Framework

The research has been divided into 6 steps, visualized in figure 5. First, representatives from both regions North and West were interviewed to understand their perspective on what it means to 'be resilient against a freshwater shortage in 2050'. Secondly, through the interviews and available literature the different methods to define a drought were examined. This step was performed in an iterative process via contact with the representatives of each region, since quantitative definitions to define drought will be set up and need to coincide with the opinions of the stakeholders. The quantitative definitions were based on the described ambitions of the regions in their strategy documents.

During the third step, the different methods to measure a drought were compared to the outputs of Qwast and other available data. This was done to identify the possible variables that will operate as drought indicators. The indicators of drought were determined to develop a way to score/quantify the extent to which the strategies cope with drought induced problems and how the strategies could help to achieve the freshwater goal in 2050. The following drought indicators were selected based on the interviews and the literature:

1. Cumulative precipitation deficit (in mm per year)
2. Duration of river discharge below a certain level (in m^3)
3. Water shortage (in % per year relative to the water demand)

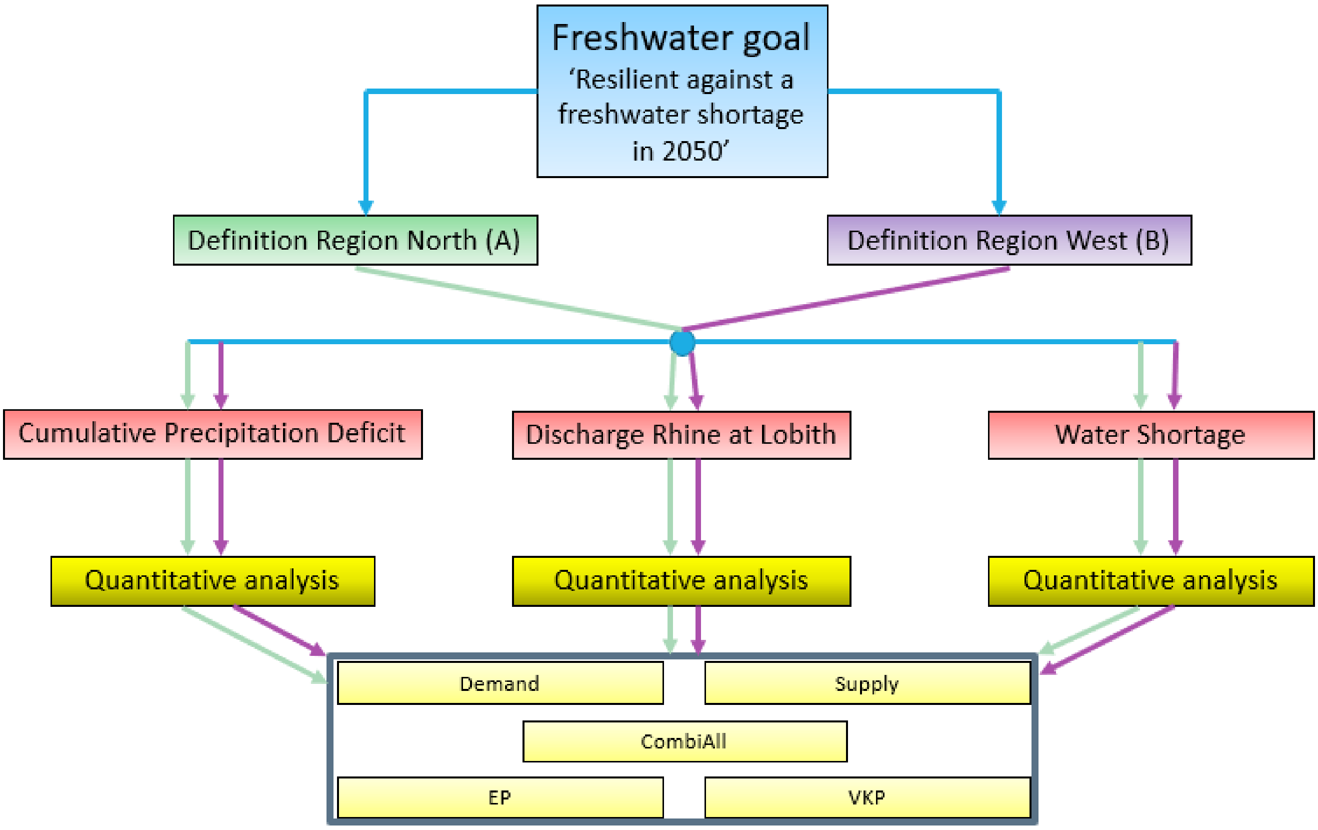

Figure 5 Framework approach research (step 1-5 displayed in a framework, each arrow represents an advancement towards the next step – Division: Region North (Green) / Region West (Purple) / Indicators (Red))

The cumulative precipitation deficit data originates from the 'Koninklijk Nederlands Meteorologisch Instituut' (KNMI), which is a Dutch institution that provides data and knowledge that is used for weather forecasts and climate analysis. Cumulative precipitation deficit is defined as the difference between potential evaporation and the amount of precipitation (Beersma & Buishand, 2004). The discharge and water shortage data are calculated in Qwast, the original data that is used as input for Qwast as boundary conditions originate from several measurements. During step 1 the definition of the freshwater goal from a stakeholder's perspective was determined and both regions have indicated at what point it is resilient enough against a freshwater shortage. In other words, both regions have indicated against what degree of extreme drought they want to be resilient. In the Results section a more detailed description is given, but for understanding the performed methods it was chosen to briefly mention the definition per region.

For region North the freshwater goal entails being resilient against a drought that occurs every 20 years (1:20 drought), region West wants to be resilient against a drought that occurs every 30 years (1:30 drought). This definition can now be used to set up thresholds for each drought indicator that will represent these severe droughts. By using this method, a clear quantitative value can be labeled per indicator on to the freshwater goal per region, once conditions exceed these values, extreme dry years occur.

The thresholds for cumulative precipitation deficit and water shortage were calculated as a value per year, since the impacts from both variables built up during the summer (high precipitation deficit and water shortage). After the summer months, the impacts from both variables decrease again. The threshold for the discharge indicator discharge is defined in such a way that it has to be exceeded for a particular time duration within a year. The reason for this difference is that a cumulative discharge value per year could undermine or overestimate the potential drought problems. A year can consist of extreme high discharge values during the winter which leads to average annual discharge values, while it still experiences severe drought impacts if the summer has low discharge values.

To receive accurate thresholds for the indicators cumulative precipitation deficit and water shortage, separate frequency curves were constructed by plotting the recurrence time on the x-axis and the corresponding value of the of the indicator on the y-axis.
The formula of Weibull (*eq. 1.1*) was used to determine probability (P), recurrence time (T) and the corresponding values for extreme droughts (Subramanya, 2013):

$$P = \frac{m}{N+1} \quad (1.1)$$

$$T = \frac{1}{P} \quad (1.2)$$

By filtering the datasets from largest to smallest, the probability and the recurrence time were matched with the corresponding value per indicator. In equation (1.1) *m* is the rank of the value (order number) and *N* is the number of years of record.

To receive an accurate threshold for the indicator discharge, which also includes a time duration, a different method was performed. The discharge data was available with a timestep of one decade (+-10 days), which results in 36 values per year. Since the ambitions of the regions were being resilient against a 1:20 and 1:30 drought, from respectively region North and West, the discharge data could be filtered in such a way that a combination of discharge value and time duration matches these 1:20 and 1:30 droughts by definition. Once this combined threshold containing a discharge value and time duration is exceeded, conditions occur that can be identified as severe droughts. The dataset contained 100 years, therefore to reach the ambitions of the regions, the threshold for the discharge data of region North could be exceeded 5 times, which translates to 5 years with severe drought. The threshold for the data for region West could be exceeded 3,3 times, which translates to 3 years with severe drought. Via this method the threshold for region West actually includes drought conditions occurring once every 33,3 years. The values for this threshold are therefore slightly overestimated, this inaccuracy was accepted in order to determine the threshold in a more convenient manner.

Next, combinations of time durations and discharge values could be identified that fit the abovementioned frequency per region. Both variables are determinative in this process, since an over- or underestimation of time duration will result in respectively an under- or overestimation of discharge value, and vice versa. Since both variables are crucial, several combinations were made based on different perspectives:

A: Stakeholders' perspective
B: Operational management perspective (LCW criteria)

The stakeholders' perspective was determined via contact with the stakeholders. The operational management perspective can be determined from the criterium that the LCW (Landelijk Coördinatiecommissie Waterverdeling) has set up (Rijkswaterstaat, 2019). The LCW is a Dutch commission which gathers information, spreads knowledge and coordinates action between regional drought consultations in times of expected water shortages. The regional drought consultations include Rijkswaterstaat, the waterboards and the provinces (ministry of infrastructure and water management, 2020. Since specific time durations (number of decades) where chosen to display this indicator, the frequency curve based on recurrence in years is not present. The graphs to display this indicator are of individual years, in which the amount of times and pattern (subsequent or separated) exceedance of the threshold can be researched. Even though the methods to identify the thresholds for the indicators slightly differ from each other, the results will be similar: a quantitative threshold that describes the ambition of the region which will lead to determining multiple extreme dry years from the available data.

Step 4 included the examination of the results from the indicators. Firstly, a comparison between the reference data (REF) and the data from a scenario in which both climate change and socio-economic development are strong (STOOM) was made. The frequency curves were plotted in the same graph to examine the differences between the scenarios and what this meant for the problems that arise from the water shortages during the extreme dry years. This comparison will indicate how, if the definition per region for the freshwater goal remains equal (1:20 and 1:30 drought), a potential future scenario will affect the thresholds of the indicators.

3.2 Strategies

Finally, strategies that contain measures to cope with the consequences of water shortages were examined. To examine the effects of the strategies on the water shortage, the STOOM scenario was once again utilized. Since it is most interesting to see the impacts of the measures in a scenario where the water shortage is largest due to strong climate change and socio-economic developments. The data from a situation where no measures are implemented (Q0_Basis_STOOM) was used as reference data.

The strategies contain various measures, while some measures are typical for certain strategies (e.g. enhance water supply Crooked Rhine), other measures are present in the majority of strategies (e.g. enhance maximum discharge capacity Eastern regions, which is present in four out of five strategies). Generally, the different strategies focus on 1) reducing water **demand**, 2) increasing water **supply**, 3) a **combination** of reducing water demand and increasing water supply, 4) **economically** feasible and cost-effective measures, 5) **preferred** measures chosen by the region. Table 1 gives an overview of the measures per strategy. The impact of the different strategies on the water shortage can be expressed in 'effectiveness' to help water managers to identify the suitable approach. Abovementioned strategies are already used in previous analysis throughout the Delta program (Mens & Muurling, 2020), the division in measures made to gain insights on how impactful reducing water demand measures are compared to measures that increase the water supply.

Table 1 List of measures which are present in the analyzed strategies

Strategy	Measures to be implemented
1) Demand	- Reduce water demand for irrigation by 10% in regions IJsselmeer, Rivierenland and West - Reduce freshwater flushing demand of sluices in Delfzijl and Harlingen by 50% - Reduce salty seepage by reducing freshwater flushing at sluice Muiden and for the drinking water industry - Reduce water withdrawal for drinking water industry from 100% to 20% in the Juliana canal
2) Supply	- Increase maximum discharge capacity Eastern regions - Optimize inlets and water distribution Rivierenland by increasing inlet Kuijkgemaal from 4,6 to 7,7 m^3/s and inlet Doornenburg from 8,0 to 13,3 m^3/s - Increase inlet Crooked Rhine from 9,8 to 15,8 m^3/s - Increase robustness Krimpenerwaard by increasing the maximum discharge from 6,0 to 12,0 m^3/s - Increase storage Markermeer and IJsselmeer by increasing the water level from -0,2 to -0,1 m and by directing water from the Amsterdam-Rhine Canal with a maximum discharge of 40 m^3/s - Increase discharge Hagestein by a larger minimum discharge from 0 to 20 m^3/s
3) CombiAll (Supply + Demand strategy)	- All measures included in 'Demand' and 'Supply'
4) EP (Economic strategy)	- Increase maximum discharge capacity Eastern regions - Reduce salty seepage by reducing freshwater flushing at sluice Muiden and for the drinking water industry - Increase robustness Krimpenerwaard by increasing the maximum discharge from 6,0 to 12,0 m^3/s - Increase discharge Hagestein by a larger minimum discharge from 0 to 20 m^3/s - Reduce freshwater flushing demand of sluices in Delfzijl and Harlingen by 50% - Increase storage Markermeer and IJsselmeer by increasing the water level from -0,2 to -0,1 m and by directing water from the Amsterdam-Rhine Canal with a maximum discharge of 40 m^3/s - Reduce water demand for irrigation by 5% in IJsselmeer region
5) VKP ('VoorKeursPakket' =Preference package)	- Increase maximum discharge capacity Eastern regions - Reduce salty seepage by reducing freshwater flushing at sluice Muiden and for the drinking - water industry - Increase robustness Krimpenerwaard by increasing the maximum discharge from 6,0 to 12,0 m^3/s - Increase discharge Hagestein by a larger minimum discharge from 0 to 20 m^3/s - Reduce freshwater flushing demand of sluice in Delfzijl by 50% - Reduce water demand for irrigation by 5% in regions IJsselmeer and Rivierenland

After the ‘effectiveness’ for water shortage per strategy was rated quantitively, the other indicators were examined. However, the cumulative precipitation deficit and discharge of the Rhine at Lobith do not change per strategy, since these variables are a result of the natural boundary conditions imposed on the Dutch hydrological system. The strategies are implemented to cope with the consequences of water shortage, since both variables are external hazards, they stay constant even though many measures are performed. To examine the impact of the strategies on these two indicators, a detailed comparison of the different measures was made.

Step 5 contained a total picture/conglomerate of the consequences from all the strategies to indicate their strengths and their weaknesses. Finally, in step 6 the results are summarized and displayed in a dashboard that was made in Power BI. This dashboard could operate as a decision support system.

3.3 Methods of data collection and kind of data

Data collection in this research was performed by a combination of literature review, interviews and usage of model 'QWAST'. The data that is necessary for step 1 and 2 followed from semi-structured interviews and so called 'strategy-documents' from each region in which they described their ambitions and the main bottlenecks of the region. Besides representatives of region North and West, interviews were performed with a water manager which has many years of experience within the Delta Program freshwater and relevant staff members from the ministry of infrastructure and water management. The latter mentioned interviews were conducted to get a less biased overview and insights on the topic, since the statements from the stakeholders from each region are potentially influenced by their own interests. Questions included how each interviewee would define the freshwater goal, what being resilient means for each region and which indicators would fit best to describe and measure their ambitions.

The data regarding the effectiveness of certain strategies will originate from scenarios that are ran in QWAST (step 3 and 4). The QWAST model allows the user to sketch a scenario with specific conditions (such as strong climate change and socio-economic growth). Subsequently, measures that mitigate arising problems can be integrated in this scenario to display the pros and cons of the measure. The western and northern part of the Netherlands is developed in much more detail in QWAST compared to the east. This is due to the fact that saline intrusion plays a significant role for the inlets in the west and therefore delivery routes are required to be more precise. In the context of water shortages, the analysis from QWAST is more focused on the right quality of water at the right time at the correct place (Gijsbers et al., 2017). The kind of data that was collected consisted of a combination of quantitative (QWAST results) and qualitative (interviews) data.

3.4 Methods of data analysis

Modelling was used to analyze data, using QWAST. Important to note is that QWAST is limited to its variables, it is therefore operable for a restricted amount of measures and some potential possibilities could be overlooked. Since drought is such an extensive concept, the drought indicators were developed with a specific threshold value which should be crossed for a minimum amount of time for it to be considered to result in a freshwater shortage. The threshold value has been derived from the insights that were gathered from the strategy documents and during the interviews (see *Results* section).

The decision support system was built in Power BI, which was used to analyze the various strategies. The Power BI ecosystem allows the user to model, conduct data analysis and data visualization. The latter feature was mainly utilized.

4. Results

4.1 Definitions freshwater goal and indicator thresholds per region

The first step of the research, which consisted of the interviews of stakeholders to understand their perspective, resulted in two different definitions of the freshwater goal. The perspective of region North is being resilient against a 1:20 drought, while the perspective of region West is being resilient against a 1:30 drought. This difference is quite significant, as will be displayed in the drought indicators later in this section. From the definition that the regions have given of the freshwater goal it can also be concluded that the regions both accept the consequences of the extreme drought conditions that occur above the set-up thresholds. Stakeholders have to accept certain potential dangers and thereby economic damage since it is not feasible, both economically and environmentally, to be resilient against all extreme droughts.

4.1.1 Region North

Freshwater region North is the largest in the Netherlands and consists of the low-lying coastal region and the higher sandy soils. This research focuses on the lower altitude coastal region. In this region, water can be supplied from the IJsselmeer, in order to supply irrigation water, flush the system for water quality purposes and water level management. If the water level cannot be maintained due to drought, damage to infrastructure and deterioration of nature occurs. Furthermore, sufficient freshwater supply is crucial since it facilitates an important function of this region, agriculture (Hoogheemraadschap Hollands Noorderkwartier, 2020). Besides a shortage of water, a reduced quality of the water via salinization occurs as well via salt leaks at the sluices and via salty seepage from the seawater and deep drains. To compensate salinization, canals are flushed with freshwater, which results in the possibility to use this surface water for irrigation.

Over the past years, many developments have been revealed in region North that were not foreseen at the start of the program. The increase in water demand that is needed for the energy transition and to reduce land subsidence, CO_2 emissions and heat stress were brought to light during the drought of 2018 (Hoogheemraadschap Hollands Noorderkwartier, 2020). This may cause additional water demand from the IJsselmeer, however due to drier and warmer summers, which increase the precipitation deficit, the water supply from the lake will decrease. The region suggests that all users that receive water from the IJsselmeer have to review their water demand again, in order to make new agreements on the distribution. It is most likely that mainly freshwater flushing and irrigation from surface water will be reduced. Scenarios indicate that the dynamics of the groundwater system will change: higher groundwater table during the winter, while in the summer the groundwater table will be lower. For the summer this could result in streams that run dry and extra water level management is required. For phase 2 of the Delta Program it is therefore determined that measures will be examined that aim to reduce the water demand, enhance prudent water usage and increase/stabilize the water supply (Hoogheemraadschap Hollands Noorderkwartier, 2020).

From the interviews and the strategy document the quantitative definition of the freshwater goal was determined and therefore the first research question was answered: region North wants to be resilient to a drought that occurs once in 20 years. From the aforementioned available data, the indicators are quantitively set up to match the ambitions of the region. Table 2 contains the thresholds and duration per indicator which represent 1:20 drought conditions for region North with the reference data (REF 2017).

Table 2 – Thresholds and time duration indicators region North REF 2017 data (1:20 drought)

Drought indicator	***Threshold***	***Duration***
1. Cumulative Precipitation Deficit	*> 310 mm*	*1 year*
2 Discharge	*<1100 m^3/s*	*>= 13 decades per year*
3. Water Shortage	*> 0,5 %*	*1 year*

4.1.1 Region West

Freshwater region West contains the most densely populated area in the Netherlands, including major cities like Amsterdam and Rotterdam, and is therefore immensely regulated. Besides the purpose of protecting inhabitants, this regulation is also in place to preserve high value cultivation, process industry, nature and transport in the harbor of Rotterdam (Hoogheemraadschap van Rijnland, 2020). Region West is highly dependent on water transport via rivers and canals, which provide the option of freshwater flushing to maintain abovementioned features intact. In dry periods this heavy dependence on supply from areas outside the region can result in significant problems. That is why the KWA (Climate-proof water supply) was implemented to deal with summers that experience low discharges and precipitation scarcity. The KWA is a system that uses weirs, sluices and pumping stations to compensate the low supply of freshwater. Once the discharge of the Rhine at Lobith (where the river enters the Netherlands) is lower than 1100 m3/s, the main water system starts to experience salinization from seawater, an example is the Hollandse Ijssel (Hoogheemraadschap De Stichtse Rijnlanden & Hoogheemraadschap van Rijnland, 2019). In order to adapt and prevent damage towards the agricultural sector and nature from saline water, it is necessary to close the sluice at Gouda, which leads to a limited water supply towards the western part of the region. The KWA is opened in such situations to supply freshwater from the Amsterdam-Rhine channel and the Lek (figure 6). Via the indicated pathways (1, 2 and 3) in figure 6, freshwater is transported to the West. This mechanism is used once every 8 years, during the drought of 2018 the KWA proved its importance. However, due to climate change and social-economic developments the demand for freshwater keeps increasing in this region and therefore the KWA is expected to be utilized more often.

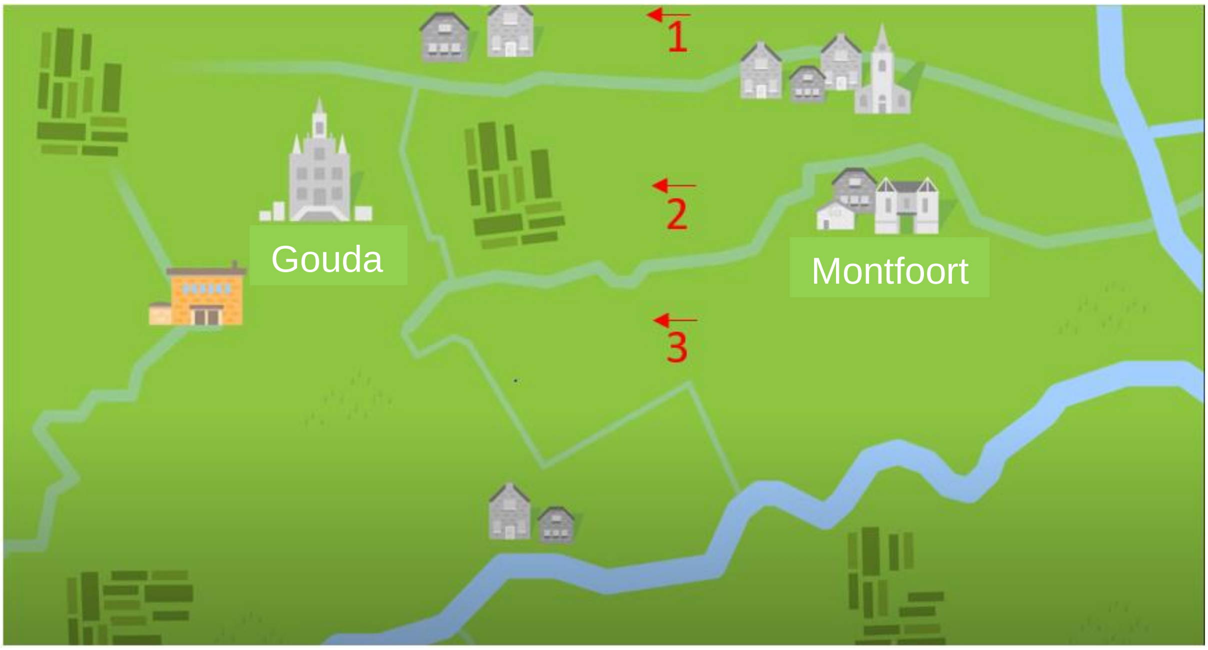

Figure 6 KWA-route to supply freshwater from the Lek and Amsterdam Rhine channel towards the West (Figure adapted from Hoogheemraadschap De Stichtse Rijnlanden & Hoogheemraadschap van Rijnland, 2019)

Since the supply of freshwater is by far the most important factor in this region, the measures that are examined to be applied during the second phase of the Delta Program focus mainly on optimization and alternative routes/sources of supplying water. Such an alternative source could be the division of brackish seepage at Horstermeer, which can be separated into fresh and salt-water, resulting in an extra drinking water for the region. Another alternative source is reuse of water via effluent from industry at Hoogvliet, which would need purification (Hoogheemraadschap van Rijnland, 2020).

From the interviews and the strategy document the quantitative definition of the freshwater goal was derived: region West wants to be resilient to a drought that occurs once in 30 years. From the aforementioned available data, the indicators are quantitively set up to match the ambitions of the region. Table 2 contains the thresholds and duration per indicator which represent 1:30 drought conditions for region West with the reference data (REF 2017).

Table 3 – Thresholds and time duration indicators region West REF 2017 data (1:30 drought)

Drought indicator	***Threshold***	***Duration***
1. Cumulative Precipitation Deficit	*> 330 mm*	*1 year*
2 Discharge	*< 1100 m^3/s*	*>= 14 decades per year*
3. Water Shortage	*> 1,2 %*	*1 year*

4.2 Indicator cumulative precipitation deficit

The precipitation data set that was used as a reference displays an average deficit in the Netherlands of 159 mm per year. The REF threshold values for both a 1:20 drought (North) and a 1:30 drought (West) is approximately two times the average, respectively 310 mm and 330 mm per year. Both threshold values increase quite significantly from the REF 2017 situation towards the STOOM 2050 situation: 310 to 370 mm and 330 to 395 mm. The years that display the extreme droughts are from smallest to largest cumulative precipitation deficit: 1911/1947/1921/1976/1959. An interesting observation which can be made from the figures is that in both regions the threshold for the STOOM data is not even reached during a 1:100 drought of the REF data (figure 7+8). This is especially true for region West, the threshold for the STOOM data is almost 10% above the 1:100 drought value of the REF data. Another noteworthy aspect is that if one would keep the REF data threshold definition of a 1:20 and 1:30 drought in a future world where climate change and socio-economic growth continues (STOOM), both these definitions would translate to approximately a 1:15 year drought for region North and West.

Table 4 – Cumulative precipitation deficit thresholds for both regions in the REF and STOOM scenario

Scenario + Region	***Cumulative Precipitation deficit***
1.1) REF North	*310 mm*
1.2) STOOM North	*370 mm*
2.1) REF West	*330 mm*
2.1) STOOM West	*395 mm*

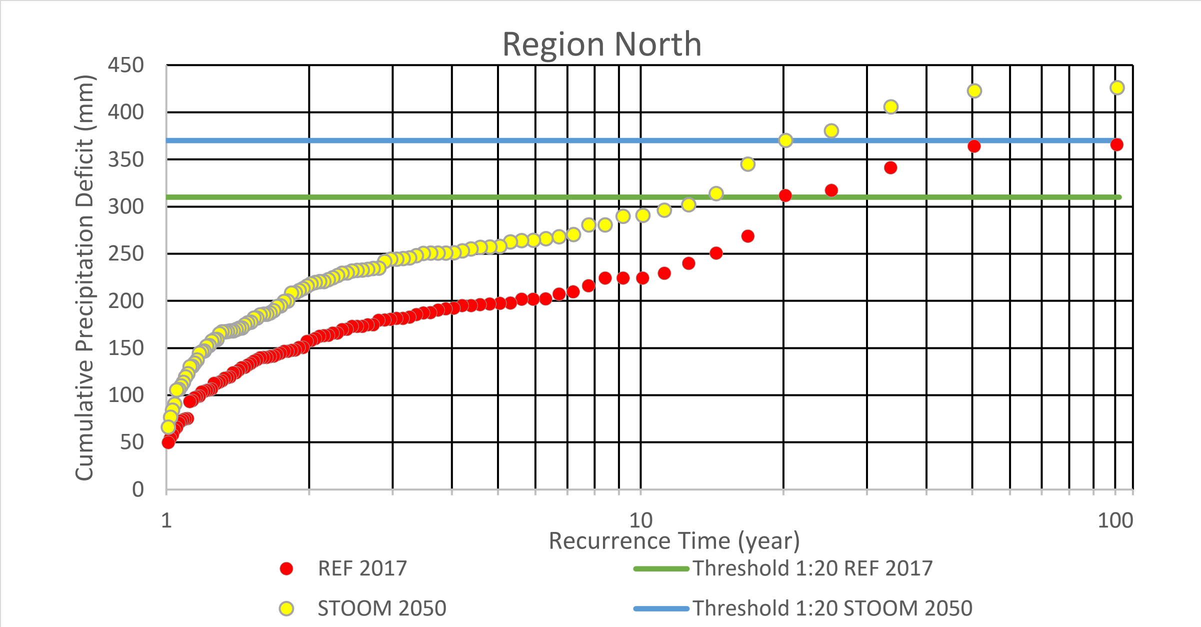

Figure 7 Cumulative Precipitation Deficit frequency curve Region North – REF vs STOOM data 1:20 (logarithmic x-axis)

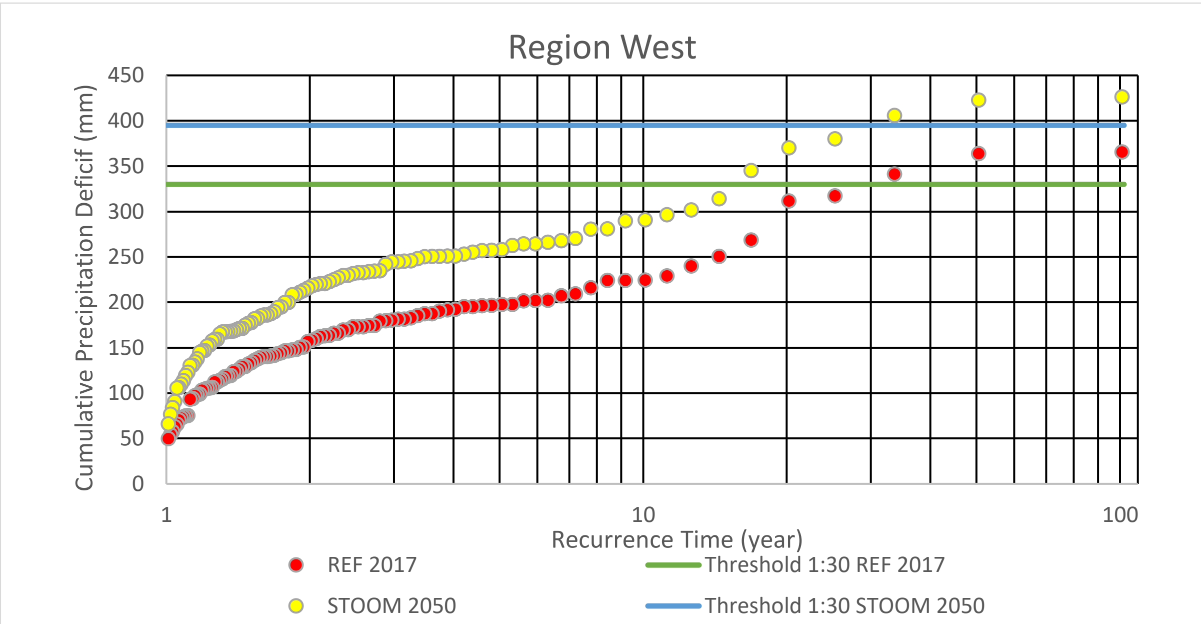

Figure 8 Cumulative Precipitation Deficit frequency curve Region West – REF vs STOOM data 1:30 (logarithmic x-axis)

4.3 Indicator duration of discharge Rhine below a certain level

Due to similar threshold values from different perspectives and lack of stakeholder response it was chosen to use one discharge value as threshold: 1100 m^3/s. By filtering the 100-year REF and STOOM data the associated time duration was determined which would indicate a 1:20 drought (five times occurring) and a 1:33 drought (three times occurring) for respectively region North and West. Table 5 gives an overview of the thresholds and time duration per scenario and region, alongside with the associated extreme dry years which exceed them. As expected, both thresholds durations increase from the REF 2017 situation in comparison to the STOOM 2050 situation. A problem which arises from this method is that by using the discharge value as a constant and using the time duration as variable to determine the extreme dry years, it is possible that a precise indication of 1:20 drought or 1:33 drought is not present. This is due to the fact that multiple years can overlap on the tipping point which would differentiate between the recurrence times. In other words, if the top 4 most extreme dry years have time durations of 23, 16, 14 and 14 decades a problem arises. A 1:33 year drought is than defined as 14 decades with a discharge lower than 1100m^3/s, however a 1:25 year drought is also defined as 14 decades with a discharge lower than 1100m^3/s. Especially region West experiences this phenomenon (Table 5), which will be mentioned further in the discussion.

Table 5 – Discharge threshold and time duration for both regions in the REF and STOOM scenario

Scenario + Region	***Discharge***	***Time duration***	***Identified years***
1.1) REF North	*< 1100 m^3/s*	*>= 13 decades*	1964 (13 decades) 1947 (14 decades) 1976 (14 decades) 1949 (16 decades) 1921 (23 decades)
1.2) STOOM North	*< 1100 m^3/s*	*>= 17 decades*	1947 (17 decades) 1976 (17 decades) 1949 (17 decades) 1934 (19 decades) 1921 (28 decades)
2.1) REF West	*< 1100 m^3/s*	*>= 14 decades*	* 1976 (14 decades) 1949 (16 decades) 1921 (23 decades)
2.1) STOOM West	*< 1100 m^3/s*	*>= 17 decades*	** 1949 (17 decades) 1934 (19 decades) 1921 (28 decades)

*The year 1947 also includes 14 decades with a discharge < 1100 m^3/s

** The years 1976 and 1947 also include 17 decades with a discharge < 1100m^3/s

Between the two scenarios in both regions a total amount of six extreme dry were identified. Even though the threshold is equally exceeded in some years, the patterns (subsequent or separated exceedance) varies significantly. Also, the differences between REF and STOOM discharge values per decade are inconsistent and vary per year.

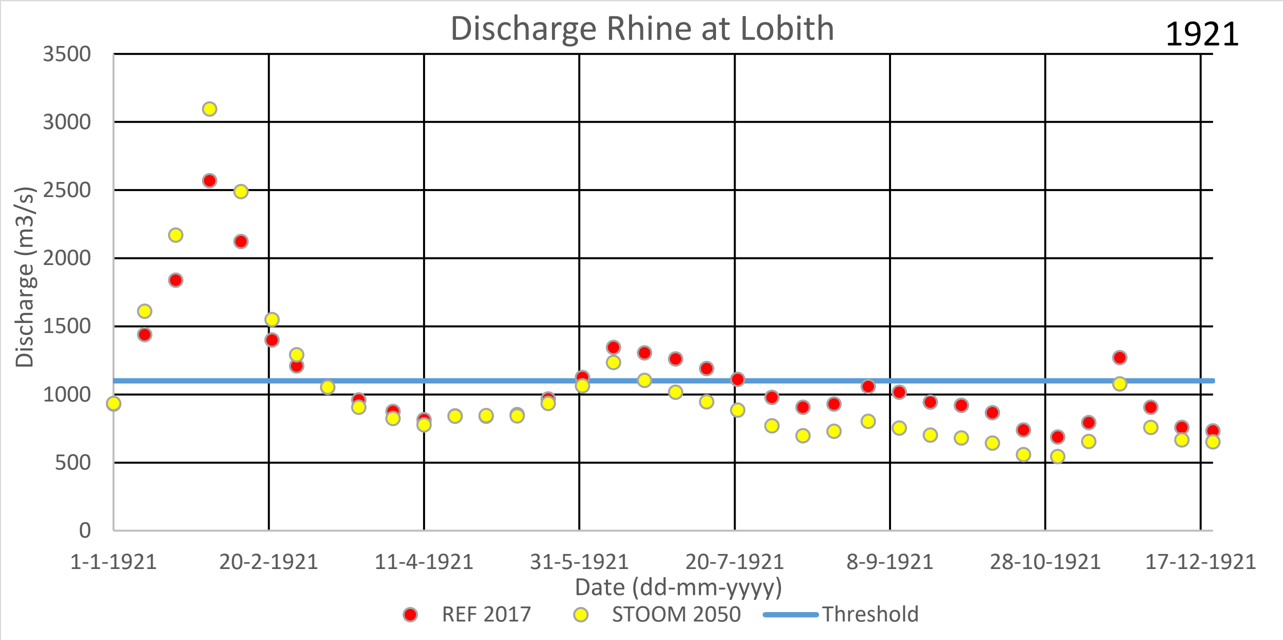

Figure 9 Discharge values during 1921 (REF and STOOM)

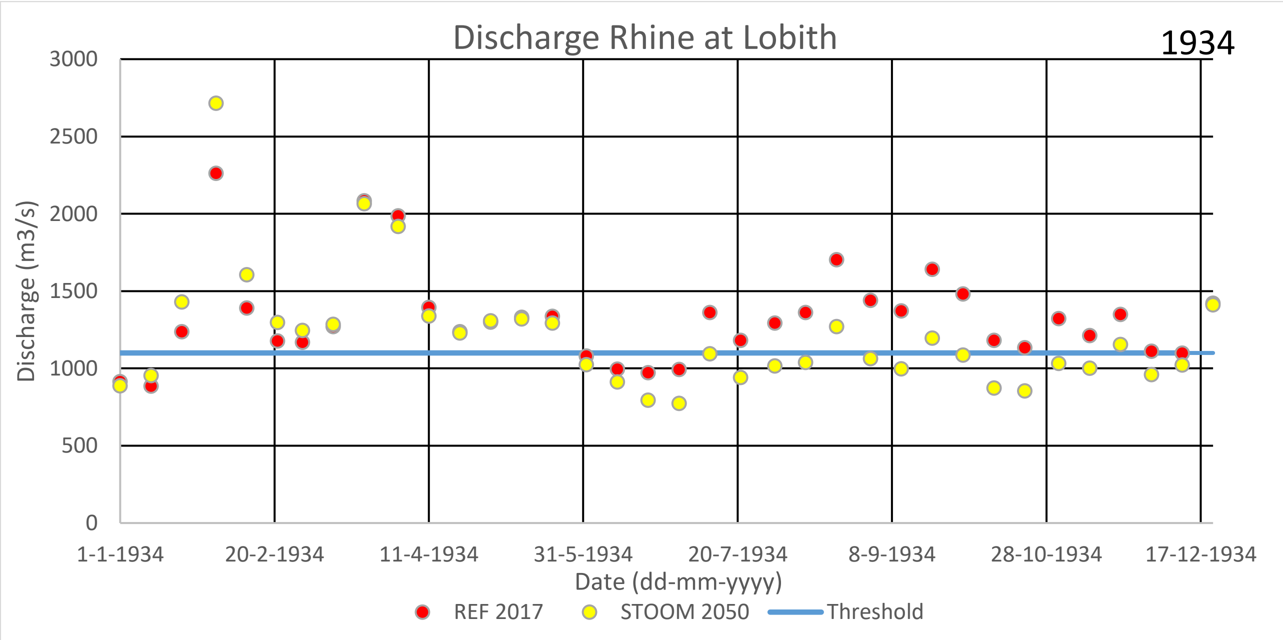

Figure 10 Discharge values during 1934 (REF and STOOM)

Another difference is the sequence of exceedance between the years: while most years display a subsequent exceedance of the threshold, e.g. 1921 which has 18 subsequent decades of exceedance, during 1934 the discharge increases back above 1100 m^3/s multiple times during the summer months and only 8 subsequent decades of exceedance occurs.

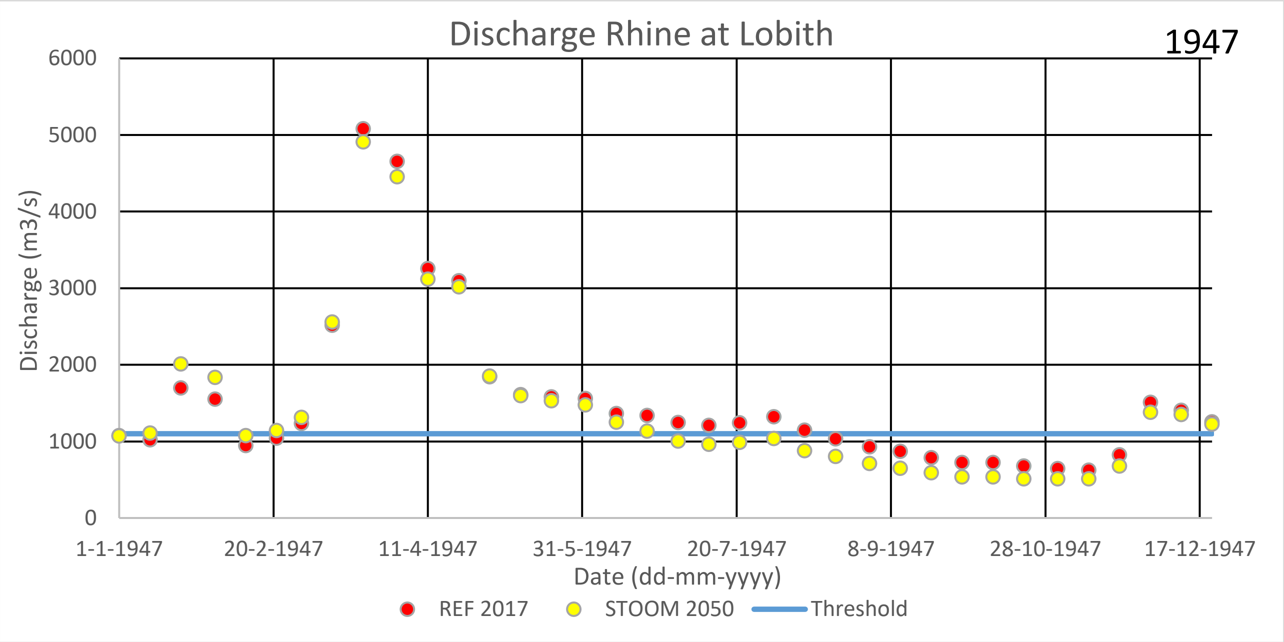

Figure 11 Discharge values during 1947 (REF and STOOM)

Generally, when comparing the REF to the STOOM data, all years display the same pattern: in the STOOM scenario during the winter the discharge increases, while during the summer the discharge decreases. However, the year 1947 displays a slightly different pattern then the other years, during March the STOOM data is already below the REF data. In the other years this will occur only consistently after the end of May.

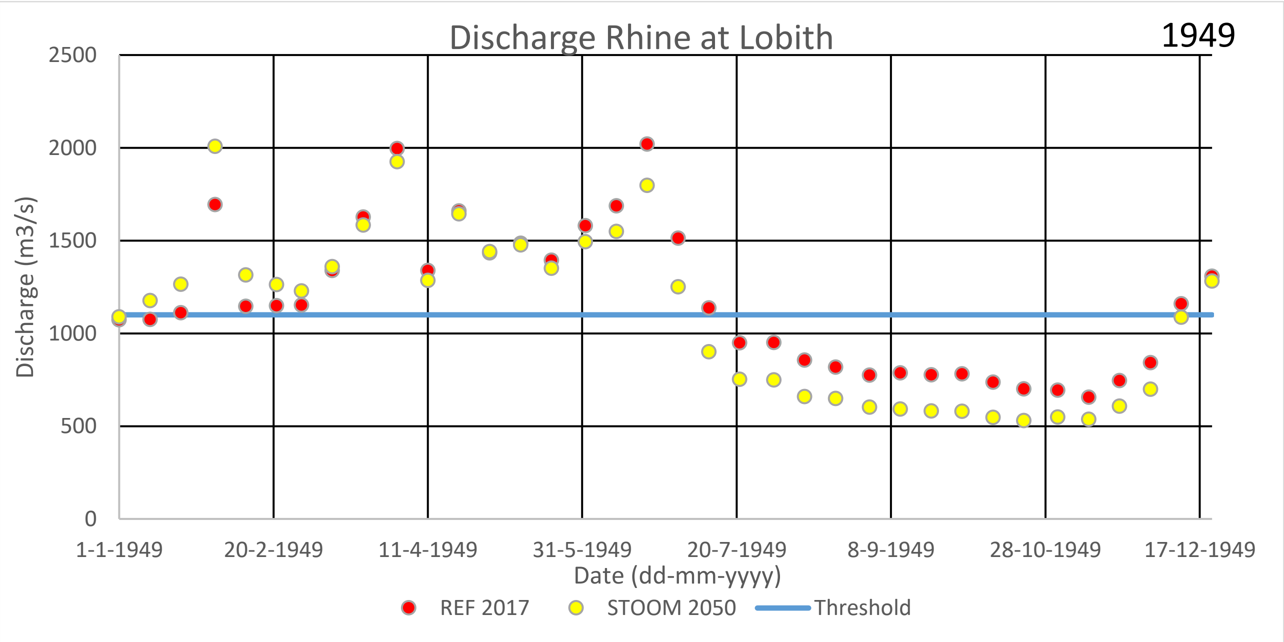

Figure 12 Discharge values during 1949 (REF and STOOM)

Furthermore, noteworthy is the difference in extent of exceedance of the discharge between the years. 1921 is the most extreme dry year from the definition of the discharge indicator. However, for only two decades the discharge is below 600 m3/s. While for 1947 and 1949 the number of exceeding decades is lower, the extent of exceedance is more extreme. During 1947 the discharge drops below 600 m^3/s for 6 decades, during 1949 this occurs for 7 decades. The discharge of the Rhine at Lobith is on average 2200 m^3/s (Rijkswaterstaat, n.d.).

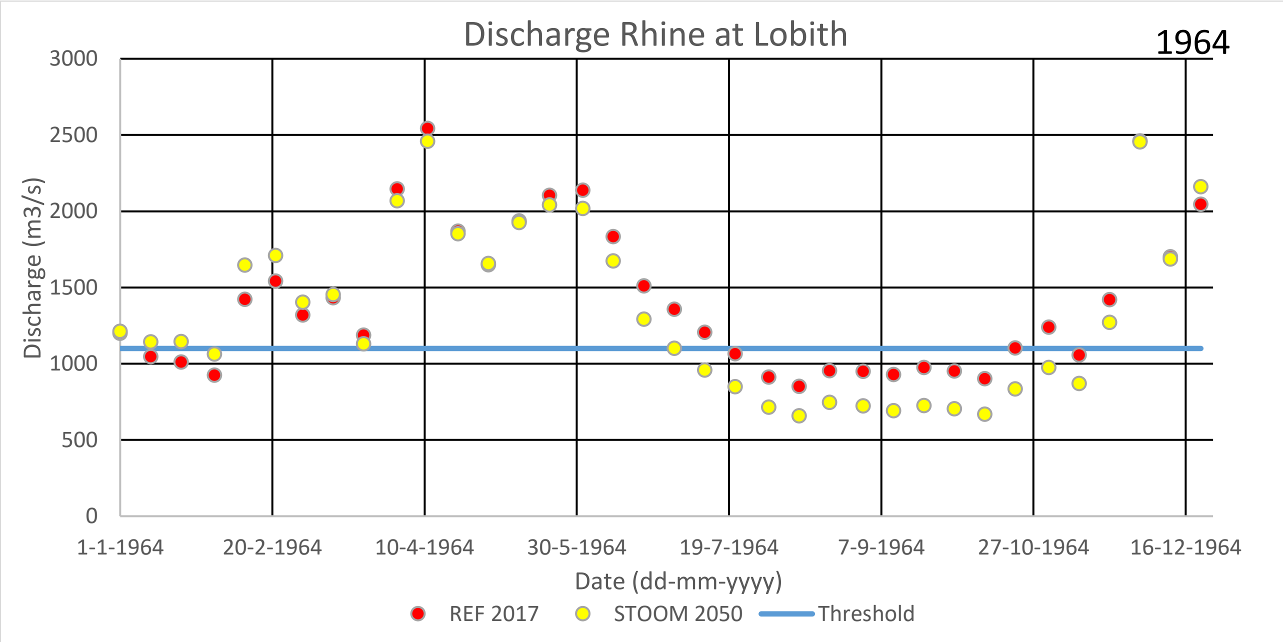

Figure 13 Discharge values during 1964 (REF and STOOM)

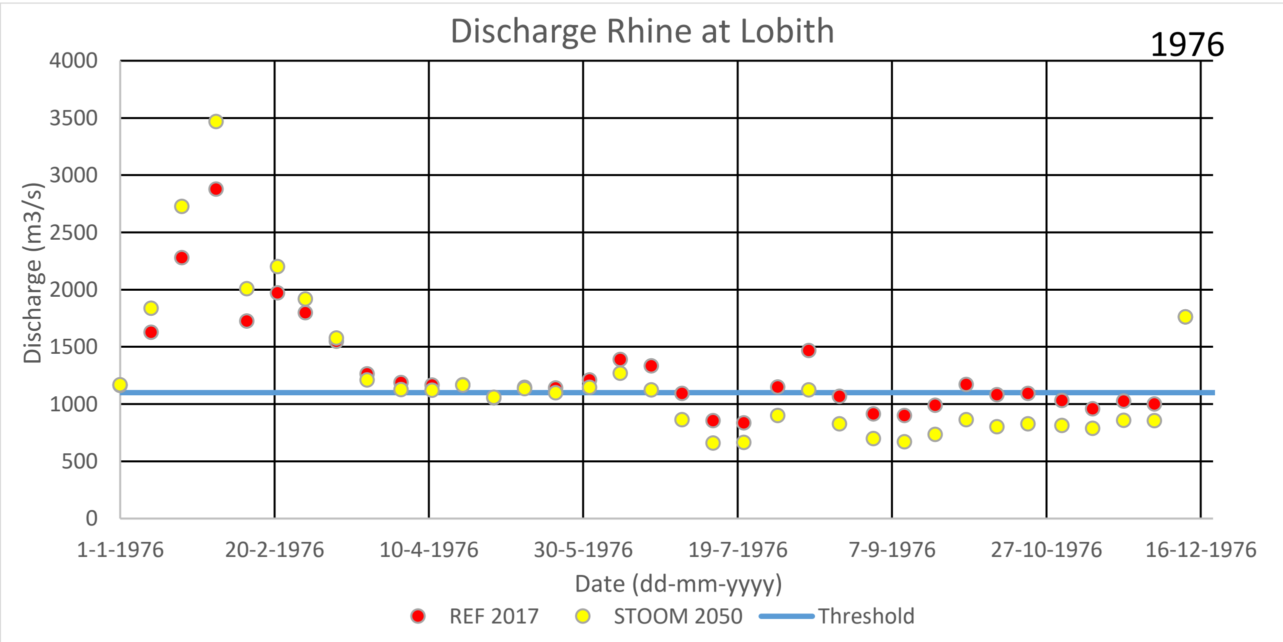

Figure 14 Discharge values during 1976 (REF and STOOM)

4.4 Indicator water shortage

The water shortage data set that was used as reference displays an average water shortage of 0,09% per year for region North and 0,10% per year for region West. The difference between the average water shortage per year and the water shortage threshold values in REF for both region North (1:20) and West (1:30) per year is relatively much larger than for the other indicators. In comparison to the cumulative precipitation deficit (159 mm REF to 320 mm STOOM, factor 2) and the discharge (2200 m^3/s REF to 1100 m^3/s STOOM, factor 2), the water shortage threshold is 0,5% per year for region North and 1,2% per year for region West. This translates to approximately a 1:6 and 1:12 factor for respectively region North and West. This is caused by the presence of many years that have 0,00% water shortage. The zero values affect the average significantly, which are not that abundant in the cumulative precipitation deficit or discharge data. Both threshold values increase significantly from the REF scenario towards the STOOM scenario: North 0,5% towards 6,6%, West 1,2% towards 11,2%.

An interesting observation is the huge differences between the extreme dry years that are identified, both between the regions and scenarios (table 6). While 1947 is the fifth most extreme drought for REF North, it is the second most extreme drought for REF West. Also, 2003 is in the top 3 most extreme droughts in REF West, while this year is barely in the top 10 most extreme droughts in REF North. Furthermore, in region North 1959 and 1941 in the REF scenario are replaced by 1949 and 2003 in the STOOM scenario. In region West 2003 and 1947 in the REF scenario are replaced by 1934 and 1921 in the STOOM scenario.

Table 6 – Water shortage thresholds for both regions in the REF and STOOM scenario

Scenario + Region	***Water shortage***	***Identified years (smallest to largest)***
1.1) REF North	*0,5% per year*	1947 1959 1941 1921 1976
1.2) STOOM North	6,6% per year	2003 1947 1949 1921 1976
2.1) REF West	*1,2% per year*	2003 1947 1976
2.1) STOOM West	11,2% per year	1934 1921 1976

For the indicator water shortage, the y-axis is logarithmically set up as well, due to the large differences between the values and the most interesting part being from 0,5% to 30%.

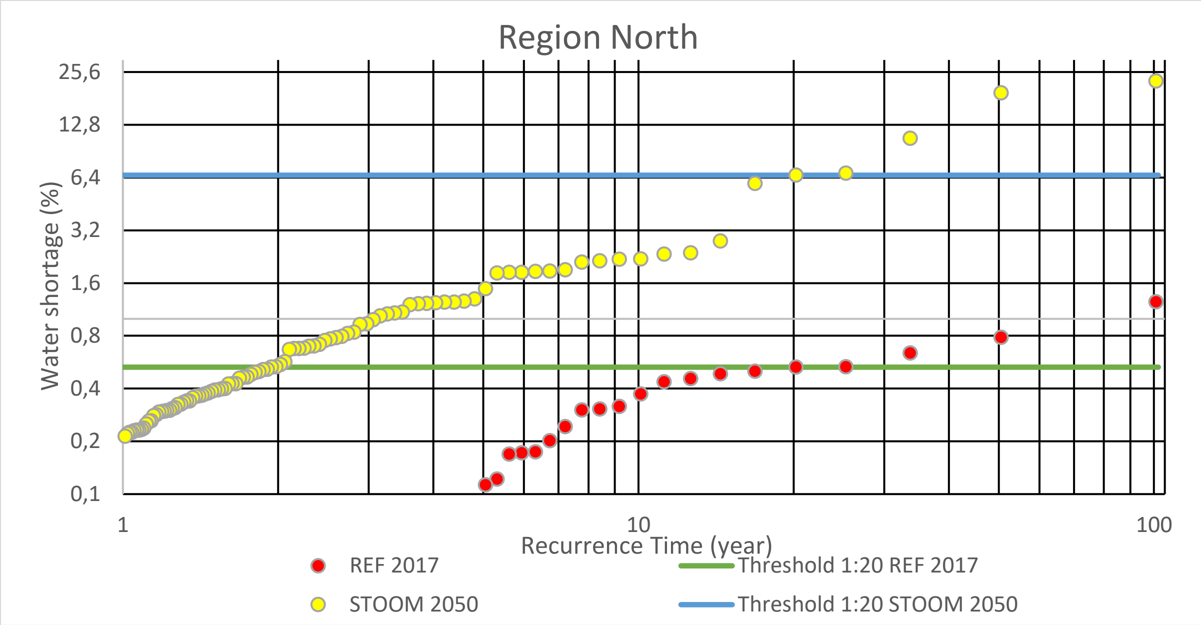

Figure 15 Water Shortage frequency curve Region North – REF vs STOOM data 1:20 (logarithmic x-axis and y-axis)

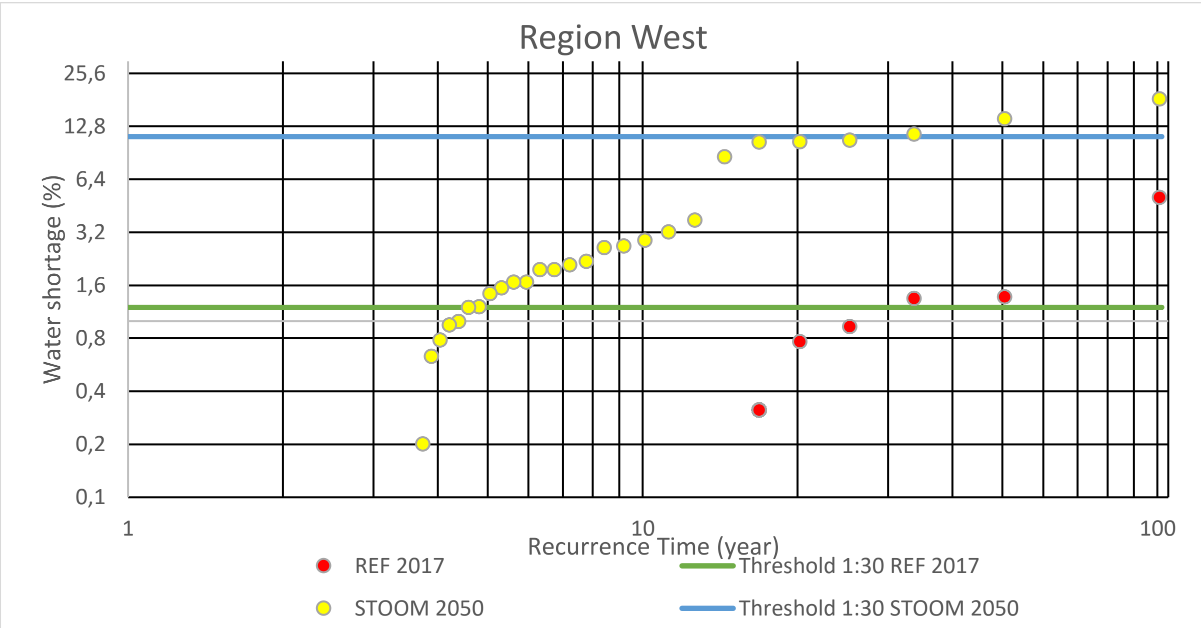

Figure 16 Water Shortage frequency curve Region West – REF vs STOOM data 1:30 (logarithmic x-axis and y-axis)

In both cases the threshold for the STOOM data is not even reached in a 1:100 years drought of the REF data. This was also true for the cumulative precipitation deficit indicator, however for the water shortage the REF 1:100 year value is not even 1/5 of the 1:20 year threshold value in STOOM for region North and not even 1/2 of the 1:30 year threshold value in STOOM for region West. While if the threshold for the REF data would stay equal in a future world where climate change and socio-economic growth continues (STOOM), the 1:20 definition would then translate to a 1:2 year drought for region North and the 1:30 definition would translate to a 1:5 drought approximately for region West (indicated in figures 15 and 16). This significant increase in water shortage relative to the other indicators from the REF scenario to the STOOM scenario could be caused by the fact that water shortage is calculated by multiple variables, which represent supply and demand. Not only is the water supply reduced due to strong climate change, the strong socio-economic growth also increases the water demand. Both variables that calculate the water shortage are affected negatively.

Region North experiences many years in which low water shortages occur, in the STOOM scenario every year a water shortage is present, however many of them are tolerable and far below the threshold as can be seen in figure 15. Although region West experiences more severe water shortages than region North (1:100 REF drought translates to 5,1% water shortage, which is only 1,2% for region North), the amount of times a water shortage actually occurs is much lower. Only 6 years in the REF scenario depict a water shortage and only 28 years in STOOM, the remaining years have a neutral balance or there is a positive water surplus in the region.

4.5 Effectiveness of the strategies

The water shortage is the only indicator in this research which can be quantitatively analyzed via Qwast on how the different strategies affect the freshwater availability. As mentioned in the method section, all five strategies are analyzed in the STOOM scenario, and the reference data originates from a STOOM scenario in which no measures are taken: Q0_Basis, in which the current policy is proceeded. The average water shortage in Q0_Basis is 1,5% and 1,2% in respectively regions North and West. The comparison between the average water shortages in scenarios which include the strategies is displayed in table 7.

The identified extreme dry years differ slightly between the scenarios, however this comparison is not included for this section, since the comparison between magnitude and dispersion of the extreme dry years results in more interesting insights.

Table 7 – Water shortage average for both regions in Q0_Basis and strategies, reduction in comparison to the reference data in brackets indicated

Scenario + Region	***Average Water shortage region North***	***Average Water shortage region West***
1) Q0_Basis	*1,5 %*	1,2 %
2) Demand	1,1 % (27%)	1,2 % (0%)
3) Supply	0,8 % (47%)	0,7 % (42%)
4) CombiAll	0,6 % (60%)	0,6 % (50%)
5) EP	0,7 % (53%)	0,7 % (42%)
6) VKP	1,1 % (27%)	0,4 % (67%)

The averages are all relatively small (<1,5%) per year, however significant percentual differences exist between the strategies. These differences are present in between the regions: VKP decreases the average water shortage in region North with 27%, while the decrease in region West is 67% with the same strategy. However, significant differences are present within the regions as well: the strategy Supply (0,8%) results in a much more effective approach than Demand (1,1%) in region North, while in region West the strategy Demand results in no improvement at all, the average water shortage does not change relative to the reference data.

Besides the average water shortage, the results from the strategies also display interesting insights regarding the extreme dry years. Firstly, the strategy which results in the lowest water shortages during extreme dry years is in region North the CombiAll strategy and in region West the VKP strategy. Even in the most extreme drought case (1:100), the VKP strategy does not exceed the 1:30 STOOM threshold for water shortage in region West (figure 18). While in region North none of the strategies display such a notable result, the measures that are taken in the strategies Supply, EP and CombiAll do decrease the water shortage significantly, resulting in exceeding the 1:20 STOOM threshold only when much severe droughts occur (figure 17), respectively 1:35, 1:44 and 1:48.

In region West certain strategies increase the water shortage in comparison to the reference scenario during extreme droughts. Implementation of these measures would provide solutions for short term mild droughts, however for long term extreme droughts, the situation is only worsened. The strategies Demand, CombiAll and EP result in 1:50 droughts with respectively 14,8%, 14,7% and 14,3% water shortage in comparison with the 14,2% water shortage in the Q0_Basis scenario. The 1:100 droughts are significantly worse, resulting in 28,5%, 28,3% and 28,0% water shortage in comparison with the 18,4% water shortage in the Q0_Basis scenario.

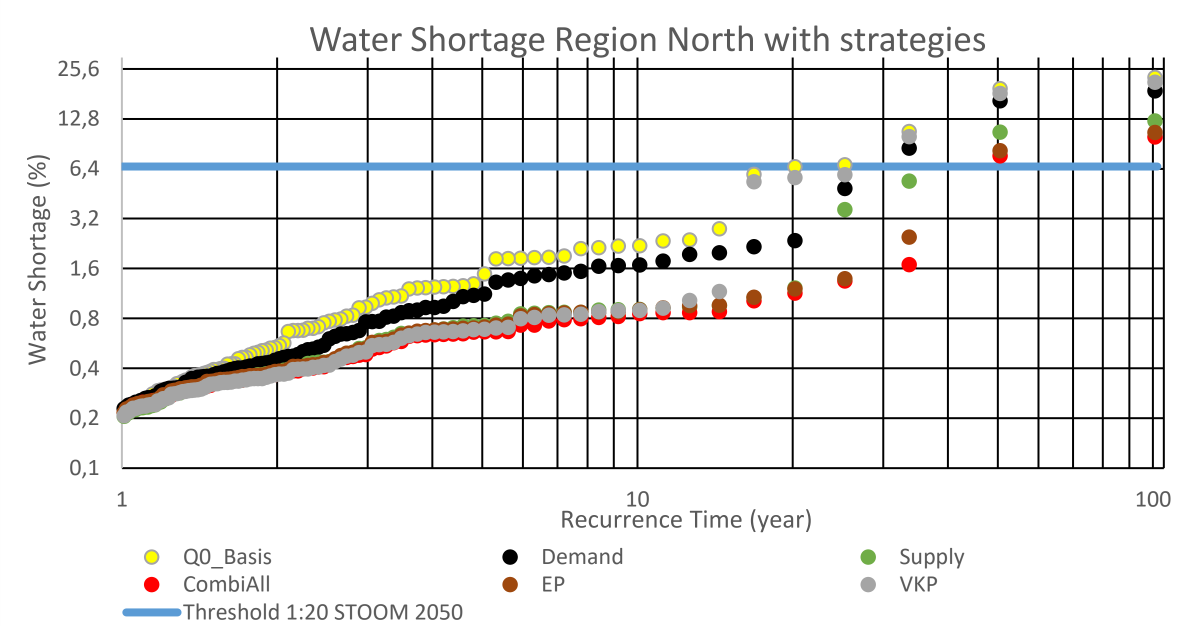

Figure 17 Water Shortage frequency curve Region North – STOOM data with Strategies 1:20 (logarithmic x-axis and y-axis)

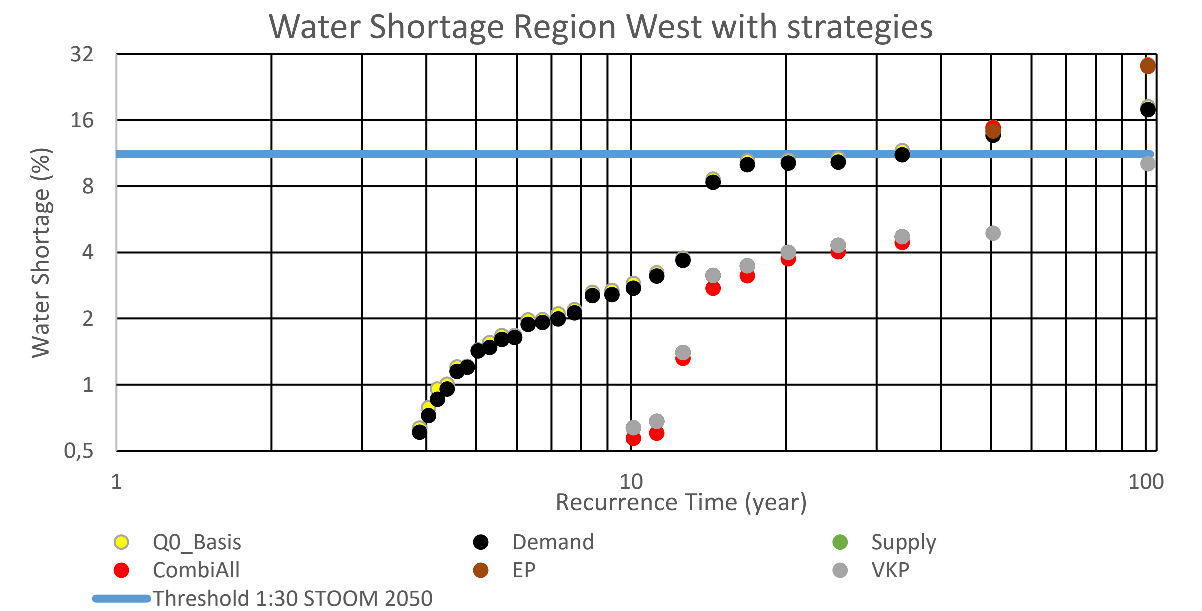

Figure 18 Water Shortage frequency curve Region West – STOOM data with Strategies 1:30 (logarithmic x-axis and y-axis)

5. Discussion

5.1 Limitations and assumptions

Qwast model

The Qwast model had a major role in this research, besides calculating the results that were used for two out of three indicators, it also performed the alterations in the main water system to simulate the strategies and their impacts on the consequences of drought. Modelling is a useful tool which can deliver immense value to a research, however its limitations should always be mentioned. Since a model is a simplified representation of reality, some uncertainty is present in the results (Ingham & Gilbert, 1991). Qwast is prone to such uncertainties as well, since it is bound to its variables and predetermined rules. Examples are the 1:100 drought water shortages in STOOM which are displayed in region West during the Supply, CombiAll and EP strategies (figure 18). Implementation of these measures would result in an increase of water shortage in comparison to the scenario where no measures are implemented. This phenomenon is caused by the prioritization that is built in to Qwast. The available water is divided in the model in the following order:

1. Water level maintenance
2. Flushing
3. Irrigation

In other words, if there is a water shortage, water that is used for irrigation is reduced first. The mentioned strategies contain a measure that delivers extra water towards region North for water level maintenance, at the expense of irrigation and flushing in region West, resulting in an increase of water shortage in region West.

Interviews

Besides model uncertainty, the interviews that were performed to answer the first research question also contain a degree of uncertainty. Representatives that attend the work sessions of the Delta program were contacted, however one person or entity can never completely represent an entire freshwater region, which consists of multiple water boards and commissions. The answers that were given during the interview could have been different if another representative would have been asked the same questions. Certain measures, projects and areas within region North and West could have been highlighted, or intentionally not mentioned due to personal reasons and bias. Another limitation that occurred during the contact with the stakeholders is the absence of answers that can be processed. Initially, the indicator regarding discharge of the Rhine was supposed to have multiple perspectives with various discharge values, derived from the stakeholders' and the operational management perspective. However, region North indicated that their limited knowledge regarding the statistics of the Rhine discharge withheld them from giving a discharge value. Region West did respond with a discharge value, nevertheless, this value was equal to the LCW criteria (1100 m^3/s). Hence, it was chosen to analyze this indicator with one discharge value as threshold.

Scenario implications

To conduct this research, various assumptions were made. Firstly, by using the STOOM scenario strong climate change and socio-economic growth is assumed. Continued climate change is predicted by many studies (Frölicher et al., 2010, Frölicher et al., 2014), however various papers have different conclusions as to which consequences continued climate change will have. According to Trenberth (2011), precipitation patterns will be influenced significantly resulting in an increase of intensity and duration of droughts, while Huntingford et al (2013) displays that interannual temperature variability is currently decreasing in Europe and North America, which results in a decrease of extreme weather conditions. The STOOM scenario includes an increase in temperature of +2 degrees in 2050 and +4 degrees in 2100. The extent of a temperature increase plays a major role in the results that follow from the indicators that were set up in this thesis. It strongly affects the cumulative precipitation deficit, mostly via an increase in evaporation, which leads to larger cumulative precipitation deficits (Philip et al., 2020). Furthermore, a temperature increase causes the discharge pattern of the Rhine to potentially change: the Rhine is currently a combined rain -and snowfed river, which could change in to a primarily rainfed river, since less water is retained in the form of snow once temperature increases (Asselman et al., 2000). This pattern change will result in lower discharge during the summer and higher discharge during the winter. The results that were derived from the discharge indicator all display this increase in intra-annual variation. Finally, the STOOM scenario assumes that, due to climate change, the potential area that needs to be irrigated increases with 55% by 2050 (Schasfoort et al., 2019). This assumption leads to an increase in water demand from the main water system, which impacts the water shortage indicator significantly.

The socio-economic growth that is assumed by using the STOOM scenario is an aspect which also impacts the indicators. An increase in urbanization is one of the consequences of this assumption, while events could occur which lead to decline of socio-economic growth or people wanting to avoid large cities: extended global economic recession/depression, which results in unemployment and civil unrest with riots. One of the effects of urbanization is an increase of temperature in comparison to rural areas, caused by human habitation. Furthermore, the daily temperature variation decreases significantly in urban areas, which could impact the cumulative precipitation deficit (Tam et al., 2015).

Threshold definitions

Limitations were also present in certain sections of the methods that were applied during this research, in particular the indicator which displayed the discharge of the Rhine below a certain level. The indicator was set up in such a way that an x number of decades needed to be below the discharge threshold per year to exceed the definition of the freshwater goal per region. The pattern in which the decades were below the discharge threshold was not determinative, while this pattern can vary substantially. In reality, a discharge which is lower than a certain level for consecutive decades per year can result in much more severe water shortage consequences than a discharge which is lower than a certain level for individually separated decades per year. If the discharge increases slightly during the spring or summer and rises above the threshold, which occurs in 1934 (figure 10), the entire system can reset. Freshwater buffers are examples that benefit a lot from a year that displays discontinues exceedance. Secondly, the extent of exceedance of the discharge threshold was also not determinative in the method. Similar to the pattern of exceedance, the extent of exceedance in a year can result in much more severe water shortage consequences. In other words, a water shortage can be much worse in a year where the discharge is significantly lower than the threshold, in comparison to a year where the threshold is only exceeded slightly. From the current method that is used for this indicator, 1921 seems to have the highest water shortage, since it includes the most decades in which the thresholds are exceeded in all scenarios. While 1947 and 1949 could have much more severe problems and damage due to the larger number of decades that the discharge is below 600 m^3/s in comparison to 1921 (figure 11+12). Thirdly, by using this method for the discharge indicator, droughts that are defined by different frequencies can consist of an equal combination of discharge level and time duration. This problem is displayed in region West in the REF scenario:

Table 8 – Discharge threshold and time duration for region West in a REF scenario

Scenario + Region	***Discharge***	***Time duration***	***Identified years***
2.1) REF West	*< 1100 m^3/s*	*>= 14 decades*	1947 (14 decades) 1976 (14 decades) 1949 (16 decades) 1921 (23 decades)

With the information given above from a 100-year dataset, a 1:25 drought would be equal to a 1:33 drought: a discharge of the Rhine that is lower than 1100 m^3/s for 14 or more decades. This problem is caused by the fact that the time duration is used as the changing variable to identify the threshold. A potential solution for this problem is to use the discharge value as the changing variable instead of the time duration. This variable can be altered more precise since it is measured in large detail, opposed to the time duration which is monitored in large fractions (+- 10 days). However, it could also be argued that a fixed discharge value is much more convenient to use in policy plans with multiple stakeholders, since it can be based on a criterium that is used already in other policies, the LCW criterium which was used in this research is such an example.

5.2 Management and policy implications derived from answered research questions

The answer that was found for the first research question 'What does the freshwater goal entail in the regions Noord-Nederland and West-Nederland?' identified a potential problem for management and policies which include a broad and/or vague goal. The stakeholders defined the freshwater goal unequally with a rather significant difference between the definitions. A possible explanation for the difference is the potential economic damage which region West evidently would prefer to avoid. Since large cities like Rotterdam which contain process industries that use freshwater are located in this area, the region wants to be resilient against a more severe drought than region North, due to the larger economic implications (Hoogheemraadschap van Rijnland, 2020). Furthermore, the experience of the extreme drought that occurred in 2018 could have caused this difference. During 2018, the discharge of the Rhine decreased drastically, displaying the vulnerable position that region West has due to its dependence on the river water (ministry of infrastructure and water management, 2019). This recent anomaly in climate (extreme drought) could have resulted in region West being more cautious in comparison to region North. If this research would have been conducted in a different period where the recent memory of the stakeholders did not include having an extreme drought, the definition potentially could have been more similar between the regions. However, broad goals are implemented to involve as many entities as possible and make collaboration easier. An objective that is too strict could result in stakeholders to depart collective management due to disagreement or unrealistic prospects. Defining goals in processes where several stakeholders are included should therefore be set up in a moderate quantified way to avoid: misunderstandings, significant differences in perspective and discontent due to unrealistic boundary conditions.

The second research question resulted in identification of various indicators that can be used to quantitatively define drought. The answer to this question could also be related to a policy recommendation, which is that a complex process can and should be quantitatively described by multiple indicators. This research displayed three quantitative indicators which could describe drought. While all of them used the same defined goal: being resilient against a 1:20 or 1:30 drought, the results and therefore their interpretation can differ significantly. Stakeholders should be aware of this knowledge and the fact that different perspectives could exist when a complex concept like drought, which can occur in multiple forms, is discussed. By doing so, during the step of developing policies and strategies to mitigate drought, different perspectives can be reviewed.

Answering the third research question adds the most value for management and policy implications, since it focuses on how the various consequences of drought are impacted by the different strategies. This analysis is performed based on the different perspectives from the drought indicators. As mentioned before, the water shortage indicator could be analyzed in Qwast and includes both supply and demand of water, while the indicators cumulative precipitation deficit and discharge below a certain level focus solely on the impact of climate change. However, the impact that the strategies will have on the consequences of drought can be analyzed by all drought indicators individually. One of the consequences of a high cumulative precipitation deficit is the depletion of water buffers. Not only will the groundwater table drop, lakes like the Markermeer and IJsselmeer will decrease in water level (ministry of infrastructure and water management, 2019). A measure which is rather effective is an increase of water buffers to mitigate the consequences of a cumulative precipitation deficit. The strategies 'Supply', 'CombiAll' and 'EP' all contain the measures which increase the water level in the Markermeer and IJsselmeer from -0,2 m to -0,1 m. Furthermore, an effective way to cope with a high cumulative precipitation deficit is to reduce the water demand. The measure 'reduce water usage for irrigation' is present in the strategies 'Demand', 'CombiAll', 'EP' and 'VKP', however in the latter two strategies the measure only accounts for 5% reduction and in a limited number of regions. In the strategies 'Demand' and 'CombiAll' the water usage for irrigation is reduced by 10%, which is performed in regions IJsselmeer, Rivierenland and West. Due to the presence and magnitude of the abovementioned measures, strategy 'CombiAll' is determined as most effective to cope with the drought consequences that arise from a cumulative precipitation deficit.

An effective way to minimize the consequences of drought that are caused by a low discharge in the Rhine is by decreasing the amount of water demand from surface water. The strategies 'Demand', 'CombiAll' and 'EP' all contain measures that decrease the amount of water demand that is required for flushing multiple sluices and flushing for the drinking water industry. Therefore, these three strategies are considered most effective in coping with the consequences of a low discharge of the Rhine.

All five strategies result in different gains and therefore provide an indication which combination of measures contributes the most towards decreasing the magnitude of water shortages. The most interesting finding from this drought indicator is that between the regions, the strategies have a significantly different impact. In region North, the strategies 'Supply', 'CombiAll' and 'EP' display the most significant decrease in water shortage (figure 17), especially during the most extreme droughts (worse than 1:25). A measure which is included in these strategies is the increase of water level of the Markermeer and IJsselmeer, which is evidently valuable for region North. The strategy VKP seems to be impacting the smaller water shortages successfully and displays a decreasing trend in comparison to the reference data (Q0_Basis_STOOM), however once the region is experiencing droughts that are worse than 1:15, the water shortage only slightly decreases in comparison with the reference data. The impact that the VKP strategy displays after this inflection point is neglectable. This could be caused by the fact that the measure 'reduce freshwater flushing demand of sluices with 50%' is only applied in Delfzijl during the VKP strategy, while other strategies that perform better also apply this measure for the sluice at Harlingen. In region West, the opposite occurs, the VKP strategy performs well for all water shortages, on top of that the strategy has the most impact in reducing the water shortages that occur during the most severe droughts, 1:50 and 1:100. This can once again be explained due to the presence of the measure that increases the water level in the Markermeer and IJsselmeer in combination with the limitation of Qwast regarding the water prioritization that was mentioned in section *5.1 Limitations and assumptions*. Since the prioritization of Qwast places water level maintenance above other variables, this measure will lead to negative effects for region West during severe droughts because the system needs to make sure this water level for the Markermeer and Ijsselmeer is maintained. However, in the strategy VKP the water level of both lakes is not required to be maintained at such a high level, resulting in more water being available in region West, and therefore much lower water shortages. The strategy Demand performs overall the worst in region West, reducing the water shortage only slightly in comparison to the reference data. This is caused by the absence of measures that increase the supply of water towards the Western parts of the Netherlands, all other strategies contain measures that optimize inlets and enhance the discharge of important waterways. Generally, by looking at the average, strategies which include measures that increase the water supply display the most impact in reducing the water shortage.

Finally, the analytics product Power BI was utilized to visualize certain parts of the results and to act as a trivial decision support system. Power BI has many features integrated to build such a system via a dashboard (figure 19). The interface is user friendly, with various options to display ones data. Furthermore, within Power BI it is easy to make connections between datasets and certain scenarios: lists of data were connected to certain strategies and indicators to display the results once a combination of strategy and indicator is chosen (figure 20). By connecting another spreadsheet that contained a list of measures to the strategies, the measures that were included in the strategies were displayed as well.

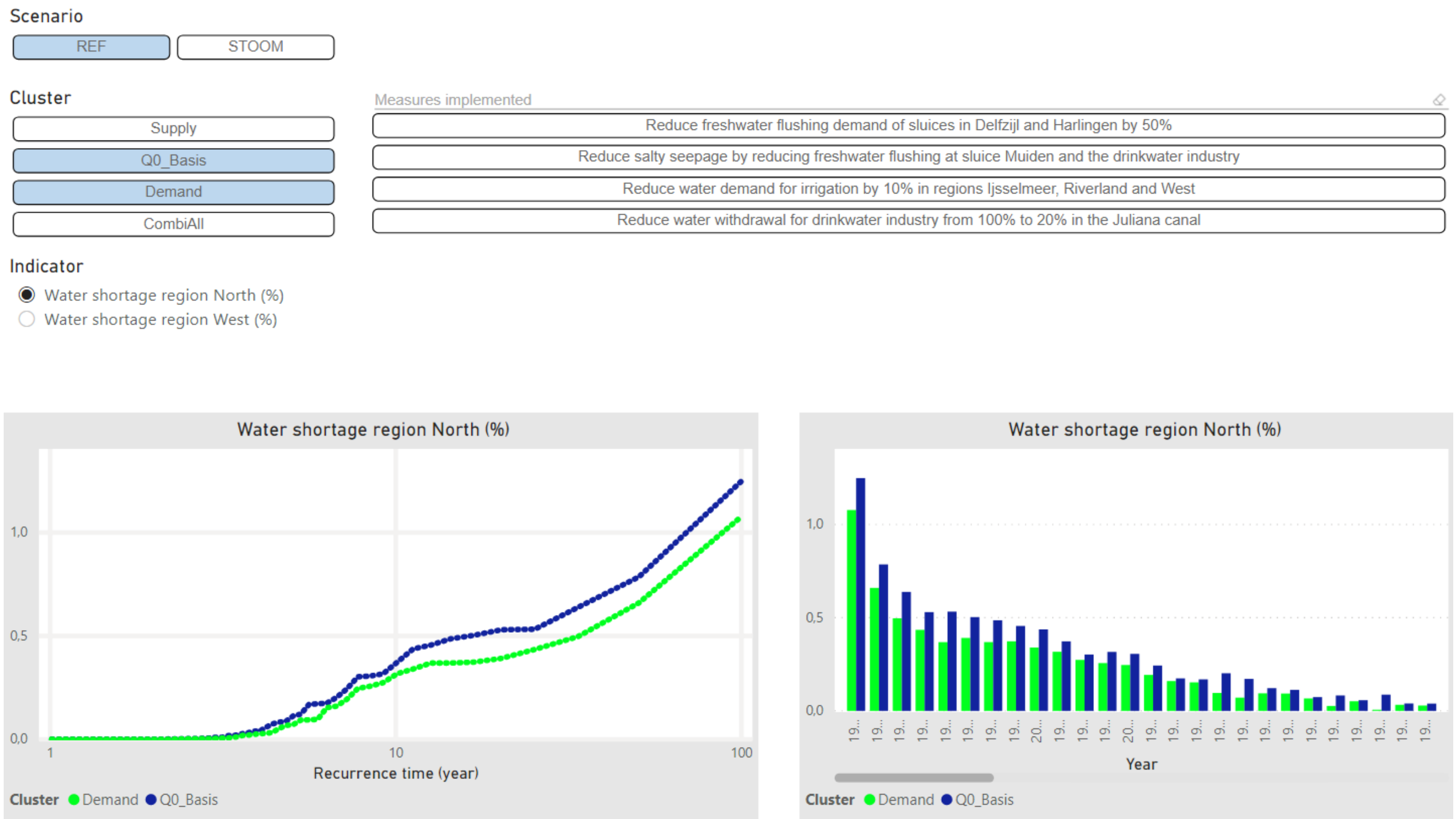

Figure 19 Power BI dashboard displaying the implemented measures of the highlighted cluster 'Demand' (top right), frequency curves of water shortage in Q0_Basis_REF and Demand_REF in region North (bottom left) and indication of years which displayed the largest water shortages in Q0_Basis_REF and Demand_REF (bottom right).

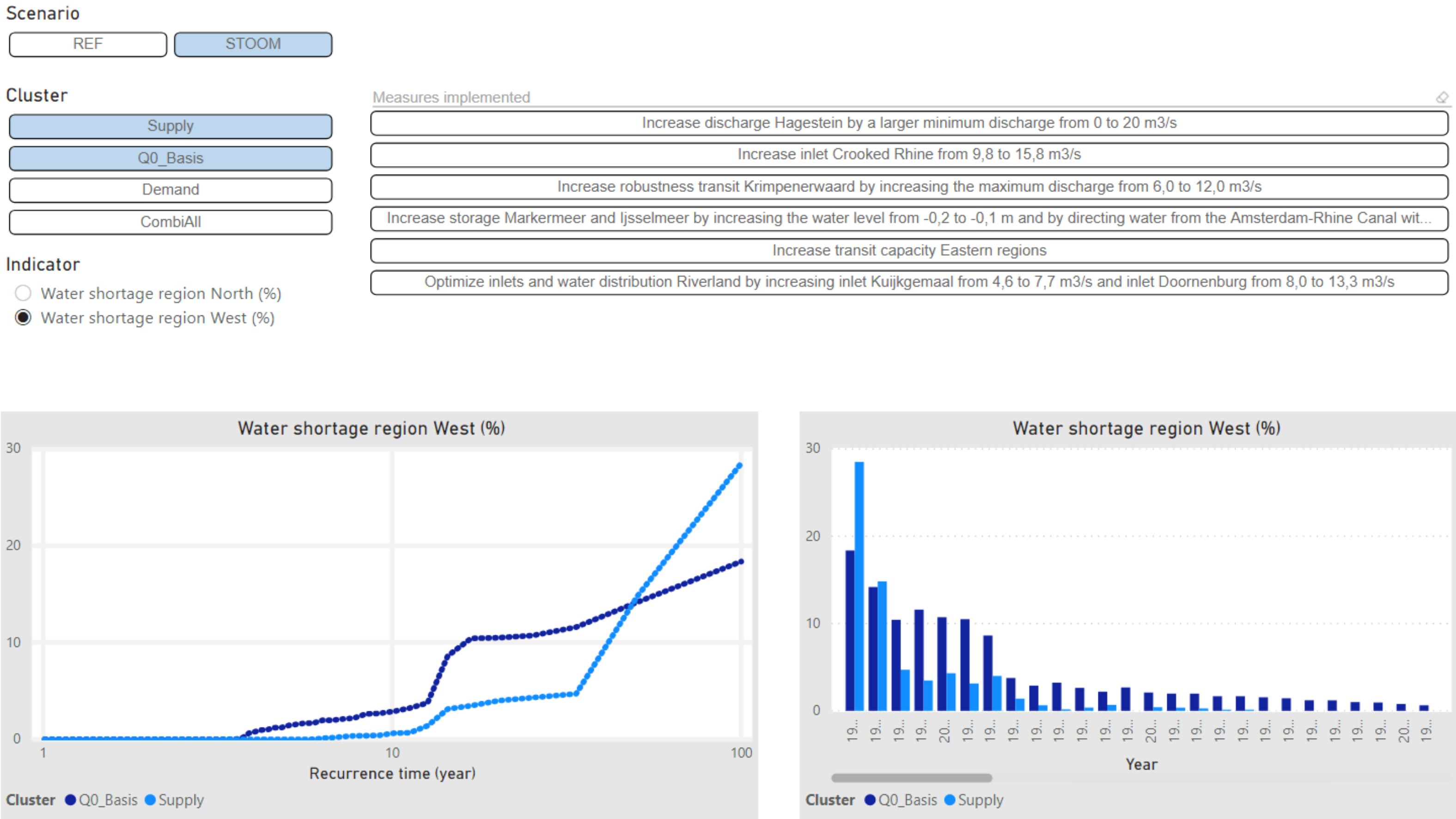

Figure 20 Power BI dashboard displaying the implemented measures of the highlighted cluster 'Supply' (top right), frequency curves water shortage in Q0_Basis_STOOM and Supply_STOOM in region West (bottom left) and indication of years which displayed the largest water shortages in Q0_Basis_STOOM and Supply_STOOM (bottom right).

The criteria which are most important for a decision support system are partially derived from Dan Power (2005), and include facilitation, interaction and task-oriented capabilities. A decision support system should be able to facilitate decision-making activities, not replace the decision makers. Through a dashboard that can be constructed in Power BI, the decision-making process can be facilitated through data visualization and comparison of scenarios (figure 19+20) for the decision makers. Through interaction the decision makers are able to alter clusters and indicators, one should be able to control the output of the dashboard adequately. Through task-oriented capabilities a decision support system should be able to perform specific data analysis and provide a display of the costs and benefits of certain alternatives.

Power BI seems to be suitable to act as a decision support system for future drought adaptation planning. The dashboard in which the user can interact and alter scenarios, clusters and indicators makes it convenient for stakeholders to review and analyze impacts which facilitates the decision making.

5.3 Scientific implications

Added value from this research is predominantly for the management aspects of freshwater availability. The results give insights for the Delta program in regard to the problem of using the current definition of the freshwater goal by region North and West. Both regions accept the consequences of these extreme droughts because it is outside of their definition of the freshwater goal. By using such definitions of being resilient against a 1:20 and 1:30 drought, the extreme droughts which exceed these thresholds have the potential of being overlooked, resulting in unpreparedness once they occur. This principle of being cautious with used language in definitions and goals is important for policies, agreements and literature in general. Furthermore, this research gives insight on how complex interactions during drought should be addressed. By using multiple quantitative indicators, which could give different perspectives and results, a thorough analysis of a complex process can be performed. Finally, this research gives insights in the usability of Power BI and displays that Power BI can be used to build a decision support system.

Further research could be performed on various sections of this thesis. First, besides region North and West, the other freshwater regions could be interviewed to examine what their definition of the freshwater goal entails. A majority could have the same definition, which could then be used nationally if it is sufficient enough. Secondly, an analysis could be made on how the strategies perform in the other freshwater regions by using the drought indicator water shortage. Strategies which perform good for region North and West might not make a large difference or even work counterproductive in other regions. Thirdly, an analysis could be added to review other combinations of measures which could potentially improve the resilience of the regions against drought.

6. Conclusion

The research question of the thesis was ‘’How effective are various strategies in reaching the freshwater goal of the Delta Program in the region ‘Noord-Nederland’ and ‘West-Nederland’?’’. To answer this question, multiple sub-questions were set up which resulted in the following conclusions. The freshwater goal entailed a different definition between the regions: the ambition of region North is to be resilient against a 1:20 drought, the ambition of region West is to be resilient against a 1:30 drought. Being resilient against a freshwater shortage is a complex concept, since the main cause of a freshwater shortage is drought, which can be quantified and measured with many different variables. In this research the freshwater goal was quantified by means of three criteria: cumulative precipitation deficit, discharge below a certain level and water shortage. These drought indicators were utilized to analyze various strategies (combination of measures) that could be implemented to cope with the consequences of drought in the Netherlands. The strategies which focus on both decreasing the water demand and increasing the water supply are expected to cope with the consequences of cumulative precipitation deficit most effective. The strategies which focus mainly on decreasing the water demand are expected to cope with the consequences of a low river discharge most effective. Finally, the strategies which focus mainly on increasing the water supply are expected to cope with the consequences of a water shortage most effective. Furthermore, Power BI was utilized to build a decision support system to analyze the suitability of the software for such systems. It was concluded that a dashboard in Power Bi is suitable to support decision makers since it is capable of facilitation, interaction and task-oriented capabilities.

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