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Forecasting the impact of groundwater extraction on the Dutch environment

An interdisciplinary impact analysis as part of the Water Sustainability Diagram

Keywords:
GENIAT, Water Sustainability Diagram, groundwater extraction, sustainability, dose effect function, REFLECT-method

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A thesis presented to Utrecht University, faculty of Geosciences, in partial fulfilment of the requirements for the degree Master of Science in Water Science and Management.

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Ultimately, I hope that this study and other studies to come will encourage drinking water managers to consider the long-term impacts of strategic decision making in order to move towards a more sustainable development.

EXECUTIVE SUMMARY

(i) Introduction. This study investigates the possibility of initiating a quick scan *'Groundwater ENvironmental Impact Analysis Tool'*, further referred to as GENIAT. The proposed GENIAT must be able to compare the impacts on the environment from present and possible future groundwater extractions for drinking water production in the Netherlands by means of a sustainability scoring system. In order to analyse impacts, existing methods and knowledge will be used to forecast the environmental changes resulting from groundwater extraction in a quantitative manner. A valid framework to setup the GENIAT is examined in order to answer the main research question, which is formulated as:

- How to quantify the impacts on the environment resulting from groundwater extraction by means of a quick scanning tool for the Water Sustainability Diagram based on sound scientific based information?

The *Water Sustainability Diagram (WSD)* is a multi-criteria decision analysis, which identifies the long-term impacts of strategic decisions in the water cycle. The purpose of the WSD is to underpin future strategic investments and innovation decisions with information about the overall impact on sustainability.

(ii) Method. A conceptual model is setup based upon findings in the theoretical framework. This conceptual model serves as main framework for the environmental synopsis and impact analysis. In addition, a sustainability guideline is proposed. This guideline is used as baseline for the scoring. GENIAT is initiated based on the conceptual model, the guideline and other findings in literature. Last, the GENIAT is validated by means of parameterization, model tests, expert judgement, a sensitivity analysis and by conducting a case study for the location Kamerik.

(iii) Theoretical framework. Findings in literature are used to initiate the GENIAT in a scientific manner and in consensus with preconditions set by Oasen N.V. Not all relevant impacts on the environment can be quantified due to delimitations and gaps in knowledge. However, findings in literature are useful to approximate the impacts resulting from groundwater extraction for several main aspects of the environment.

(iv) Results. The GENIAT needs a synopsis of the initial situation in order to analyse the state of geo- and eco-hydrological aspects. In order to forecast the impacts on the environment, a groundwater extraction is modelled with a certain location, pumping rate and well screen depth. Based upon the findings in the theoretical framework, environmental impacts are quantitatively (and to some extent qualitatively) determined. Results of these calculations are considered as midpoint results. First, midpoint results are classified as sustainable or unsustainable based on the proposed guideline. Then, results are aggregated to an impact category by means of the geometric- or arithmetic mean, based upon the skewness and interrelation of the population.

A scoring system is proposed, in which 'worst case scenarios' (0) and 'best case scenarios' (5) are identified for impact categories. A linear relation between worst case and best case is determined. Impacts on the environment can be assigned to a score based upon the linear relationship. The following scoring system is proposed:

- 0 = extreme negative influence;
- 1 = very high negative influence;
- 2 = high negative influence;
- 3 = moderate negative influence;
- 4 = low negative influence;
- 5 = very low or positive influence.

The score of each of the seven identified impact categories is determined in the scoring system, resulting in seven scores. These scores are then aggregated by means of the arithmetic mean in order to obtain an end score. This end score indicates the overall environmental impact of a certain groundwater extraction, expressed in a number ranging from 0 to 5. Moreover, this score correlates with aspects of sustainability, due to the used guideline for GENIAT. It is stated that an end score close to 5 indicates that the investigated groundwater extraction is sustainable. The lower the score, the less sustainable the investigated groundwater extraction.

A sensitivity analysis shows that the forecasted geo-hydrological correlation in GENIAT coincide with expectation of experts and with findings from literature. Results from the case study indicate that is it possible to use geo-hydrological data from e.g. TRIWACO as baseline for the environmental synopsis in GENIAT. Moreover, it is shown that the GENIAT may be used to approximate hydrological changes and that output data coincides with findings in literature and expert knowledge. In addition, it is shown that a simplified manner to estimate lowering of the piezometric surface may be useful in some cases. From these findings, it is concluded that the proposed GENIAT is practicable in order to approximate the impact on the environment resulting from groundwater extraction.

(v) Discussion. The theoretical framework provides scientific and (inter)nationally accepted methods and frameworks in order to initiate the GENIAT in consensus with preconditions. However, assumption, simplifications, uncertainties and bias are adopted in the setup of the GENIAT. Model performance has been validated to some extent, but model uncertainties are currently not assessed nor taken into account. It is argued that transparency of model simplifications and assumptions, and in addition an assessment of uncertainties is needed. A DELPHI-study is recommended to improve the setup of the GENIAT. Support is gained for the results of GENIAT by initiating a DELPHI-study, therefore providing more legitimacy and acceptance to use results of the GENIAT for the WSD. In addition, a list of identified improvement to enhance GENIAT is incorporated.

CONCLUSION

This study is conducted in order to answer the following research question:

- How to quantify the impacts on the environment resulting from groundwater extraction by means of a quick scanning tool for the Water Sustainability Diagram based on sound scientific based information?

What became apparent in this study is that it is possible by means of the used methodology to quickly and quantitatively forecast the environmental impacts resulting from groundwater extraction. It is possible to further validate the midpoint results of the GENIAT by comparing results with for instance other case- or field studies. However, it is recognized that the 'sustainability scoring system' in GENIAT cannot be validated by means of a literature review. Moreover, it is unknown how useful the proposed sustainability score is due to scientific uncertainties and gaps in knowledge. These shortcomings creates space for competing assertions, which might mislead decision making and may lead to unsubstantiated bias concerning the sustainability impacts of a certain groundwater extraction.

Beside scientific limitation, it is recognized that conflicting assumptions exist in the framework of GENIAT due to the different perspectives of organizations and individuals. Conflicting assumptions arise from taking a stance in the following questions:

- what aspects of sustainability should be analysed due to their significance, and how?;
- what subjects should be prioritized during aggregation, based on statistically determined degree of distress?;
- how should sustainability be defined and how can the sustainability scoring system be arranged based on this definition and based on science?

Overall, it is argued that the results of GENIAT must be both scientifically and non-scientifically legitimate in order to provide adequate input for the Water Sustainability Diagram. The degree of scientific and non-scientific legitimacy for GENIAT is not yet well studied. Further research and development is recommended. However, it is hypothesized that by means of a DELPHI study, and additional improvements to GENIATs computational model, it will be possible to provide scientific based and legitimate information which will be useful for the WSD. Also, the sustainability scoring system may become scientifically based by being investigated and improved by a DELPHI-study.

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LIST OF ABBREVIATIONS

BDIV	-	Beleidsplan Drink- en Industriewater Voorziening
DEMNAT	-	Dose Effect Model NAture Terrestrial
EIA	-	Environmental Impact Analysis
GENIAT	-	Groundwater ENvironmental Impact Analysis Tool
LC(I)A	-	Life Cycle (Impact) Assessment
MCDA	-	Multi Criteria Decision Analysis
MSGL	-	Mean Spring Groundwater Level
RIVM	-	Rijksinstituut voor Volksgezondheid en Milieu
POD	-	Programma Oasen Duurzaam
RO	-	Reverse Osmoses
SD	-	Sustainable development
STOWA	-	Stichting Toegepast Onderzoek Waterbeheer
SWAP model	-	Soil-Water-Atmosphere-Plant model
DWC	-	Drinking Water Cycle
VSD(+)	-	Very Simple Dynamics (+)
WFD	-	Water Framework Directive
WSD	-	Water Sustainability Diagram

CHAPTER 1. INTRODUCTION

1.1. A CHANGING WORLD

Dutch drinking water companies are internationally known for their high service quality as consumers get potable water of high quality without the usage of chlorine (Smeets, Medema, & Van Dijk, 2009). Sentiments are high because the cost price of drinking water is low and the overall production is done in an efficient and environmentally conscious manner (Vewin, 2013; Loubet et al., 2014). Despite high sentiments, there is no guarantee that the drinking water supply preserves its current service quality (Van den Berg et al., 2006; Delpla et al., 2009). This paragraph describes how the demand for a more sustainable and resilient way of drinking water production and supply management will increase due to environmental, technical and ethical changes.

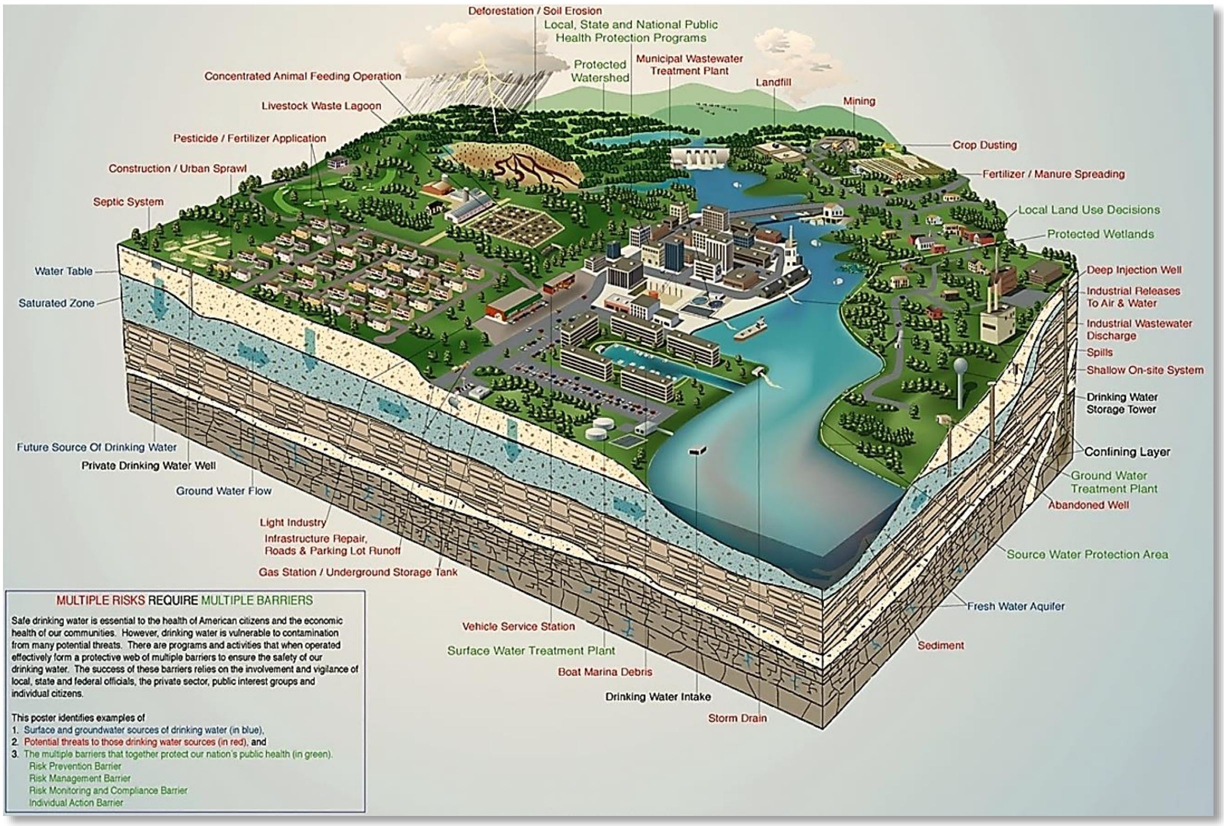

Figure 1 – Visualization of threats for drinking water sources (red), potential drinking water sources (blue) and the barriers in place to help ensure the safety of used drinking water sources (green) **(United States Environmental Protection Agency, 2009)**.

1.1.1. PROBLEM DESCRIPTION: A CHANGING ENVIRONMENT

Changing environmental circumstances are already threatening the Dutch drinking water supply. Anthropogenic activities and natural stressors are increasingly exerting pressure on the quality and quantity of fresh water resources used for the drinking water supply. The visualization in figure 1 indicates general threats. Why one must take care of global fresh water resources is outlined in annex 1. Identified threats for the Dutch drinking water supply are (Helmer & Hespanhol, 1997; Schwarzenbach et al., 2006; Wuijts & Van Rijswick, 2007; Houtman, 2010; Hooijboer & de Nijs, 2011; Van den Hurk et al., 2014; "Helpdesk Water," 2015):

- residues of pesticides;
- nutrient emissions;
- residues from medicines and cosmetics;
- desiccation;
- salinization;
- implications of climate change;
- competitive activities in the soil;
- excavation and drilling activities.

1.1.2. CONTEXT DESCRIPTION: CHANGING KNOWLEDGE

SCIENTIFIC INSIGHT

Due to the changing environment and new scientific insights, there is a growing need for a more resilient drinking water supply in order to guarantee the future potable water quality (Wessels, 2005; KIWA N.V., 2006; Frijns et al., 2013; Rijkswaterstaat, 2014). Technical innovations and scientific research are fostered by water policy, thus stimulating new developments which may offer opportunities to design novel drinking water purification systems with associated infrastructure (Ministerie van Infrastructuur en milieu, 2008; Frijns et al., 2008; Ministerie van Infrastructuur en milieu, 2011).

An example of an innovative and robust purification technique which is becoming more feasible to implement is *Reverse Osmoses (RO)*. RO allows one to use saline water as resource for the drinking water production. As a result, the possibility arises to think about new and innovative, possibly decentralized, infrastructural systems (De Vet et al., 2009).

MIND-SET

It seems that in recent decades, there is a gradual shift from a hierarchical- to an egalitarian worldview due to new insights (Keuning & Smit, 2010). This shift has led to a different mind-set with respect to the nature and extent of environmental issues. Incentives which make one think differently concerning prospective water supply management originate from: population growth, demographic change, growth in water demand per capita, demand for a better potable water quality, new scientific insights, expanding regulations, citizens engagement and the demand for lower overall production and distribution costs (Vörösmarty, 2000; Bayer et al., 2009; McKinsey & Company, 2011; Frijns et al., 2013).

It was mentioned that technical innovations may lead to novel opportunities concerning strategic systems settings. The gradual shift in mind-set can also be a driving force for managers to reason differently concerning strategic decision making. For instance, one of the results of the change in mind-set is that water and soil are viewed in a more holistic perspective and become more embedded in a wider social context (Rotmans, 2003). This is reflected in the increasingly integrated and more proactive approach of modern water management (Offermans, Haasnoot, & Valkering, 2011). Rotmans (2003) made an overview of characteristics of the hierarchical- and egalitarian worldview, included in annex 2. The change in management style would potentially pose opportunities to design and assess novel strategic system settings for the drinking water supply.

THE CHANGE

Currently, it seems that the change in the environment, new scientific insights and the shift in mind-set are to some extent leading in thinking more long term instead of short, thinking more in circular processes instead of linear, thinking more in connected system instead of self-contained. Through this, there is an increased consideration for sustainable issues (Van Dijk, 1992; Gleeson et al., 2012; Van der Meer, 2013; Frijns et al., 2013; Zantkuijl & Schmaal, 2014).

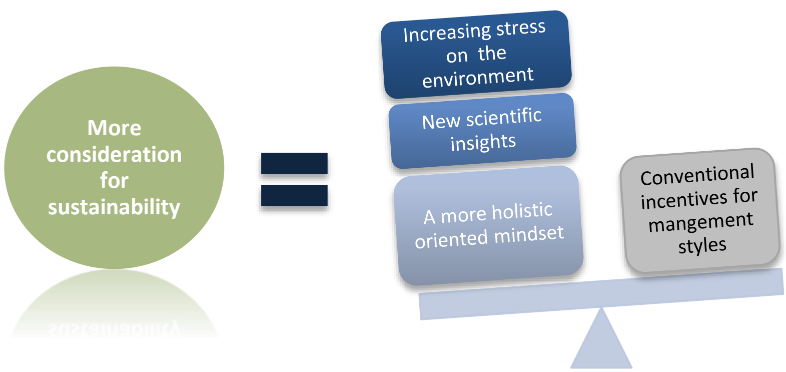

Figure 2 – Visualization of driving forces for water manager to reason differently concerning decision making, taking more consideration for sustainability aspects.

1.2. THE AMBITION: QUANTIFY THE IMPACT

Oasen N.V., introduced in annex 3, wants to determine the impact of a change of strategic business operations in a quantitative way, thereby identifying a pathway to a more sustainable business plan ("Oasen," 2013; Zantkuijl & Schmaal, 2014). The driving forces for Oasen N.V. to improve business operations, while taking aspects of sustainability into account, are also described in annex 3. Driving forces emerge from the problem and context description in paragraph 1.1: A changing world. The definition of sustainability is examined in annex 3.

From the ambition to improve business operations comes the idea to create a comprehensive quick scan *Multi Criteria Decision Analysis (MCDA)*. This analysis would make it possible to identify the long term impacts of decisions making in the water cycle in figure 3, and may therefore underpin decision making with information about future environmental damage, health implications and overall costs. The depicted water cycle is further referred to as the *Drinking Water Cycle (DWC)*. The MCDA is referred to as: 'the *Water Sustainability Diagram*' *(WSD)* (Zantkuijl & Schmaal, 2014). The reason why the WSD quantifies the total impact of a DWC-system, instead of the current business operations of Oasen N.V., is explained in annex 4. The different components making up a DWC are visualized in figure 3.

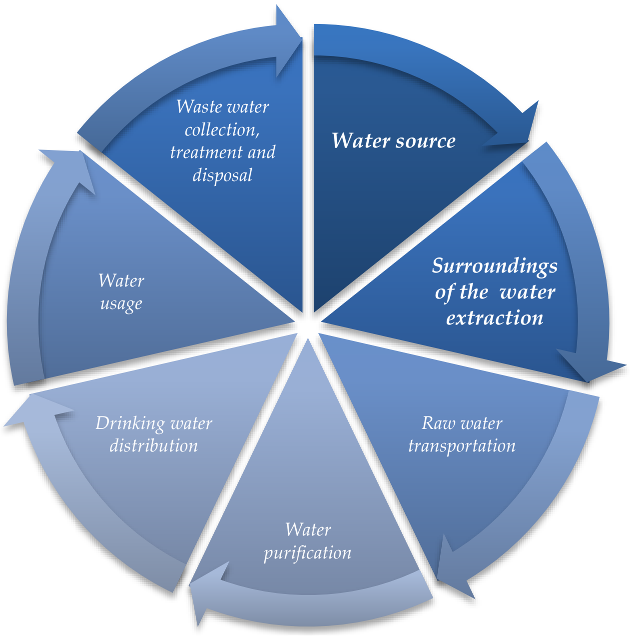

Figure 3 – Cyclical relationship between main components of the drinking water cycle **(Bahri, 2012; Loubet et al., 2014)**.

The overall study program of the WSD tool is divided in several smaller studies. This report describes the finding of a secondary study for the WSD research program. This secondary study has been conducted in order to find a method to assess the environmental damage resulting from groundwater extraction, while regarding sustainability aspects. Therefore, this study has been limited to the DWCs components 'Water source' and 'Surroundings of the water extraction', depicted in figure 3. Due to the interconnectedness of the two analysed components, the study describes the overall analysis for a single integrated component and refers to the overall inflicted damage resulting from water extraction by mentioning 'environmental impact'.

This study reaches unexplored area by analysing the environmental impacts resulting from groundwater extraction for the two interconnected DWCs components while regarding sustainability issues.
On the other hand, there are an increasing amount of studies that quantify the impact of chemical- & energy consumption and material use for the DWCs components 'Raw water transportation' and 'Water purification', by means of for instance the software SIMAPRO or LCAqua (Vince et al., 2008; Loubet et al., 2014)**.** These blocks are also investigated within the WSD study, as is further described in annex 4. Results of these studies will not be regarded in this report.

1.3. GOAL AND RESEARCH QUESTION

1.3.1. GOAL

The main goal of this research is to initiate a quick scan method to determine the environmental impacts resulting from groundwater extraction, with an eye to sustainability. A valid framework to setup a *Groundwater ENvironmental Impact Analysis Tool*, further referred to as GENIAT, will be investigated. The proposed GENIAT must be able to compare the environmental impacts of strategically favourable groundwater extractions in the Netherlands by means of a scoring system. The tool will integrate existing knowledge in order to forecast the environmental impacts. In addition, the setup of the tool must be valid in line with several limiting preconditions, determined by Oasen N.V:

- the used software for the GENIAT is Microsoft Office Excel;
- the tool is scientific based;
- the tool must operate on low quality and accessible data;
- the tool must give a valid quick scan result within a single day;
- the impacts must be aggregated into a 'sustainability scoring system', based on an indices from 0 to 5.

1.3.2. RESEARCH QUESTIONS

The main research question of this study is formulated as follows:

- **How to quantify the impacts on the environment resulting from groundwater extraction by means of a quick scanning tool for the Water Sustainability Diagram based on sound scientific based information?**

The following questions are answered as part of the main research question:

1. What model method is suitable in order to quantitatively forecast the impacts on the environment resulting from groundwater extraction while regarding sustainability aspects?

2. What data can be used in order to quantitatively analyse environmental impacts for certain geo- and eco-hydrological scenarios?

3. What output is relevant in order to analyse impacts and how should output be weighted, aggregated and ranked in order to build a scientific based scoring system?

1.3.3. DELIMITATION

As explained in paragraph 1.2: The ambition: quantify the impact, this research is part of a study in order to design a tool called WSD, for which the main goal is formulated as:

- *Initiate a scientific based and (inter)national accepted MCDA which could underpin DWC-managers with information about the sustainability impacts resulting from strategic decision making.*

The components "Water source" and "Surroundings of the water extraction" (figure 3), will be interconnected in this report. The conceptual model in figure 4 depicts the boundary conditions of this analysis. Findings of other studies will be used in order to build a quick scanning GENIAT.

This research will not examine possible mitigating or adapting measures for instance against desiccation[1] or eco-hydrological[2] implications. Also, this research will not study correlations between hydrology and ecological value, biodiversity or eco-toxicity. The study does not quantify the impacts on the environment due to energy use by high pressure pumps, nor will it assess the (change in) chemical groundwater quality, nor the impact of damaged clay layers as a result of drilling activities.

For now, this study will focus on the Dutch situation. Subsequent studies might attempt to create an internationally applicable and accepted GENIAT. The overall analysis can eventually be used to identify rules of thumb that could easily be applied when approximating the environmental damage of a (new) groundwater extraction in a quantitative way.

1.4. THESIS OUTLINE

In this thesis is explained how insight is obtained in order to forecast and score the impacts on the environment resulting from groundwater extraction. The research goal is set in paragraph 1.3. Chapter 2. explains the research phases and explains how the study aims to answer the research questions. Chapter 3. describes the used theoretical framework in order to initiate the GENIAT. Paragraph 3.1. to 3.3., present literature findings used to setup a conceptual framework and to guide the scoring system while regarding sustainability aspects. Paragraph 3.4., presents the literature findings which are used to forecast the environmental impacts resulting from groundwater extraction. Chapter 4. examines the results of the proposed GENIAT. Paragraph 4.1. briefly describes the setup of GENIAT. In paragraph 4.2., expectations based on expert judgement and literature are described. The identified expectations are used in order to validate the results of the sensitivity analysis, which is explained in paragraph 4.3. In paragraph 4.4., a case study is presented in which a groundwater extraction in Kamerik, the Netherland, is analysed by GENIAT. Chapter 5. discusses the research methodology and GENIATs setup in a discussion. In addition, recommendations are formulated.

[1] *In Dutch, environmental stress is known as 'verdroging'. The English term most frequently used is desiccation, but the term 'verdroging' is used within a broader interpretation, for instance, also including changes in (soil)water quality due to groundwater depletion (Van EK, 2000).*

[2] *A term to describe the understanding between hydrological processes with integrated ecological processes, as part of achieving sustainable water management as described by Zalewski et al. (2008).*

CHAPTER 2. RESEARCH METHODOLOGY

This chapter describes the phased plan used in the research trajectory. Figure 4 visualizes and briefly describes the different phases.

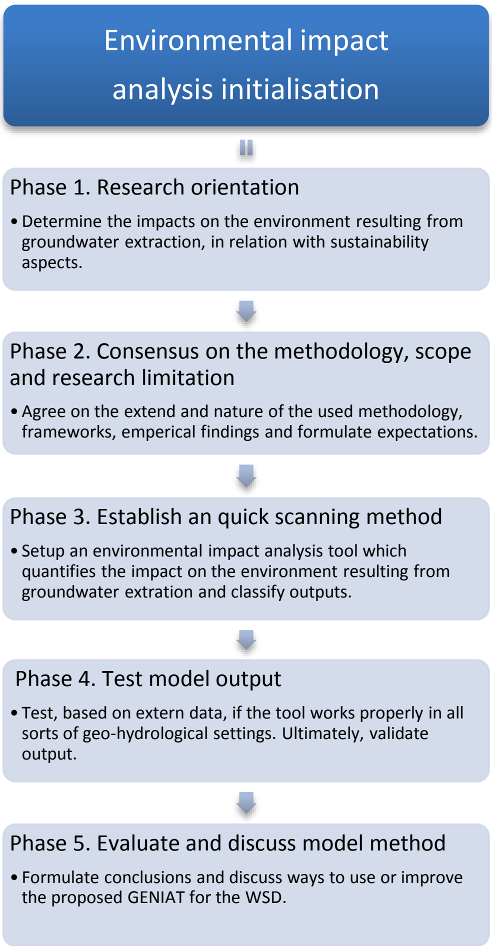

Figure 4 – Schematic overview of the research phases.

PHASE 1. ORIENTATION

Environmental aspects, which may change as a result of groundwater extraction, are identified by looking into area dossiers, EIAs, the REFLECT-methodology and by means of expert judgement. Consulted document are included in annex 5. Findings are depicted in the conceptual model in figure 6.

A guideline to determine which impacts are considered sustainable or unsustainable is used as framework for the proposed scoring system. This guideline is described in table 2. An iterative, conceptual thinking process will be conducted to identify relevant input variables and system parameters for the GENIAT. Input data must be easy accessible for most cases.

PHASE 2. SCOPE AND LIMITATION

Relations between groundwater extraction and geo-hydrological impacts may differ per type of groundwater source. In order to get a glimpse of which relations and parameters are significantly important for a certain geo-hydrological scenario, half-standardized interviews will be conducted with experts in the field of geo-hydrology and literature shall be consulted. In addition, existing models and findings in literature are used in order to approximate the impacts on the environment, resulting from groundwater extraction, in a practicable manner.

PHASE 3. ESTABLISH THE GENIAT

The findings of phase 1 and phase 2 will guide the setup of a quick scan meta-tool in Microsoft Office Excel. Microsoft Office Excel is chosen because it is easily accessible for third parties and is used internationally. Moreover, this software is flexible in data processing, which is needful in order to work with different kinds of data quality and quantity. The GENIAT must be easy adaptable, facile and must be based on proven and/or accepted science.

PHASE 4. MODEL VALIDATION

It is important to note that users of the model will incorporate a geo-hydrological scenario based on their chosen location for a groundwater extraction. Therefore, the GENIAT must be capable of dealing with all sorts of geological and hydrological scenarios. Adequate initial- and boundary conditions will need to define the model setup. The GENIAT will be validated by means of parameterization, model tests, expert judgement and by conducting a case study for the location 'Kamerik' with extern data in order to check whether the model deals adequately with input and midpoint results.

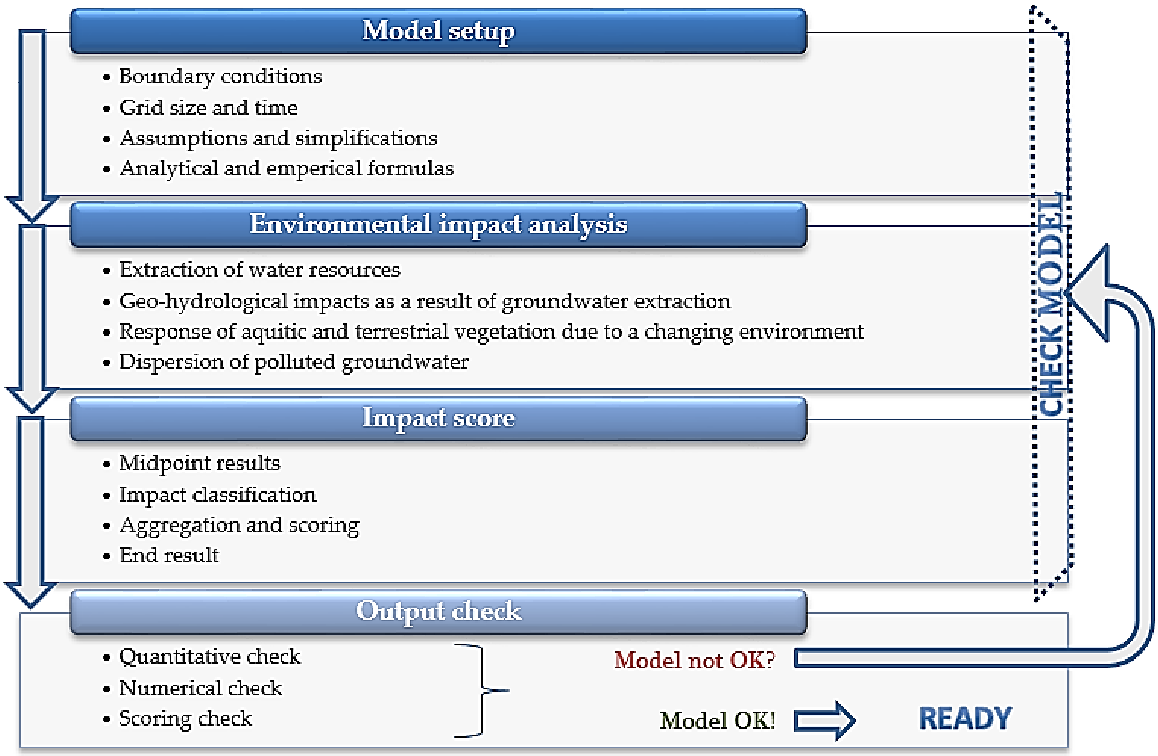

Figure 5 – The GENIAT setup and checking method.

PHASE 5. EVALUATION

The GENIAT processes midway outputs and aggregates these to impact categories. Weighting, aggregation and scoring methods are discussed based on findings in literature. An iterative output check is conducted as visualized in figure 5. Model outputs will be checked by means of expert judgement, a sensitivity analysis and to some extend by comparing related findings in literature. The main findings of this research will answer the main research question which is formulated as:

- **How to quantify the impacts on the environment resulting from groundwater extraction by means of a quick scanning tool for the Water Sustainability Diagram based on sound scientific based information?**

HYPOTHESIS

A hypothesis is that there will be sufficient knowledge accessible and practicable in order to forecast environmental impacts resulting from groundwater extraction. However, not all relevant changes in the environment can be quantified for instance due to gaps in knowledge.

A challenge will be to score and aggregate the quantitative output, without subjectivity, into an underpinned sustainability score. The sustainability score must be valid in order to serve as input for the WSD, which strives to be scientific based and must be (inter)national accepted by decision makers.

CHAPTER 3. THEORETICAL FRAMEWORK

Figure D in annex 5 describes the process method used as outline for the theoretical framework. This chapter describes examined methods and underpins choices for the setup of GENIAT by referring to the findings in literature. A conceptual model visualizes the relationship between potentially impacted environmental aspects. It will be explained which impacts on the environmental resulting from groundwater extraction are considered (un)sustainable. Findings of other studies have been used to forecast the quantitative impact. A meta assessment is proposed, in which the impacts of geo-hydrological changes on the environment and vice versa are interconnected and in which extern data is importable.

3.1. IMPACT ANALYSIS

There is a variety of methodology to analyse impacts or to assess the degree of environmental impacts of a product or process. In addition, there is a variety of ways to aggregate numerical output to impact categories. Moreover, it is possible to combine all sorts of methods in a hybrid meta assessment (Chen, Ngo, & Guo, 2012). Table 1 shows identified methodologies which may be used as main framework for the GENIAT.

Table 1 – List of identified methods which potentially can be used to assess environmental impacts and/or aggregate scores.

A world of methods		
Analytical Hierarchy Process	Geometric mean	ReCiPe
Arithmetic mean	Groundwater Sustainability Infrastructure Index	Risk Assessment
Cost-benefit analysis	Harmonic mean	Sustainable development indicators
Canadian Watershed Sustainability Index	Input Output Analysis	Sustainability Index for Integrated Urban Water Management
Dow Jones Sustainability Index	Life Cycle Analysis	TELOS Todo
Environmental Footprint	Material Flow Analysis	Waterfootprint
Environmental Impact Assessment	Preference Ranking Organization Method for Enrichment Evaluation	Watershed Sustainability Index

The GENIAT must determine the impact on the environment (i) in a quantitative manner, (ii) possibly for non-existing extractions, (iii) within a limited timeframe (iv) bases on low quality data. Previous studies which quantify the impact on the environmental resulting from changing flow regimes state that it is useful to combine hydrology with ecology and land use in an interdisciplinary analysis (Batelaan et al., 2003; Poff & Zimmerman, 2010; Van Ek et al., 2014). The term impact analysis is often used. There is no clear set up for a certain impact analysis on the environment: the framework for an *Environmental Impact Analysis* (EIA) is based upon the research findings and research constraints (Glasson, Therivel, & Chadwick, 2013; Wathern, 2013). In case of using an inventory data concerning characterization factors and flow paths, one may speak about a *Life Cycle (Impact) Assessment (LCIA)* (Bayer et al., 2009; Zelm et al., 2010). The EIA and LCIA are widely accepted methods to study environmental impacts.

Due to the criteria: (ii) possibly for non-existing extractions, it is not possible to include an inventory data. Moreover, other identified methodologies in table 1 do not fully comply with research criteria (i) (ii) (iii) & (iv), mostly due to their dependence on inventory data or needed timeframe. Therefore, it is chosen to initiate an impact analysis, referred to as EIA. The used EIA framework for GENIAT is based on literature findings which are in consensus with preconditions. The framework is depicted in paragraph 3.2. Conceptual model.

Which aggregation method is used, is underpinned in paragraph 4.1.6. Sustainability scoring system.

3.2. CONCEPTUAL MODEL

The quantitative modelling in the GENIAT requires a system analysis based on a synopsis of the affected environment with in addition an impact forecast (Canter, 1996). For the environmental synopsis, a set of interdisciplinary aspects that are possibly affected must be identified (Royal Haskoning, 2004), to then forecast the impacts resulting from groundwater extraction. Consulted documents used in order to identify affected environmental aspects are listed in annex 5. Changing environmental aspects are included in the conceptual model in figure 6. The GENIAT uses the conceptual model as framework for the quantitative modelling. The framework includes an environmental synopsis and an identification of relevant environmental changes due to groundwater extraction. The tools and figures used for the impact forecast is described in paragraph 3.4. Impact forecast. First is described which environmental changes are considered unsustainable, in paragraph 3.3. Sustainability guideline.

CONCEPTUAL MODEL

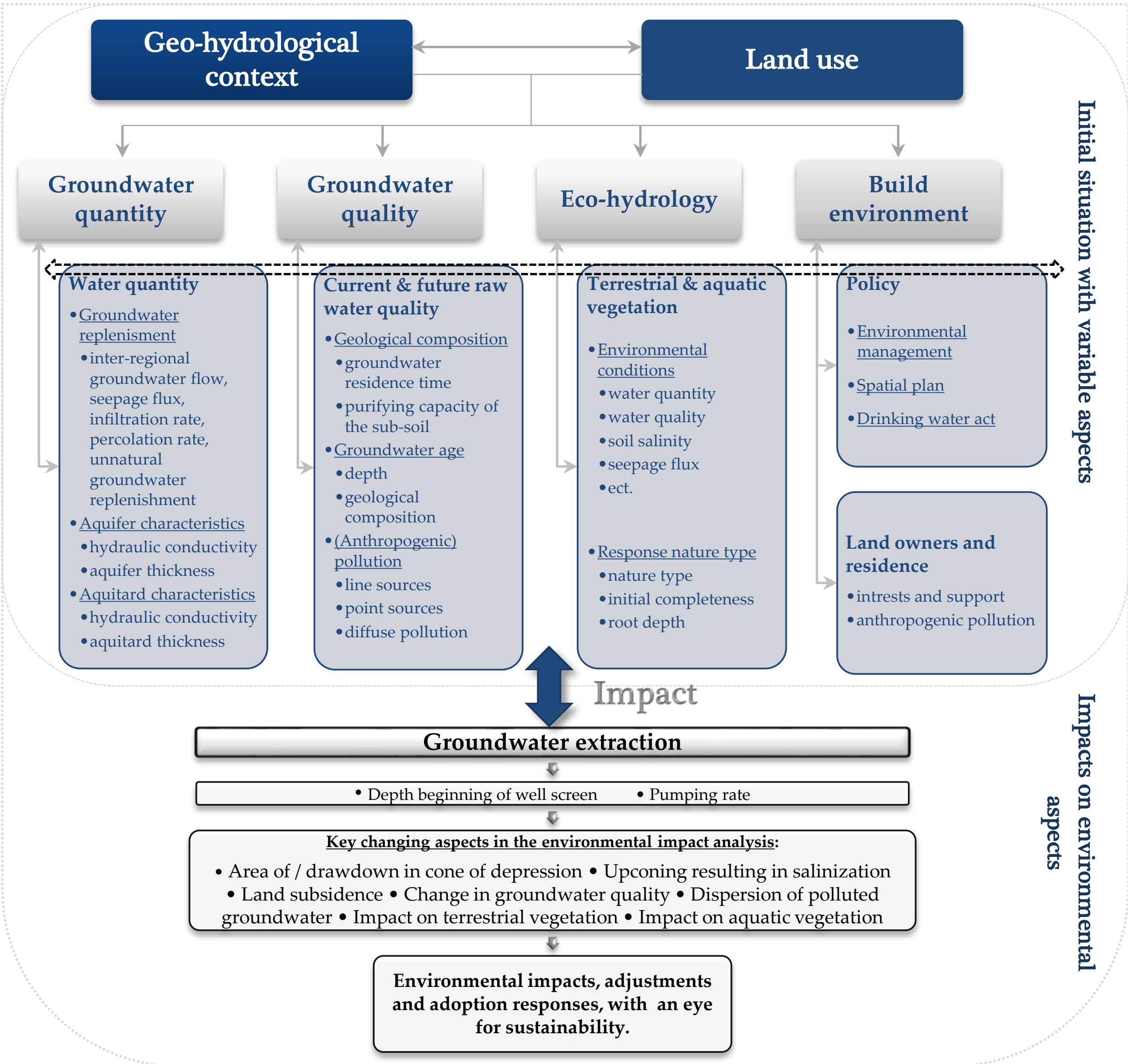

Figure 6 – Relations between groundwater extraction and the environment, visualized in a conceptual model which serves as the framework for the GENIAT. In addition, the conceptual model provides boundary conditions for the overall research. This framework is based upon the mind-set of the egalitarian worldview, described in annex 2.

3.3. SUSTAINABILITY GUIDELINE

Royal Haskoning (2004) performed an environmental impact assessment for several case studies in order to allocate a groundwater extraction in a sustainable manner. The results of this assessment are based on the findings of the BDIV-study[3] and previous studies of *RIVM (Rijksinstituut voor Volksgezondheid en Milieu)* and Hydron N.V (Beugelink et al., 1992; Van Dijk, & Schulting, 1994; Royal Haskoning, 2004). Their EIA framework describes which impacts on the environment resulting from groundwater extraction are considered sustainable or unsustainable. The EIA framework of Royal Haskoning (2004) will serve as guideline for the sustainability scoring system in the GENIAT. In addition, other documents have been consulted (including the list in annex 5) in order to complete the guideline. Common environmental changes are briefly mentioned in table 2 and are categorized in sustainable or unsustainable. A remark on the description in table 2 is that environmental changes may vary in certain geo-hydrological scenarios.

Table 2 – Guideline of which impacts, resulting from groundwater extraction, are mainly considered sustainable or unsustainable **(Industriewatervoorziening, 1993; Foster & Chilton, 2003; Royal Haskoning, 2004; Ponce, 2006; Boers et al., 2014)**.

Unsustainable impact	Explanation	Sustainable impact	Explanation
Desiccation (e.g. due to the cone of depression).	Decrease in water resources. In addition, there is a correlation with a decline in base flow and in physical- and chemical surface water quality.	-	-
Upconing of the saline water interface.	Decreases the quantity of fresh water resources.	Extracting deep saline groundwater.	The quantity of fresh water resources does not decrease and downconing may occur.
Land subsidence.	Subsidence is an irreversible impact which may damage utility facilities and private property.	-	-
Changing (ground)water quality.	Spreading of anthropogenic diffuse pollution due to an increase in groundwater flow. May cause stress on fauna and flora.	-	-
Extraction of old and fresh groundwater.	Ancient fresh groundwater resources are considered non-renewable.	Extraction of young and polluted groundwater.	Young groundwater is considered renewable. Extracting polluted water may lead to an overall better (ground)water quality.
Negative impacts on terrestrial vegetation.	Stress on phreatophytic vegetation due to eco-hydrological implications.	-	-
Negative impacts on aquatic vegetation.	Decline in upward seepage flux and base flow may negatively affect aquatic vegetation types.	-	-

[3] *The BDIV-study (Beleidsplan Drink- en Industriewatervoorziening) is initiated by the Dutch ministry of Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. This policy document stems from a large-scale investigation and is in the Netherlands appointed as Planologische Kern Beslissing (Key Planning Decision) (Beugelink, Claessen, & Mulschlegel, 1992; Industriewatervoorziening, 1993).*

3.4. IMPACT FORECAST

A short description of findings by other studies, which are used for the impact forecast in GENIAT, are described for relevant changing aspect in the environment, as identified in table 2.

3.4.1. GROUNDWATER QUANTITY AND QUALITY

Analytical formulas are used in order to set up a synopsis of the environment and to forecast the impacts of groundwater extraction on geo-hydrological aspects. The used formulas are:

- initial groundwater level variation by Wesseling & Wesseling (1984), Braunsfurth & Schneider (2008) or Bear (2012);
- drawdown due to groundwater extraction by Theis (1935) or Verruijt (1970);
- change in seepage flux by Wesseling & Wesseling (1984) or Darcy's Law (Whitaker, 1986);
- land subsidence due to a decrease in pore pressure by Therzagi (1925);
- land subsidence due to peat oxidation by Hoogland, Van Den Akker, & Brus (2012).

Analytical formulas are used in order to forecast the impacts of groundwater extraction on variables that correlate with raw water properties. The used formulas are:

- upconing of the saline water interface due to groundwater extraction by Dagan & Bear (1968);
- change in seepage flux by Wesseling & Wesseling (1984) or Darcy's Law (Whitaker, 1986);
- groundwater traveling time by De Vries (1974) and Chapuis & Chesnaux (2006);
- age of groundwater as a function of depth by Meinardi (1994).

Formulas are further described in annex 6. Groundwater extraction will not lead to a decrease of purification capacity of the subsoil (Boers et al., 2014). This sub-aspect is therefore not quantified.
Seepage flux reaching ground level and precipitation lens height correlate with precipitation surplus/deficit. Moreover, groundwater extraction correlates with the precipitation lens height. These theoretical findings are not quantitatively incorporated in GENIAT, due to the lack of accessible and practicable forecasting methods (Kemmers, Delft, & Gaast, 2005; Hoogland, Kemmers, & Hunink, 2010).

The used analytical formulas in order to assess groundwater quality and quantity are valid under a certain set of assumptions (e.g. the DePuit-assumption) and boundary conditions (e.g. fully penetrating well screen) (Theis, 1935; Verruijt, 1970). Important assumptions are listed in annex 6. A note is that the GENIAT must deal adequately with a variety of boundary conditions. In addition, the model input must comply with assumptions made in the formula derivation (annex 6). Using analytical formulas is a scientific based and practicable method to approximate the geo-hydrological impact. Microsoft Office Excel is capable of handling numerical solutions in different geo-hydrological settings.

A possible pitfall of analysing geo-hydrological scenarios is combinatorial explosiveness, which states an exponential increase in scenarios when assessing system with many degrees of freedom (Vink, 2006). Indeed, the GENIATs environmental synopsis has many degrees of freedom. Moreover, necessary simplifications in order to adequately use analytical formulas may threaten the validity of the GENIATs output. Therefore, it is chosen to extent the GENIAT with the ability to incorporate output data of hydrological models, such as MODFLOW, SOBEK or TRIWACO, in order to strengthen the overall analysis. Data from extern hydrological tools is referred to as 'extern data'. In case of using extern data, combinatorial explosiveness becomes less of a concern. In case there is a shortcoming in geo-hydrological information, the GENIAT may use its internal geo-hydrological model in order to approximate the geo-hydrological impacts resulting from groundwater extraction.

3.4.2. ECO-HYDROLOGY: TERRESTRIAL VEGETATION COMPLETENESS

Dose Effect Model NAture Terrestrial (DEMNAT) is an eco-hydrological analysis tool which is used to analyse the effect of different scenarios, resulting from to water management strategies and land-use functions, on terrestrial vegetation types (Witte et al., 1993; Van Ek et al., 1996a; Van Ek et al., 1996b; Witte, 1998). Eco-hydrological changes as function of the soil characteristics and vegetation types (figure 7) are expressed by dose-effect functions. These functions describe changes of terrestrial vegetation for a period of 10 to 20 years based on empirical data and expert knowledge. (Runhaar, Witte, & Verburg, 1997; Van Ek et al., 2000; Tamis et al., 2000). Dose-effect functions, integrated in DEMNAT 2.1 and 3.0 (released in 1996 and 2000), are published in Van Ek & Bos (1997) and Van Ek et al. (2000). An example of a dose-effect function is illustrated in figure 8. Additional used dose-effect functions in the GENIAT are included in annex 7. The framework used by DEMNAT is described by Runhaar et al. (1996), but not used in this study due to the research constraints set in figure 6.

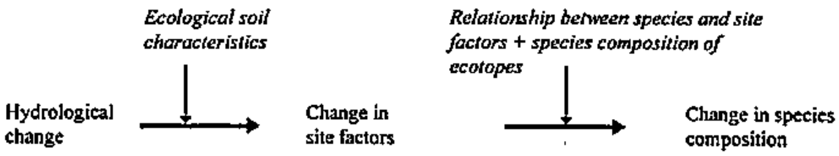

Figure 7 – Cause effect change as modelled by DEMNAT **(Van Ek et al., 2000)**.

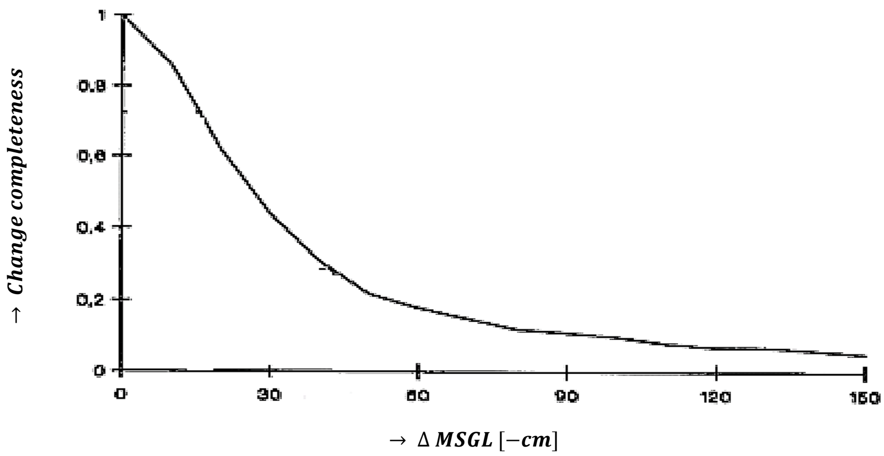

Figure 8 – Dose effect functions which describe the empirical relationship between lowering *Mean Spring Groundwater Levels (MSGL)* and terrestrial nature completeness **(Van Ek et al., 2000)**.

Dose effect functions are practical in order to quantify the eco-hydrological impact on terrestrial vegetation types. Microsoft Office Excel is capable of determining the dose effect curves intersect related to the local hydrological changes. Although the latest publication originates from 2000, DEMNATs methodology is still being used and evaluated by the Dutch Delta Program (Van Ek et al., 2014; Prinsen, Weiland, & Ruijgh, 2015).

Other possible environmental forecasting systems for terrestrial vegetation completeness are:

- *PROBE* by *KWR Watercycle Research*, which assesses the implications of climate change on the successiveness of terrestrial vegetation. *PROBE2* is currently under construction (Witte et al., 2015);
- *Kansrijkdommodule Waternood* by *STOWA*, which determinates what types of vegetation can be developed at a site with a particular combination of soil, hydrology and management (De Haan, Runhaar, & Cirkel, 2011);
- *VSD(+) (Very Simple Dynamics)-model* by *Alterra Wageningen UR*, extended with relationships between nitrogen deposition and greenhouse gas emissions, on a European-wide scale, to predict the impact of nitrogen deposition on forest ecosystem services (De Vries, 2014).

The impact predictions in the listed environmental forecasting systems do not comply with the purpose of the GENIAT such as DEMNAT does. Therefore, the more practicable empirical data of DEMNAT is used in the GENIAT.

Environmental forecasting systems are often linked to geo-hydrological-, climatological-, chemical impact models and/or habitat distribution databases, thereby creating a more integral meta-analysis module (Van Ek et al., 2014). This idea will be elaborated in a simplistic manner in the GENIAT, by integrating the geo-hydrological impact model directly related with the impact analysis on terrestrial and aquatic vegetation, and on other environmental aspects described in table 2.

3.4.3. ECO-HYDROLOGY: TERRESTRIAL VEGETATION BIODIVERSITY

Bayer et al. (2009) argues how the LCIA, which is the standardized method for determining the environmental impact of a product or service, should be incorporated in water resource management. More sustainable groundwater resource management is the result when integrating hydrologically-based impacts from human interaction with aquifers by means on the LCIA. There are several LCIA-publication which describes the findings of environmental changes due to a change in groundwater regimes, for instance the LCIA study of Van Ek et al. (2002) and I Canals et al. (2009). LCIA findings will be incorporated in the GENIAT as described below.

The GENIAT incorporates the findings a study by Zelm et al. (2010). In their study, LCIA was used to identify the effect of groundwater extraction on a decrease of species richness in the Netherlands. Their findings suggested a maximum of 8,5% loss of plant species for each decimetre of drawdown inflicted by a groundwater extraction in case the MSGL is higher than 1,25 meter below surface. If groundwater regimes are deeper than 1,25 meter, findings suggest a 9,2% decrease of plant species richness due to each inflicted decimetre of drawdown. Runhaar et al. (1997) also found a linear relationship between groundwater extraction and loss of biodiversity, suggesting a maximum of 13,5 % decrease in species richness due to each inflicted decimetre of drawdown. However, the findings of Runhaar et al. (1997) and Zelm et al. (2010) which may forecast quantitative values of biodiversity loss are not used to analyse impacts while these studies suggests a linear relationship. However, it is argued that nature response is often nonlinear due to environmental complexity caused by (Vink, 2006):

- dose-response relations – nonlinear relations between physical- & chemical conditions and ecological processes;
- discontinuity – occurrence of sudden leaps in impact functions, like species mortality;
- interdependency – response of a variable which is linked to the present state of other variables or processes;
- feedback loops – small errors or differences in initial variables may lead to large errors in predicted states.

In addition, Michelsen & Lindner (2015) conclude from a literature review on LCIA-studies that it is unlikely that all aspects of biodiversity can be included in a single indicator, due to the low tangibility level of biodiversity. Instead, the findings to forecast the quantitative change in biodiversity are used to give an extra dimension to the impact on eco-hydrology by using the forecasted change in biodiversity as a weight factor in the analysis.

3.4.4. ECO-HYDROLOGY: AQUATIC VEGETATION

The growth response of submerged aquatic vegetation correlates with nutrient level and therefore with seepage fluxes (Graillot et al., 2014). A study by Frandsen et al. (2012) showed that there was no growth response in case of downward seepage flux (percolation) for *Littorella uniflora* and *Myriophyllum alterniflorum,* which are two fully submerged macrophytes. In addition, final plant mass was on average 70% higher in case of upward seepage fluxes. Royal Haskoning (2004) assumed that a decrease in initial seepage flux of 10% could potentially harm aquatic plant life and predicted aquatic vegetation damage by means of expert judgement based on this figure. The findings of Lange (2001) are useful to quantify the discharge flux of seepage rich groundwater into surface water.

In addition, aquatic vegetation completeness also correlates with base flow discharges rates (Frandsen et al., 2012). Kennen, Riskin, & Charles (2014) determined a flow-ecology response, relating the mean annual flow and aquatic vegetation. The study found a base flow decrease of 0.1 to 0.6 $[\mathrm{m^3 s^{-1}}]$ due to groundwater extraction and related this figure to an ecological response. Though, these findings could not be incorporated in the overall study due to limitation of hydrological modelling as surface base flow rates in ditches and rivers are not quantified within the GENIAT.

3.4.5. BUILD ENVIRONMENT

So called 'gebiedsdossiers', from now called: area dossiers, are information documents drafted by involved governmental institutes. These documents contribute to the understanding of (ground)water quality and geo-hydrology, regarded within several defined water protection zones (Wuijts, 2007). The REFLECT-methodology is used in area dossiers to qualify the degree of anthropogenic and natural diffuse pollutions as a function of land use and groundwater vulnerability. The REFLECT-score relative to a certain land use is decided by means of a DELPHI-study and a panel of experts. Three sub-scores of the REFLECT-score are (Laeven et al., 1999; Van den Brink et al., 2013):

- diffuse pollution load, which;
- risk of calamities;
- enforceability of policy.

EXPLANATION

For the input of the GENIAT, the findings of Van den Brink et al. (2013) are used in order to assess the diffuse pollution load corresponding to a certain land use. Dispersion of polluted groundwater increases due to groundwater extraction in case when pumping capacities are sufficient (Park et al., 2014).
An approximation is made of the qualitative degree of polluted groundwater dispersion by assessing:

- the degree of historic and local diffuse pollution load;
- the area in which diffuse pollution is being dispersed based on the water divide;
- local specific discharge.

Diffuse load scores are used to assess the effect that groundwater extraction has on polluted groundwater dispersion. This method is not based on literature findings but may prove insightful for the overall analysis. It is assumed that the diffuse pollution load, corresponding to the land functions in a strategically chosen groundwater extraction, correlate with local water, spatial and environmental policy.

JUSTIFICATION

In this simplified approximation, pollutants streamlines, the effects of biodegradation, retardation, diffusion, advection, sorption and other aspects influencing the breakthrough curves are left out of the analysis. This delimitation is set due to the complex effect of the vadose zone, the non-quantifiable effect of the purifying capacity of the subsoil, the need for a transient transport model and the variety in chemical compositions and reactions (Jamin et al., 2012; Kourakos, 2012). A large data set and large computational resources are needed if one wants to include a more complex approximation of the impacts of diffuse pollution resulting from land functions, like is done by Kourakos (2012). This does not fit within the preconditions determined by Oasen N.V, as described in paragraph 1.3. Goal and research question. Therefore, the more simplified method is being used to approximate the impact of groundwater extraction on dispersion of polluted groundwater.
The impacts of groundwater extraction on the interests and support of local land owners, and also the impacts of policy restrictions which may be enforced in groundwater protection zones, are not included in the EIA of the GENIAT, as is described in paragraph 3.2. Conceptual model. This delimitation arises due to the non-existence of quantifying frameworks nor empirical data.

AGRO-HYDROLOGY

The agro-hydrological impacts resulting from e.g. desiccation will not be quantified. The *Soil-Water-Atmosphere-Plant* (SWAP) module is an impact analysis tool capable of predicting the agro-hydrological on production yield (Bartholomeus, 2013). The SWAP-module uses the 'HELP-tabellen', based on empirical data from 1987, revisited in 2005 (Xie, 2013). The empirical data of HELP-tabellen coincides with the empirical data from DEMNAT. Only, the HELP-tabellen are focussing on individual crop types. It is chosen to use the empirical data of DEMNAT in order to forecast the decrease of agricultural crops/plant completeness, in order to avoid combinatorial explosiveness and due to time constraints. Therefore, agro-hydrological impact is integrated in the term 'terrestrial vegetation completeness'.

3.5. CONCLUSION THEORETICAL FRAMEWORK

Findings in literature are useful to quantitatively approximate and classify impacts resulting from groundwater extraction in consensus with preconditions set in paragraph 1.3. Goal and research question. However, not all identified aspects identified in the conceptual model can be quantified due to delimitation and gaps in knowledge. Various subjects are excluded from the impact analysis due to the absence of quantitative forecasting methods and/or empirical data. Some excluded subject have been explained in paragraph 3.4. Impact forecast. Other non-quantifiable subject are identified in a literature review by Poff & Zimmerman (2010)* or in the documents listed in annex 5. The excluded subject are:

- impact on primary production*;
- impact on (sub-soil) fauna population*;
- impact on infiltration capacities due changes in vegetation composition*;
- impact on and of the precipitation lens;
- impact of policy restrictions;
- soil acidification and eutrophication;
- geological context of the supply area.

It is chosen not to incorporate expert judgement in order to estimate the impacts on the environment based upon the findings of Rogut & Piasecki (2011). By involving expert judgement, agreement must be required on for instance: How to find suitable experts? How to balance the opinions of different experts and combine them? etc. Moreover, it may be very hard even for an expert forecast the future in a system with many degrees of freedom (Witte et al., 2015). It is however chosen to incorporate forecasts based on frameworks originating from expert judgement in case of existing consensus on the methodology and data. For instance, the qualitative data of the REFLECT-methodology, provided by means on a DELPHI-study, is overall proved as insightful and is widely used in area dossiers (Van den Brink et al., 2013). The proposed method to qualitatively determine the dispersion of diffuse pollution loads may therefore add value to the overall analysis.

Table 3 summarizes the forecasted changes of the environment resulting from groundwater extraction. Environmental changes are then expressed by a certain numerical output, referred to as midpoint results. Suggested midpoint results may be referred to as indicators that regard environmental sustainability in a quantitative or qualitative way (Moldan et al., 2012). The forecast analysis will be based upon midpoint results.

Table 3 – Summarized description of the used findings in order to forecast environmental impacts and a description of the mid-point results following from the approximated impact.

Local changes are forecasted by analysing	Midpoint result
• Initial groundwater level variation • Drawdown due to groundwater extraction	• Area impacted by cone of depression [km²] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]
• Upconing of the saline water interface due to groundwater extraction	• Volume of water affected by upconing saline interface [km³]
• Change in seepage flux due to lowering of piezometric levels	• Change in seepage flux [mm/d]
• Land subsidence as a result of drawdown and geological context • Land subsidence due to peat oxidation	• Area impacted by subsidence [km²] • Average level of subsidence [m] • Maximum level of subsidence [m]
• Terrestrial vegetation responses as described by dose effect function • Decrease of species richness	• Decline in terrestrial vegetation completeness [%] in combination with a weighting factor
• Age of groundwater as a function of depth • Groundwater traveling time • Diffuse pollution load as qualified by the REFLECT-methodology	• Normative age of raw water [y] • Salinity of raw water [saline/brackish/fresh] • Degree of raw water pollution [REFLECT]/[%]
• Diffuse pollution load as qualified by the REFLECT-methodology • Location of the water divide • Specific discharge	• Qualitative dispersion of pollution [-]

CHAPTER 4. RESULTS

The GENIAT has been initiated in consensus with the preconditions set in 1.3. Goal and research questions, and based on the findings in chapter 3. Theoretical framework. Chapter 4. describes and examines the midway and end results of the GENIAT. Expertise of geo-hydrologist is used in order to identify and score expected impact per 'type' of groundwater extraction. The results of the sensitivity analysis are shown and compared with expectation. Last, a case study is performed to check the performance of GENIAT in case extern geo-hydrological data is used. First, the setup of GENIAT is described.

4.1. GENIAT SETUP DESCRIPTION

This paragraph describes the setup of the GENIAT. An important note is that the analysis requires a synopsis of the initial situation in order to assess the state of geo- and eco-hydrological aspects. States are considered spatially homogenous. Helpful for the synopsis are interactive open-source maps or atlases, like from Breure et al. (2014). (http://www.atlasnatuurlijkkapitaal.nl/kaarten)

In the forecasted situation, a groundwater extraction pump is introduced with a location, well screen depth and pumping rate. In this forecasted situation, environmental impacts are quantified by means of the findings presented in the literature framework, described in paragraph 3.4. Impact forecast. As also mentioned in this paragraph, GENIAT conducts an interdisciplinary meta-analysis, wherein first (i) the change in hydrology, then (ii) the change in geology, then (iii) raw water properties, stress on vegetation types and dispersion are forecasted.

4.1.1. GEO-HYDROLOGICAL ANALYSIS

INITIAL SITUATION

In order to set up a synopsis of the initial situation, geo-hydrological data is entered by the user for a single relevant cross section. The porous medium in this section is assessed as homogenous and isotropic. The yearly average precipitation surplus or deficit is considered for each scenario. Groundwater mound (opbolling) between ditches is calculated as well as other hydrological conditions in steady state. The user may choose to incorporate geo-hydrological data from for instance MODFLOW in order to set up the synopsis. A visualization of an initial scenario is included in annex 8, figure S in which a situation without groundwater extraction is depicted. The visualization is drawn by the GENIAT for the user to see whether model input is realistic and accurate.

IMPACT FORECAST

The degree of drawdown is calculated with the analytical formula of Theis (1935) or Verruijt (1970), depending on the geo-hydrological setting and pumping depth. The model calculations are performed on gridlines in the cross section. The distance between gridlines is determined by dividing the distance between the boundary conditions by 200, thus forming 200 gridlines in total. The geo-hydrological changes are calculated on each gridline. The user may choice to incorporate geo-hydrological data from for instance MODFLOW in order to set up a synopsis of the new situation. A visualization of a scenario with forecasted impacts resulting from groundwater extraction, is included in annex 8, figure T.

The following geo-hydrological changes are expected and forecasted:

- change in piezometric levels;
- change in seepage flux;
- change in quantity of fresh water resources due to upconing or downconing ;
- a degree of subsidence due to soil consolidation and possibly peat oxidation.

Based upon the findings in table 2, a scoring system is proposed in which:

- none or no significant impact is classified as sustainable and is set as a best case scenario;
- the more severe the impact, the less sustainable;
- the most extreme impact is classified as unsustainable and is set as a worst case scenario.

A note is that any degree of downconing is classified as a sustainable impact.

MULTILAYER FORMULAS

It is deliberately chosen not to use multilayer formulas in GENIAT due to the limited timeframe of the study. Multilayer formulas are useful to assess the change in piezometric levels as a result of groundwater extraction beneath various confining layers. This delimitation makes is necessary to work with input from other hydrological models.

In case there is no data available concerning the hydrological situation, but there is knowledge about the geological composition of the area, GENIAT is able to estimate the lowering of piezometric surface in case of deep groundwater extraction. The method used to approximate phreatic drawdown is explained in annex 6.2.

4.1.2. RAW WATER ANALYSIS

The properties of raw water are only determined for the situation with drawdown. Raw water properties are estimated by forecasting the:

- raw water salinity, subdivided in saline, brackish or fresh;
- age of groundwater as the result of travel times;
- the degree of raw water pollution, based on the diffuse pollution score and travel time.

Based upon the findings in table 2, a scoring system is proposed in which:

- the more saline the water, the more sustainable;
- the younger the water, the more sustainable;
- the more polluted the raw water, the more sustainable.

4.1.3. ECO-HYDROLOGICAL ANALYSIS: TERRESTRIAL VEGETATION

INITIAL SITUATION

In order to set up a synopsis of the initial terrestrial vegetation, nature type, location, normative root depth, MSGL, vegetation replaceability and other eco-hydrological states are entered in the GENIAT. Replaceability takes accounts for the needed development time in order for terrestrial vegetation types to reach completeness. This is entered in the GENIAT in accordance to the findings and indices of COMPENSATIEBEGINSEL & EHS (n.d.).

Initial terrestrial vegetation completeness is calculated by means of the corresponding dose effect functions, as depicted in annex 7, figure M and O (Runhaar & Van Ek, 1996). The initial vegetation completeness is expressed in percentage relative to full completeness.

IMPACT FORECAST

The following geo-hydrological changes may lead to implication for phreatophytic vegetation:

- decline in MSGL;
    - a linear relation is assumed between the phreatic drawdown and a change in MSGL;
    - a differentiation is made between ‘moisture to wet’ dependent vegetation and ‘dry to moisture’ dependent vegetation (Runhaar & Van Ek, 1996);
    - a differentiation is made of the response of phreatophytic vegetation based on regional geographic context. It is found by Runhaar & Van Ek (1996) that vegetation response on a high hill is different than nature response in a deep polder as depicted in annex 7, figure P & Q;
    - a differentiation is made between soil characteristics, in order to take capillary forces into account;
- decline in seepage flux in case of seepage dependent vegetation;
    - a differentiation is made between vegetation dependent on seepage fluxes and vegetation not dependent on seepage fluxes;
    - It is not determined whether seepage fluxes reach the root zone in the new situation due to the seasonal variability of rainwater lenses and seepages fluxes as mentioned in paragraph 3.4.1. Groundwater quantity and quality;
- freshening in case of saline seepage dependent vegetation.

The impact of soil acidification is not incorporated in the impact forecast, as explained in paragraph 3.2. Conceptual model, in order to avoid combinatorial explosiveness.

New terrestrial vegetation completeness is deterministically calculated by multiplying initial vegetation completeness with factors determined by the dose effect function. This forecasted terrestrial completeness is expressed in percentages. Vegetation response is calculated on each gridline. An example of a calculation on a single gridline is presented in box 1. In addition, the results of completeness are aggregated with the impact on biodiversity, as is assessed by using the findings of Zelm et al. (2010).

INITIAL VEGETATION COMPLETENESS = 80 [%]

VEGETATION RESPONSE BASED ON A DECLINE IN MSGL = 0.6
VEGETATION RESPONSE BASED ON A CHANGE IN SEEPAGE FLUX = 0.4
VEGETATION RESPONSE BASED ON FRESHENING = 1

NEW VEGETATION COMPLETENESS IS:
$80\,[\%] * 0.6 * 0.4 * 1 = 19{,}2\,[\%]$,
WHICH IMPLIES A INTRINSIC CHANGE OF 76 [%]

THIS CHANGE IN PERCENTAGE WILL BE AGGREGATED WITH THE INFLUENCE ON BIODIVERSITY.

INFLUENCE ON BIODIVERSITY IS VERY HIGH

CONCLUSION: INFLUENCE ON TERRESTRIAL VEGETATION IS CONSIDERED AS **VERY HIGH**

Box 1

The impacts of groundwater extraction on terrestrial vegetation biodiversity and completeness are assessed in a scoring system, which is as follows:

- change between 80% and 100 % = 0
- change between 60% and 80 % = 1
- change between 40% and 60 % = 2
- change between 20% and 40 % = 3
- change between 10% and 20 % = 4
- change between 0 and 10 % = 5

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or no negative influence.

4.1.4. ECO-HYDROLOGICAL ANALYSIS: AQUITIC VEGETATION

INITIAL SITUATION

Initial aquatic vegetation completeness is not assessed due to the absence of dose effect functions or other methods which could quantitatively determine the initial status. Dose effect relations are currently studied and determined by for instance by Hoop et al. (2015).

IMPACT FORECAST

Due to the high correlation between seepage flux and aquatic vegetation completeness, as mentioned in paragraph 3.4.4. Eco-hydrology: aquatic vegetation, a scoring system is proposed based on the findings presented in table 2. In this scoring system, the following is assumed:

- increase in seepage flux is considered sustainable;
- non-changing seepage flux is not considered in the scoring system;
- decrease of seepage flux is considered unsustainable.

No scoring system is proposed for a change in the salinity of upward seepage flux.

4.1.5. BUILD ENVIRONMENT ANALYSIS

The assessment in order to qualitatively forecast the dispersion of polluted groundwater is described in paragraph 3.4.5. Build environment. The used methodology is briefly explained below.

The diffuse pollution load, representative to a certain land function, is entered in GENIAT based on the associated REFLECT-sub score. The dispersion of polluted groundwater is analysed in GENIAT by determining:

- the local degree of diffuse pollution;
- the area in which diffuse pollution is being dispersed based upon the location of the water divide;
- local specific discharge.

Based upon the findings in table 2, a scoring method is proposed in which:

- the more dispersion, in terms of subjected area and REFLECT-sub score, the less sustainable the impact is considered;
- the higher the REFLECT-sub score of diffuse pollution being pumped up by groundwater extraction within a certain timeframe, the more sustainable the impact is considered.

4.1.6. SUSTAINABILITY SCORING SYSTEM

The setup of the proposed sustainability ranking system is partly based on the scoring system of Chaves & Alipaz (2007) and Pandey et al. (2011). GENIATs quantitative impact forecast is considered a midpoint result. Midpoint results are aggregated to the related impact category as identified in table 2. The aggregation method is described below. Impact categories are referred to as:

- desiccation;
- salinization;
- subsidence;
- pollution;
- raw water properties;
- terrestrial vegetation;
- aquatic vegetation.

AGGREGATION

Three commonly used approaches useful to aggregate weighted numerical data are: the arithmetic mean (1.1), the harmonic mean (1.2) and the geometric mean (1.3) (Abramowitz & Stegun, 2006).

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i \qquad (1.1)$$

$$H = \frac{n}{\sum_{i=1}^{n} \frac{1}{a_i}} \qquad (1.2)$$

$$G = \sqrt[n]{\prod_{i=1}^{n} a_i} \qquad (1.3)$$

The arithmetic mean is best used when data is not skewed or interrelated. The harmonic mean is best used in case of a large uniform population with a few high outliners. The geometric mean is best used when data are interrelated (Matuszak, 2010). In addition, the geometric mean dampens the effect of high and low outliners (Tan, 2010). Both the arithmetic mean and the geometric mean will be used to aggregate midway and endpoint output in GENIAT, depending on the nature and uniformity of data. The harmonic mean will not be used GENIAT, because data do not consist of a large, uniform population.

Weights could be appointed to results, based on the statistically determined stress, in order to prioritize impacts. It is found that (i) reliability decreased due to subjective probability judgements when aggregating non-related issues, (ii) there are no significant benefits resulting from unequal weighting schemes and (iii) bias is avoided by using equal weights (Pandey et al., 2011; Bolger & Rowe, 2015). Therefore, it was chosen to equally weight results during aggregation.

INDICES

A scoring system is proposed, in which 'worst case scenarios' (0) and 'best case scenarios' (5) are identified for impact categories in GENIAT. A linear relation between worst case and best case is determined. The forecasted environmental impacts can be assigned, based on the linear relationship, to a score in the proposed scoring system which is as follows:

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

The score of each of the seven impact categories is determined in the scoring system, resulting in seven scores. These scores are then aggregated by means of the arithmetic mean in order to obtain an end result. This end result indicates the overall impact on the environment resulting from groundwater extraction, expressed in a number ranging from 0 to 5.

In paragraph 4.1. GENIAT setup description, is described which impacts on the environment are considered sustainable or unsustainable, based on the guideline explained in 3.3. Sustainability guideline. By using this guideline in GENIAT, a correlation is established between the impact environmental resulting from groundwater extraction and sustainability issues. Therefore, the outcome in the scoring system indicates the impact on sustainability aspects. It is states that an end results close to 5 indicates that the analysed groundwater extraction is sustainable. The lower the end result, the less sustainable the groundwater extraction.

Table 4 – Midpoint results, which are being aggregated to a single result based on an impact classification. Results of impact classifications are then aggregated to an end result, indicating the sustainability of groundwater extraction.

Midpoint result per variable	Impact category	End result
• Area impacted by cone of depression [km^2] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]	Desiccation Scored from 0 to 5	Scores of impact categories are aggregated by means of the arithmetic mean Expressed in a scoring system from 0 to 5 0 is considered unsustainable to 5 is considered sustainable
• Volume of water infected by upconing saline interface [km^3]	Salinization Scored from 0 to 5	
• Area impacted by subsidence [km^2] • Average level of subsidence [m] • Maximum level of subsidence [m]	Subsidence Scored from 0 to 5	
• Change in seepage flux, correlating with aquatic vegetation completeness [m/d]	Aquatic vegetation Scored from 0 to 5	
• Decline in terrestrial vegetation completeness [#]	Terrestrial vegetation Scored from 0 to 5	
• Normative age of raw water [y] • Salinity of raw water [saline/brackish/fresh] • Degree of raw water pollution [REFLECT]/[%]	Raw water Scored from 0 to 5	
• Qualitative dispersion of pollution [-]	Pollution Scored from 0 to 5	

4.2. FORECASTED IMPACTS: INTERVIEWS

Half-standardized interview have been conducted. Participants have knowledge in the field of geo-hydrology. The purpose of conducting interviews is to identify and assess geo-hydrological impacts resulting from groundwater extraction. The results of interviews have been completed with findings of the BDIV-study (Van Dijk, 1992; Van Dijk & Schulting, 1994), introduced in paragraph 3.3. Sustainability guideline. The results from conducted interviews, completed with findings from the BDIV, are summarized in table 5. The description in table 5 can be used in order to validate the results of the sensitivity analysis of GENIAT, described in paragraph 4.3. Sensitivity analysis.

Interviews were conducted with non-suggestiveness questions. Questioned was which environmental impacts of a certain 'type' of groundwater extraction are common and significant. Extraction types have been classified on their geo-hydrological setup. Distinguished types are: confined deep groundwater, confined riverbank filtration, confined shallow groundwater and phreatic groundwater (Beugelink, Claessen, & Mulschlegel, 1992; Royal Haskoning, 2004; Moel et al., 2006). All geo-hydrological settings are considered in steady state with uniform recharge, leaky aquitards and precipitation surpluses.

In addition, it was asked how participants would score the environmental influence arising from geo-hydrological changes due to the cone of depression. It was chosen not use a certain hydrological setting for this part of the analysis. Therefore, the estimated influence is general. The scoring systems is as follows:

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

What became apparent during the interviews is that, in spite of the classification and the predetermined boundaries conditions, there are still too many variables which complicate the overall assessment of geo-hydrological impacts (e.g. polder scenario, semi confined aquifers or perched water tables). Nevertheless, there is consensus about common geo-hydrological changes and partly in the scoring of estimated influence.
A note is that no distinction was made between saline or fresh groundwater in the BDIV-study (Van Dijk & Schulting, 1994). Also noted is that the current line of reasoning states that nature value increases in the ground water protection zone due to environmental regulation. This is not taken into account in the framework of GENIAT because the impact of policy restrictions are not quantifiable, as described in 3.4.5. Build environment.

As can be concluded from table 5, it is expected that extracting deep saline groundwater has the least influence on the environment. Fresh phreatic groundwater extraction results in a very high influenced environment. For comparison, deep groundwater was considered most sustainable in the BDIV-study. Also, phreatic groundwater was considered most unsustainable by the BDIV-study (Van Dijk & Schulting, 1994).

Scoring system

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

Table 5 – Results of the half-standardized interviews: Monique van de Aa, Johannes Lijzen, Arjen Roelandse & Harrie Timmer. Results are completed with findings of the BDIV-study **(Beugelink, Claessen, & Mulschlegel, 1992; Van Dijk, 1992; Van Dijk & Schulting, 1994)**.

Groundwater extraction type	Salinity	Significant geo- and eco-hydrological impacts due to the lowering of piezometric levels	Estimated environmental influence
Confined deep groundwater	Saline water	• Consolidation of the top soil • Change in seepage flux	• 5 • 3
	Fresh water	• Consolidation of the top soil • Upconing of saline water interface • Change in seepage flux • Exploitation of ancient non-renewable groundwater	• 5 • 3 • 3 • 1
Confined riverbank filtration	Saline water	• Change in seepage flux • Consolidation of the top soil	• 3 • 3
	Fresh water	• Environmental management regulations • Upconing of saline water interface • Change in seepage flux • Consolidation of the top soil	• 5 • 3 • 3 • 2
Confined shallow groundwater	Saline water	• Change in seepage flux • Consolidation of the top soil	• 3 • 0
	Fresh water	• Environmental management regulations • Upconing of saline water interface • Change in seepage flux • Exploitation of ancient non-renewable groundwater • Consolidation of the top soil	• 5 • 3 • 3 • 3 • 0
Phreatic groundwater	Saline water	• Environmental management regulations • Change in seepage flux • Consolidation of the top soil • Desiccation	• 5 • 3 • 1 • 0
	Fresh water	• Environmental management regulations • Upconing of saline water interface • Change in seepage flux • Consolidation of the top soil • Desiccation	• 5 • 3 • 3 • 1 • 0

4.3. SENSITIVITY ANALYSIS

The GENIAT is checked based on the description in chapter 3. Research methodology. Model results coincide with findings in literature and comply with the guideline presented in table 2. A sensitivity analysis has been conducted in GENIAT on a hypothetical and typical geo-hydrological setting, with in addition a hypothetical land use. In the sensitivity analysis is check how impact categories respond to a change in pumping rate, as described in table 6. The results of this analysis will be compared with the findings presented in paragraph 4.2. Forecasted impacts: interviews. In this manner, it is examined weather the computational module of the GENIAT as explained in paragraph 4.1. GENIAT setup description, works in consensus with expectation for different geo-hydrologic scenarios.

Three scenarios have been setup. The changing conditions of scenarios are (i) the pumping depth, (ii) occurrence of upconing and (iii) composition of the top soil. An overview of the geo-hydrological setting per scenario and the sensitivity of additional outputs are included in annex 8. The scenarios are shortly described in table 7, 8 and 9. The scenarios coincide with the groundwater extraction types (i) confined deep groundwater (ii) confined shallow groundwater and (iii) phreatic groundwater. The geo-hydrological setting for riverbank filtration is analysed in paragraph 4.4. Case Kamerik.

Table 6 – Description of the outline for the sensitivity analysis.

Scenarios	Variable input	Midpoint result per scenario	Impact category
1. Phreatic fresh water extraction 2. Confined and shallow fresh water extraction 3. Confined and deep saline water extraction	Pumping rate	• Area impacted by cone of depression [km²] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]	Desiccation
		• Volume of water infected by upconing saline interface [km³]	Salinization
		• Area impacted by subsidence [km²] • Average level of subsidence [m] • Maximum level of subsidence [m]	Subsidence
		• Change in seepage flux [m/d]	Aquatic vegetation
		• Decline in terrestrial vegetation completeness [#]	Terrestrial vegetation
		• Qualitative dispersion of pollution [-]	Pollution

The impact category 'Raw water properties' is not incorporated in the sensitivity analysis as not all midpoint results correlate with pumping rates.

The following explanation is given for the figures 9 to 26:

- the **higher** the trend line indicating **desiccation** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **salinization** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **subsidence** score, the more negative the forecasted influence;

- the **lower** the trend line indicating **pollution**, the more negative the forecasted influence;
- the **lower** the trend line indicating **aquatic vegetation** score, the more negative the forecasted influence;
- the **lower** the trend line indicating **terrestrial vegetation** score, the more negative the forecasted influence.

4.3.1. SENSITIVITY OF SCENARIO PHREATIC

Table 7 – Description of the phreatic scenario.

Scenarios	Pumping depth	Occurrence of upconing	Composition of the top soil
Phreatic fresh water extraction	15 [m] below ground level	No upconing	Non-confining layer (sand)

The sensitivity of the impact categories are visualized for the phreatic scenario (table 7) in figure 9 to 14 with a trend line. The sensitivity of midpoint results of desiccation and subsidence are included in annex 8.1. In this scenario, desiccation occurs, resulting in consolidation of the sandy topsoil. There is a low degree of upconing, mostly due to the geo-hydrological setting. Stress on phreatophytic vegetation occurs due to eco-hydrological implications. There is an increase in upwards seepage flux, which might benefit aquatic vegetation. Last, diffuse pollution loads are being dispersed in the top soil.

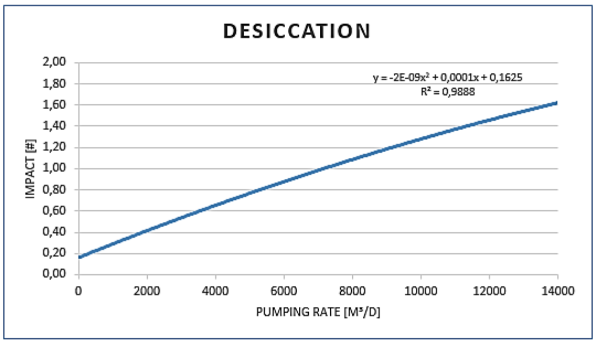

Figure 9 – Quantitative forecast, indicating an almost linear relation between pumping rates and occurrence of desiccation.

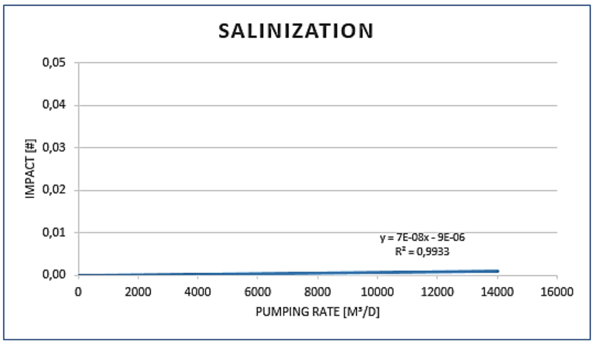

Figure 10 – Quantitative forecast, indicating a linear relation between pumping rates and the upconing of saline interface.

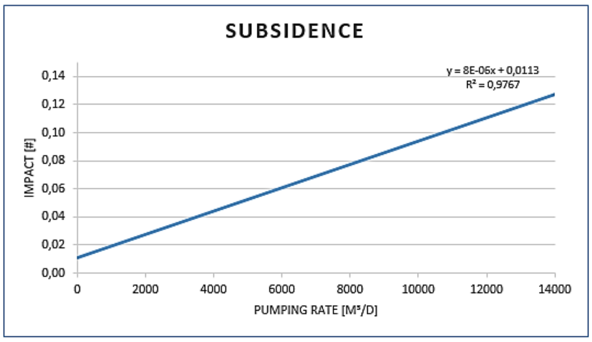

Figure 11 – Quantitative forecast, indicating a linear relation between pumping rates and the occurrence of subsidence.

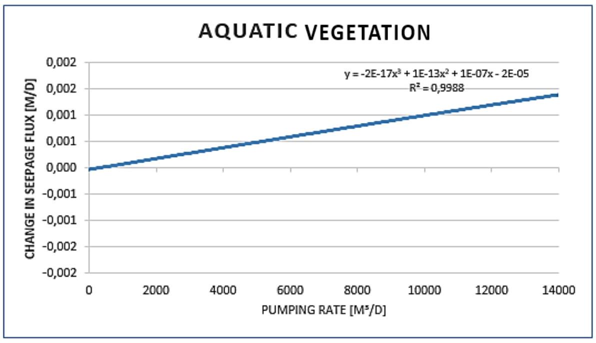

Figure 12 – Quantitative forecast, indicating a linear relation between pumping rates and the increase of seepage flux.

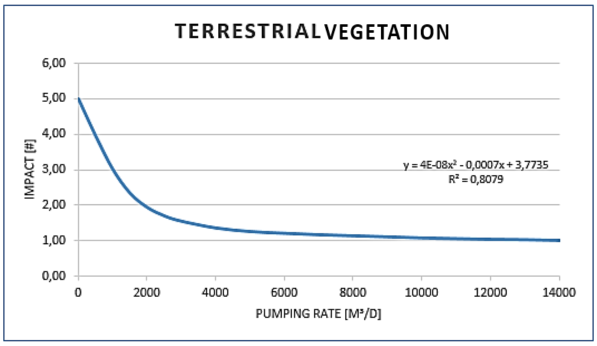

Figure 13 – Quantitative and qualitative forecast based on dose effect functions and **Zelm et al. (2010)**, indicating a hyperbolic relation between pumping rates and phreatophytic stress.

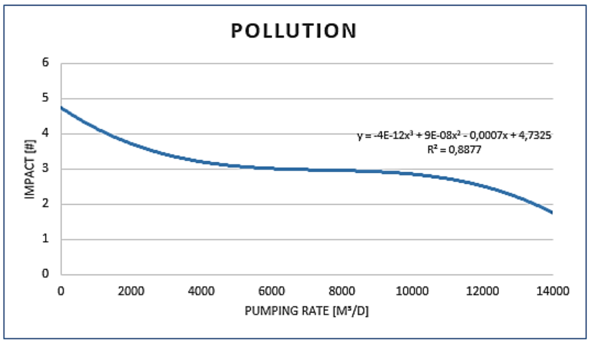

Figure 14 – Qualitative forecast. Impact resulting from local specific discharge, indicating a sinus hyperbolic relation between pumping rates and the dispersion of pollution. Note: analysis is very dependent on the layout of the build-environment.

4.3.2. SENSITIVITY OF SCENARIO SHALLOW

Table 8 – Description of the shallow scenario.

Scenarios	Pumping depth	Occurrence of upconing	Composition of the top soil
Confined and shallow fresh water extraction	15 [m] below ground level	Upconing occurs	Confining layer (clay)

The sensitivity of the impact categories are visualized for the shallow scenario (table 8) in figure 15 to 20 with a trend line. The sensitivity of midpoint results of desiccation and subsidence are included in annex 8.2. In this scenario, desiccation is less of a concern. Consolidation of the clay topsoil occurs. There is upconing, due to the assumption made in the scenario. Stress on phreatophytic vegetation occurs due to eco-hydrological implications, probably mostly due to the used findings of Zelm et al. (2010). There is a low influence on seepage flux. Last, diffuse pollution loads are not being dispersed due to the low hydraulic conductivity of the clay topsoil.

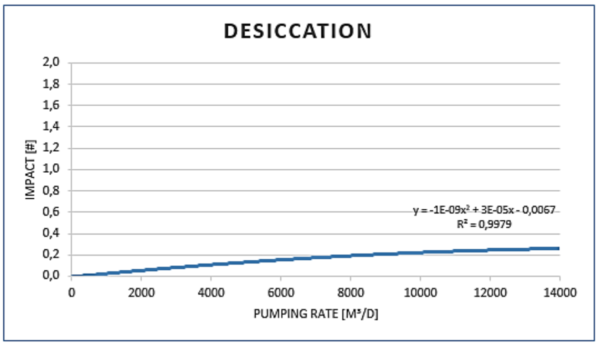

Figure 15 – Quantitative forecast, indicating square root relation between pumping rates and occurrence of desiccation.

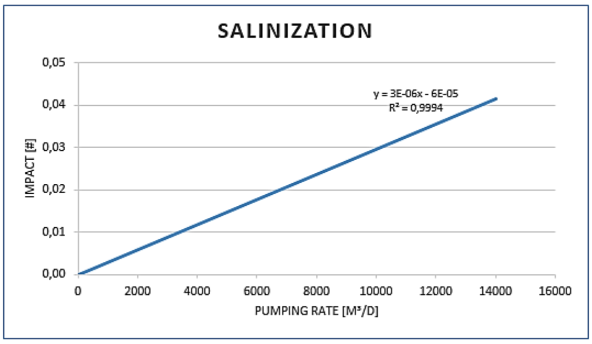

Figure 16 – Quantitative forecast, indicating a linear relation between pumping rates and the upconing of saline interface.

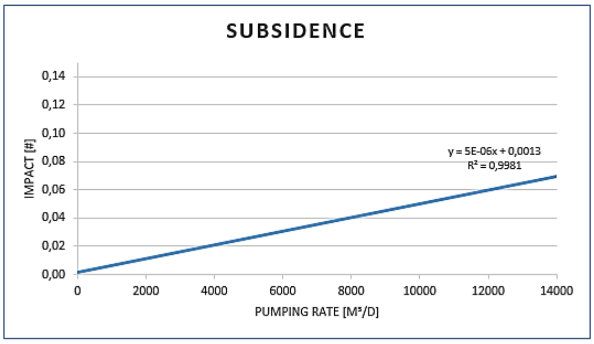

Figure 17 – Quantitative forecast, indicating a linear relation between pumping rates and the occurrence of subsidence.

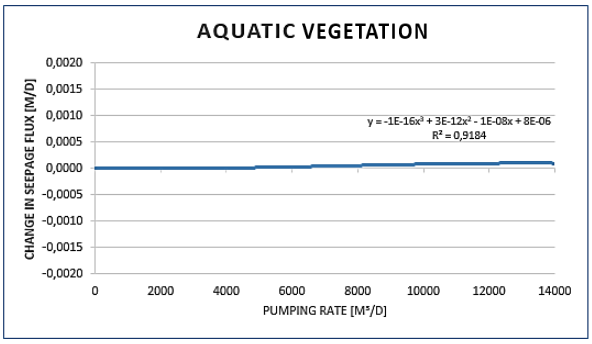

Figure 18 – Quantitative forecast, indicating a linear relation between pumping rates and the increase of seepage flux.

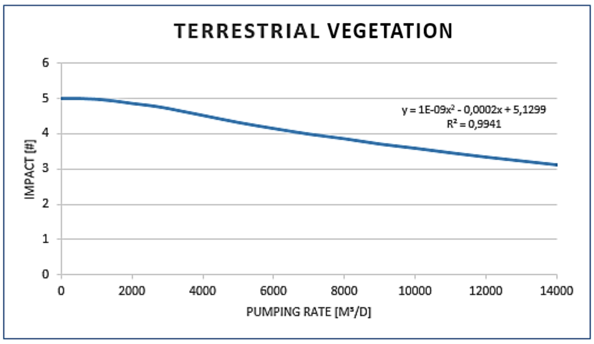

Figure 19 – Quantitative and qualitative forecast based on dose effect functions and Zelm et al. (2010), indicating an almost linear relation between pumping rates and phreatophytic stress.

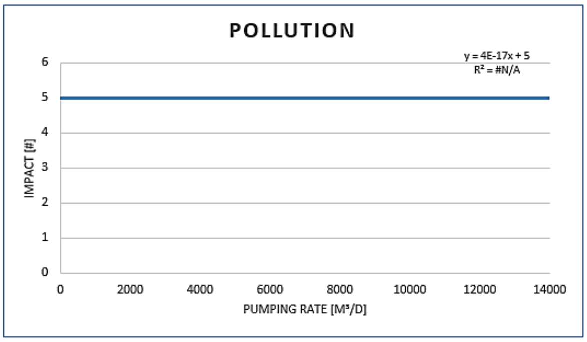

Figure 20 – Qualitative forecast. No impact, resulting from the low hydraulic conductivity of the top clay layer.

4.3.3. SENSITIVITY OF SCENARIO DEEP

Table 9 – Description of the deep scenario**.**

Scenarios	Pumping depth	Occurrence of upconing	Composition of the top soil
Confined and deep saline water extraction	55 [m] below ground level, beneath an aquitard	Downconing occurs	Non-confining layer (sand)

The sensitivity of the impact categories are visualized for the deep scenario (table 9) in figure 21 to 26 with a trend line. The sensitivity of midpoint results of desiccation and subsidence are included in annex 8.3. In this scenario, influence of desiccation is low. There is almost no consolidation of the clay topsoil. There is downconing, due to the pumping depth. Stress on phreatophytic vegetation is low. There is a high influence on seepage flux, as piezometric levels are lowered according to the findings of Theis (1935). Last, diffuse pollution loads are not being dispersed due to the low hydraulic conductivity of the clay topsoil.

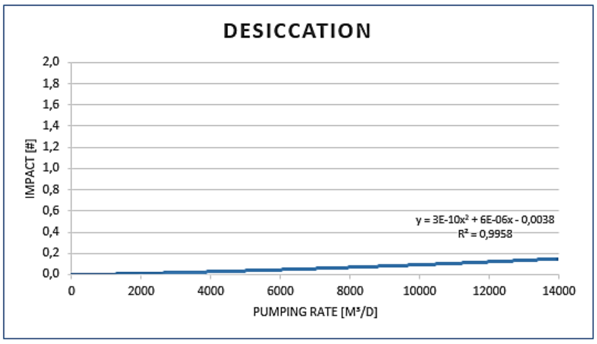

Figure 21 – Quantitative forecast, indicating an exponential relationship between pumping rates and the occurrence of desiccation.

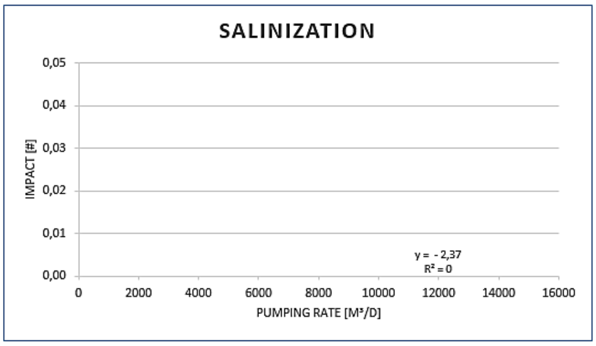

Figure 22 – Quantitative forecast, Indirectly indicating of the positive effect of downconing, which is not visualized.

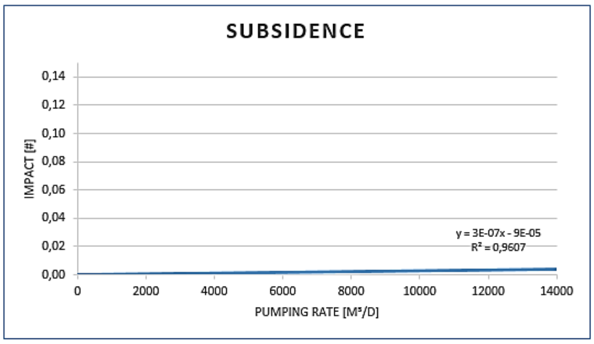

Figure 23 – Quantitative forecast, indicating a linear relation between pumping rates and the occurrence of subsidence.

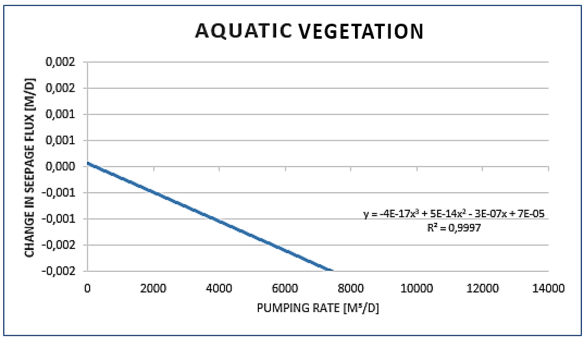

Figure 24 – Quantitative forecast, indicating a linear relation between pumping rates and the increase of seepage flux.

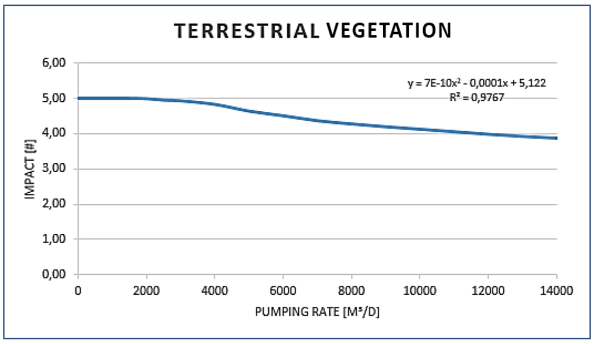

Figure 25 – Quantitative and qualitative forecast based on dose effect function and **Zelm et al. (2010)**, indicating an almost linear relation between pumping rates and phreatophytic stress.

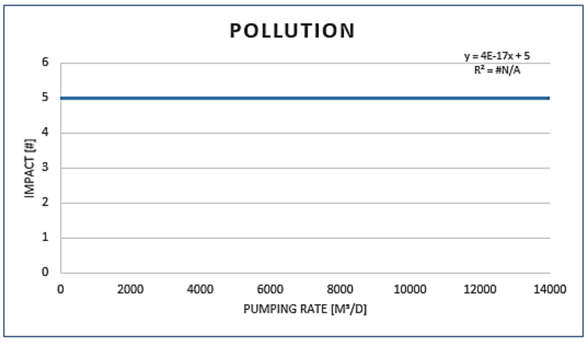

Figure 26 – Qualitative forecast. No impact, resulting from the low hydraulic conductivity of the top clay layer.

4.3.4. CONCLUSION SENSITIVITY ANALYSIS

The results of the sensitivity analysis coincides with expected eco- and geo-hydrological impacts described in table 5. The slope of trend lines of midpoint results, depicted in annex 8, are not the logical result of the underlying formulas described in annex 6. This is due to the fact that the impact on an area is regarded, instead of the impact on a single gridline. Therefore, GENIATS computational situation (not depicted) was compared with the findings of Gaast (2013). It was found that the initial hydrological situation and drawdown is modelled correctly in GENIAT. Midpoint results of subsidence showed realistic figures as function of hydrological changes.

It was presumed by experts and literature that the occurrence of desiccation correlates with stress on phreatophytic vegetation (Van Ek, 2002; I Canals et al., 2009). The trend line indicating the phreatophytic stress is the result of dose effect functions, included in annex 7, and the findings of Zelm et al. (2010). These trend lines are comparable with findings of Vink & Schot (2002), who used a genetic algorithm in order to identify Pareto-optimal solutions for e.g. sustainable groundwater extraction versus damage to phreatophytes, expressed in$\%.ha$. Their findings are included in annex 8.4.

Overall, the results of the sensitivity analysis shows realistic trend line. Moreover, the analysis reveals expected and logical geo-hydrological correlations. It may be concluded that the geo-hydrological assessment in the GENIAT can be used in order to approximate geo and eco-hydrological changes. It may not be concluded that impact forecasts are valid in a quantitative manner. In order to partly validate the quantitative output of GENIAT in case of extern geo-hydrological data, a case study is conducted. The results of the case study are described in paragraph 4.4. Case Kamerik.

4.4. CASE KAMERIK

This paragraph describes three different scenarios for case Kamerik. First, the groundwater extraction in Kamerik, the Netherlands, is visualized. The extraction type concerns a riverbank filtration. The outcome of analysed scenarios will be examined. Scenarios are briefly described in table 10. The intention of this paragraph is to conclude if hydrological changes forecasted by GENIAT coincide with changes calculated by TRIWACO. Moreover, it is check whether it is valid to use the multilayer approach as explained in annex 6.2. in case of no extern hydrological data.

Table 10 – Short description of the scenarios of case Kamerik, setup in consultation with Oasen N.V.

Scenarios	Raw water salinity	Input data	Including drawdown input data?	Beginning well screen depth
1. Scenario A	Fresh	Extern geo-hydrological data from TRIWACO	Yes	-15 [m]
2. Scenario B	Fresh		No	-15 [m]
3. Scenario C	Saline		No	-80 [m]

The extraction in Kamerik is operational since 1932 and currently permitted to extract 3 million cubic meters of groundwater per year. The well screen reaches from -15 to -40 meter below ground level (Gemeente Woerden et al., 2012). A schematic cross-section is visualized in figure 27. The surroundings are visualized in figure 28. The considered cross-sections in the case study are visualized in annex 9.

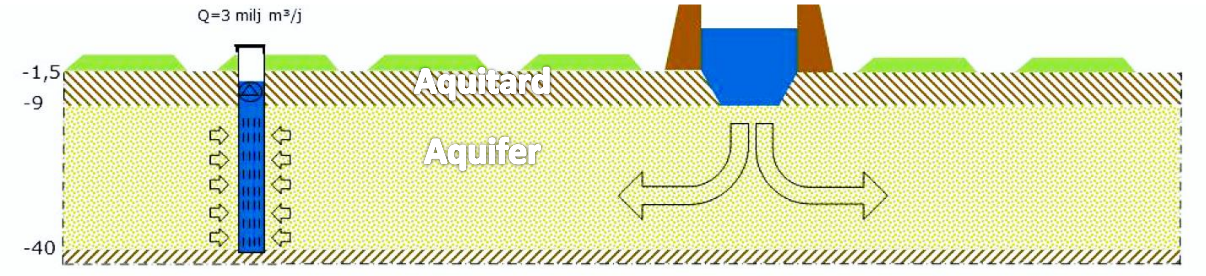

Figure 27 – Schematic visualisation of the river bank extraction in Kamerik **(Gemeente Woerden et al., 2012)**.

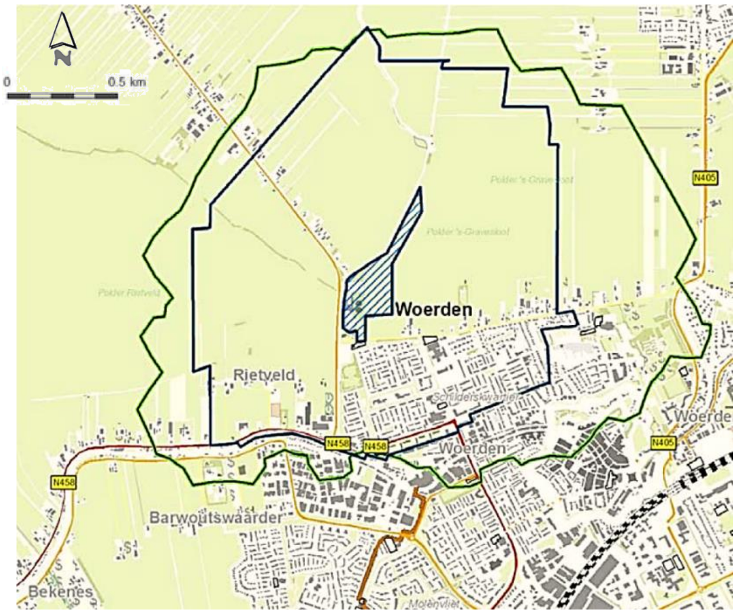

Figure 28 – Top view of the situation in Kamerik, with in highlighted blue the watercollection area, in the blue circle the groundwater protection area and in the green circle the 100 year focus area **(Gemeente Woerden et al., 2012)**.

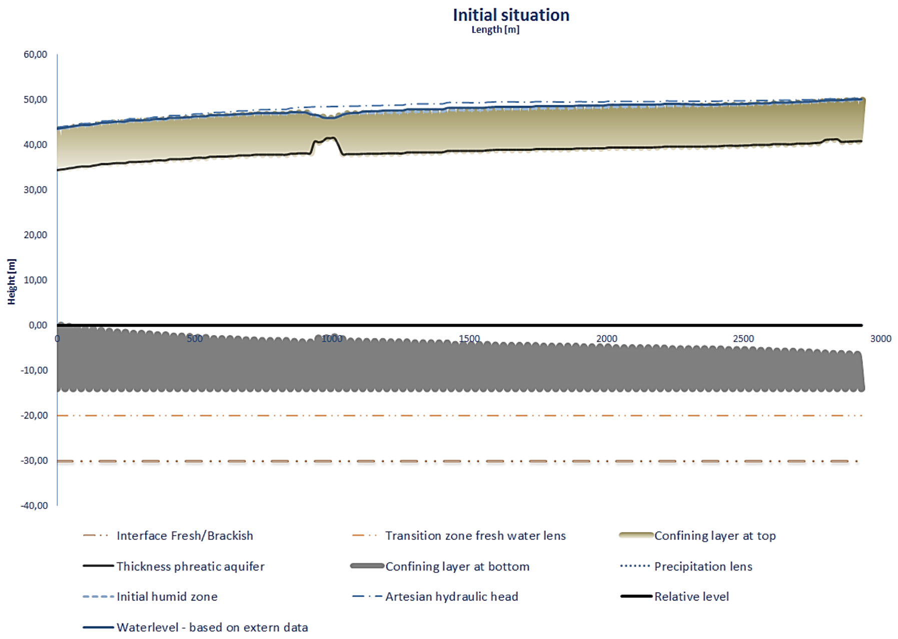

Figure 29 – Initial situation in Kamerik, visualized by the GENIAT. This situation is used as initial for scenario A, B and C.

Figure 29 depicts the initial situation used for scenario A, B and C. In this initial situation, it is assumed that the groundwater level is the controlled polder level. Land use is determined by means of the area dossiers Woerden (Gemeente Woerden et al., 2012). There is no area with terrestrial or aquatic vegetation types, only agricultural grass which is also not considered as crop type. Consequently, aquatic and terrestrial vegetation completeness are left out of all the scenarios.

4.4.1. KAMERIK SCENARIO A

Geo-hydrological data is provided by TRIWACO for the situation with drawdown. This data is used as baseline for the impact forecast in GENIAT. The situation with drawdown is visualized in figure 30. The output of GENIAT is given in table 11.

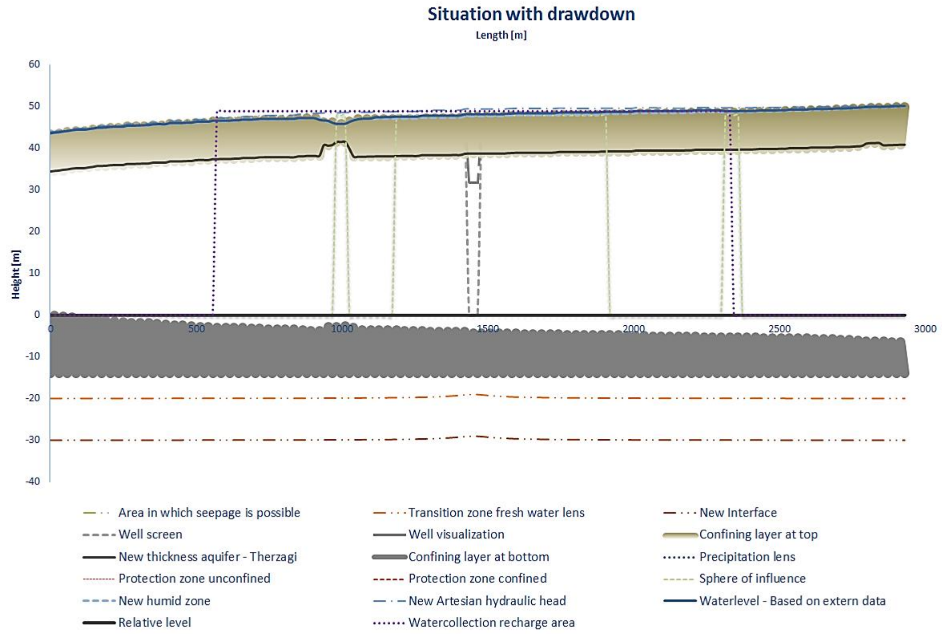

Figure 30 – Scenario A - Kamerik with drawdown from TRIWACO.

Scoring system

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

Table 11 – Midpoint- and end results for scenario A.

Midpoint result per variable	Score midpoint result	Impact category	Score per category	End result
• Area impacted by cone of depression [km^2] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]	○ 0,5 [km^2] ○ 0,06 [m] ○ 0,07 [m]	Desiccation	5	End result **4,2**
• Volume of water infected by upconing saline interface [km^3]	○ 0,00 [km^3]	Salinization	4	
• Area impacted by subsidence [km^2] • Average level of subsidence [m] • Maximum level of subsidence [m]	○ 0,001 [km^2] ○ 0,004 [m] ○ 0,016 [m]	Subsidence	4	
• Change in seepage flux, correlating with aquatic vegetation completeness [mm/d]	○ -0,1 [mm/d]	Aquatic vegetation	-	
• Decline in terrestrial vegetation completeness [#] • Change in seepage flux [mm/d]	○ 0 [#] ○ -0,1 [mm/d]	Terrestrial vegetation	-	
• Normative age of raw water [y] • Salinity of raw water [saline/brackish/fresh] • Degree of raw water pollution [REFLECT]/[%]	○ ≠73 [y] ○ fresh ○ 100 %	Raw water	3	
• Qualitative dispersion of pollution [-]	○ 0 [-]	Pollution	5	

RESULTS

In this scenario, there is sufficient groundwater replenishment in the extraction area because ditches are positioned approximately 50 meter from each other. In addition, the aquifer is sufficiently replenished by the river. This results in a low degree of desiccation, which scores a 5. As can be seen in figure 30, upconing occurs and scores a 4. Subsidence occurs due to the consolidation properties of clay and scores a 4. Impact on aquatic and terrestrial vegetation is not scored as there is no initial vegetation. The young age of raw water and the percentage polluted water are considered as sustainable, as mentioned in table 2. Extracting fresh groundwater is considered an unsustainable activity. Overall, the raw water scores a 3. Due to the low specific discharge it is calculated that there is a very low degree of dispersion of diffuse polluted loads. Therefore, pollution scores a 5.

The midpoints results and the scores per impact category of scenario A, will be compared with the midpoint results and the scores per impact category of scenario B.

4.4.2. KAMERIK SCENARIO B

For this scenario, the same initial situation is incorporated as described in paragraph 4.4.1. Kamerik scenario A. The difference in scenario B is that the drawdown calculated by TRIWACO will not be used, as described in table 10. Instead, the GENIAT will calculate the drawdown based on the methodology described in annex 6.2. Midpoint results of scenario B will be compared with the midpoint results in scenario A.

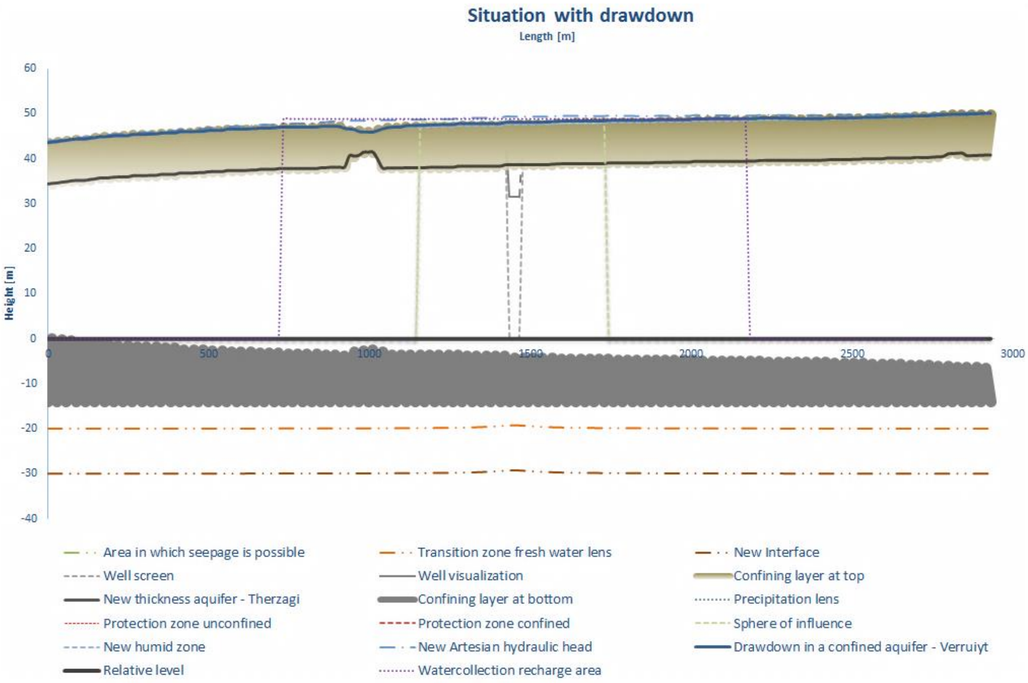

Figure 31 – Scenario B in Kamerik with drawdown calculated by GENIAT.

Scoring system

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

Table 12 – Midpoint- and end results for scenario B.

Midpoint result per variable	Score midpoint result	Impact category	Score per category	
• Area impacted by cone of depression [km²] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]	○ 0,3 [km²] ○ 0,05 [m] ○ 0,09 [m]	Desiccation	5	**End result** 4,2
• Volume of water infected by upconing saline interface [km³]	○ 0,00 [km³]	Salinization	4	
• Area impacted by subsidence [km²] • Average level of subsidence [m] • Maximum level of subsidence [m]	○ 0,005 [km²] ○ 0,02 [m] ○ 0,01 [m]	Subsidence	4	
• Change in seepage flux, correlating with aquatic vegetation completeness [mm/d]	○ 0 [mm/d]	Aquatic vegetation	-	
• Decline in terrestrial vegetation completeness [#] • Change in seepage flux [mm/d]	○ 0 [#] ○ 0 [mm/d]	Terrestrial vegetation	-	
• Normative age of raw water [y] • Salinity of raw water [saline/brackish/fresh] • Degree of raw water pollution [REFLECT]/[%]	○ ≠73 [y] ○ fresh ○ 100 %	Raw water	3	
• Qualitative dispersion of pollution [-]	○ 0 [-]	Pollution	5	

RESULTS

As can be seen, the midpoint results in table 12 correspond to the midpoint results in table 12. The differences are not significant: the score per impact category is the same. It may be concluded that the drawdown calculation based on the methodology described in annex 6.2. is usable in order to approximate lowering of piezometric surface resulting from groundwater extraction beneath clay layer(s). The methodology in annex 6.2 will be used in scenario C in order to determine the end score of a deeper extraction in Kamerik.

4.4.3. KAMERIK SCENARIO C

For this scenario, the same geo-hydrological is incorporated as described in paragraph 4.4.1. Kamerik scenario A, depicted in figure 29. Extraction activities are displaced below the second confining layer, as depicted in figure 32. The GENIAT will calculate the drawdown for this scenario, based on the methodology described in annex 6.2. Midpoint results of scenario C are shown in table 13 and will be used in order to check whether deep groundwater extraction is actually more sustainable. Also in case of no terrestrial or aquatic nature.

Oasen N.V. is curious about the outcome of this analysis, because there currently are experiments with an RO installation in Kamerik. This innovation makes it possible to use saline groundwater, as explained in paragraph 1.1.2. Context description: changing knowledge. The end result in scenario C answers whether deep groundwater extraction in Kamerik is more sustainable than the current extraction depth.

Note: this scenario only assesses the environmental damage for the DWC components “Water source” and “Surroundings of the water extraction”, depicted in figure 3. A remark is that the environmental impacts of the conventional raw water treatment are different than the impacts of a RO installation. The total difference in environmental impacts for these two scenarios must also be quantified within the WSD study, in order to underpin decision making with information about environmental damage, health implications and overall costs. Therefore, the outcome in table 13 will not lead to recommendation for allocating the groundwater extraction.

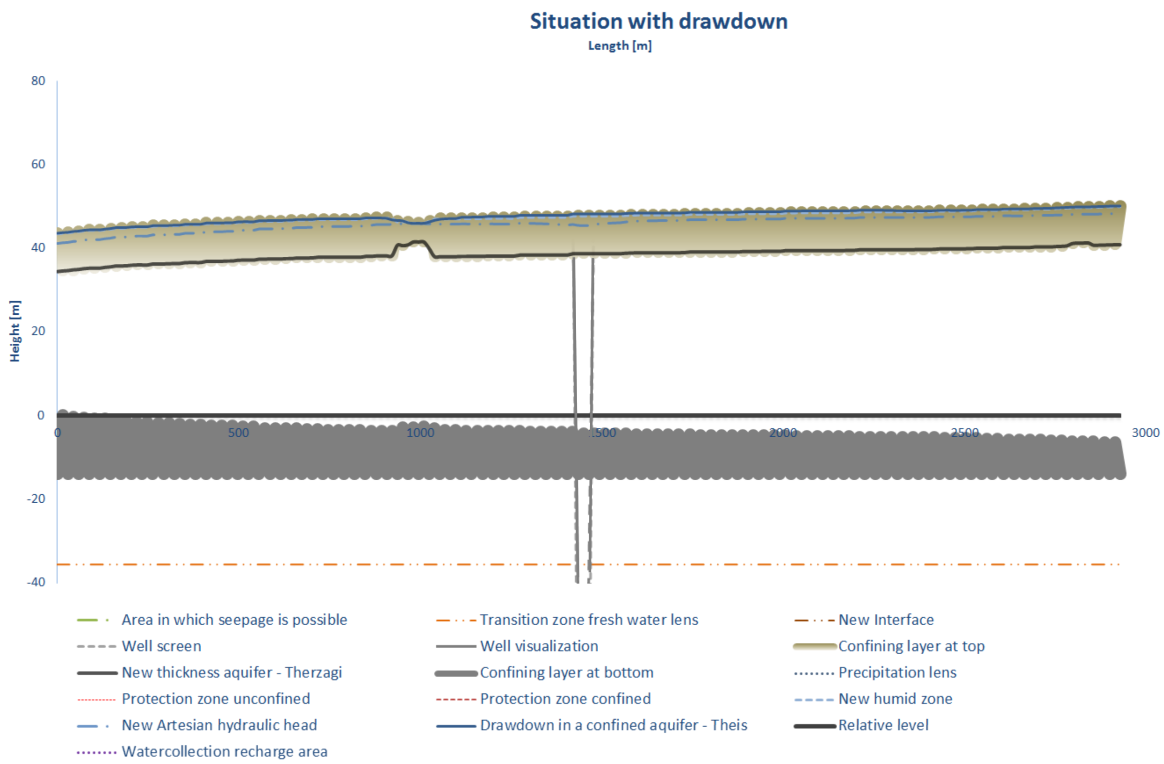

Figure 32 – Scenario C in Kamerik with drawdown calculated by GENIAT.

Scoring system

0 = extreme negative influence;
1 = very high negative influence;
2 = high negative influence;
3 = moderate negative influence;
4 = low negative influence;
5 = very low or positive influence.

Table 13 – Midpoint- and end results for scenario C.

Midpoint result per variable	Score midpoint result	Impact category	Score per category	End result
• Area impacted by cone of depression [km^2] • Average drawdown in cone of depression [m] • Maximum drawdown in cone of depression [m]	○ 5,1 [km^2] ○ 0,02 [m] ○ 0,04 [m]	Desiccation	5	End result 4,6
• Volume of water infected by upconing saline interface [km^3]	○ < 0,00 [km^3]	Salinization	5	
• Area impacted by subsidence [km^2] • Average level of subsidence [m] • Maximum level of subsidence [m]	○ 0,013 [km^2] ○ 0,0002 [m] ○ 0,0004 [m]	Subsidence	5	
• Change in seepage flux, correlating with aquatic vegetation completeness [mm/d]	○ -2,5 [mm/d]	Aquatic vegetation	-	
• Decline in terrestrial vegetation completeness [#] • Change in seepage flux [mm/d]	○ 0 [#] ○ –2,5 [mm/d]	Terrestrial vegetation	-	
• Normative age of raw water [y] • Salinity of raw water [saline/brackish/fresh] • Degree of raw water pollution [REFLECT]/[%]	○ ≠5700 [y] ○ Saline ○ 0 %	Raw water	3	
• Qualitative dispersion of pollution [-]	○ 0 [-]	Pollution	5	

RESULTS

The results in table 18 show that the piezometric surface in scenario C decreases less than in scenario A and B. On the other hand, the area were a decrease in piezometric surface occurs is larger. This is an expected and known implication of deep groundwater extracting, resulting from the fact that there are no boundary conditions in the deeper exploited aquifer in scenario C. It remains so that desiccation impact scores a 5 due to the use of the geometric mean. Downconing occurs in this scenario, resulting in a score of a 5 for salinization. Subsidence occurs in a bigger area, while the actual degree of subsidence is less compared with scenario A and B, due to the lower decrease in piezometric surface. Overall, subsidence scores a 5. Impact on aquatic and terrestrial vegetation is not scored as there is no initial vegetation. The old age of raw water is not considered due to the salinity of the raw water. Extracting saline groundwater is considered sustainable. However, raw water pollution is considered and therefore the raw water score is a 3. Dispersion of diffuse pollution loads scores a 5 as hydraulic conductivity in the top clay layer is low.

CONCLUSION

The results of the geo-hydrological analysis in scenario B does not differ much from that of TRIWACO, analysed in scenario A. Therefore, it is stated that GENIAT is useful in order to estimate the geo-hydrological changes. However, more research is needed in order to conclude whether the GENIAT is widely applicable and to determine how accurate the hydrological analysis of GENIAT is.

Scenario C, scores better in the end result compare to scenario A and B, as coincides with the findings summarized in table 5. This indicates that deep groundwater extraction results in less impacts on the environment and is therefore classified as more sustainable. It might be suggested, based on the findings in paragraph 4.3. Sensitivity analysis, that Scenario C would score even better relatively in case of initial terrestrial vegetation, if independent of seepage. Vice versa, in case of aquatic vegetation, Scenario C would score relatively poorer due to the decrease in upward seepage flux.

CHAPTER 5. DISCUSSION

This chapter discusses the research methodology and the setup of the GENIAT. Examined is to what extend the research questions in paragraph 1.3.2. Research questions, can be answers based on the findings. In addition, the discussion will address pros and cons of pre-conditions, choices made in the research method and the used quantitative impact predictions.

5.1. METHODOLOGY

In consensus with the preconditions described in paragraph 1.3. Goal and research question, a quick scanning EIA has been proposed. A conceptual model has been setup (figure 6) based upon findings in literature and expert judgement. This conceptual model is used as framework in order to initiate the GENIAT. The sustainability scoring system in GENIAT is based upon the findings of Royal Haskoning (2004) listed in table 2. Through this, the baseline of the research methodology is built upon the findings in the theoretical framework.

A synopsis of the environment is based on external data or a geo-hydrological approximation by means of analytical formulas described in annex 6. The forecast of the quantitative change in the environment due to groundwater extraction is based on qualitative, analytic and empiric tools and data from findings in literature. The results of the initiated GENIAT have been analysed by model tests, a sensitivity analysis, a case study and by expert knowledge. It was stated that the current results show expected and realistic correlations between geo-hydrology, eco-hydrology and the build environment. Moreover, the GENIAT proved to be useful in order to analyse the environmental changes. This answers the research question:

1. What model method is suitable in order to quantitatively forecast the impacts on the environment resulting from groundwater extraction while regarding sustainability aspects?

UNCERTAINTIES

Using findings in literature provided scientific and (inter)nationally accepted tools in order to initiate the GENIAT in consensus with preconditions. However, by applying literature findings, tools and frameworks, assumption, uncertainties, bias and simplification are taken over in the setup of the GENIAT. Moreover, used findings are integrated in a quick scan meta-analysis which is further simplified. What misses in the research methodology is the statistically uncertainty of the GENIATs input and output, leaving room for conflicting assumptions during research interpretation by decision makers. The origin of output uncertainties are identified in paragraph 5.2. GENIATs setup. In addition, it has already been stated that the current validation process is not comprehensive enough to conclude how accurate the quantitative output of the GENIAT is in all sorts of geo-hydrological scenarios. More research is needed to completely validate the GENIAT.

HYPOTHESIS

The hypothesis of this research was formulated as follows:

- *There will be sufficient knowledge accessible and practicable in order to forecast environmental impacts resulting from groundwater extraction. However, the challenge will be to score and aggregate the quantitative output, without subjectivity, into a scientifically underpinned and legitimized sustainability score.*

Sustainability aspects are classified in table 2, based upon findings in published literature. However, is it recognized that the sustainability scoring system is not and cannot be validated with current knowledge. Therefore, it may not be concluded that the sustainability score is legitimized, indicating the hypothesized difficulty to setup a scientific and underpinned sustainability score.

5.2. GENIATs SETUP

This paragraph describes the required input data for the GENIAT to perform the impact forecast. It is critically explained how assumptions and simplifications in the GENIAT may lead to implications for legitimacy when using the end result of GENIAT for decision making. Last, the method to determine the sustainability score is evaluated.

5.2.1. INPUT DATA

Used control constants, system parameters and system variables are accessible and do not require large data sets. Interactive open source dataset, like for instance the atlas from Breure et al. (2014), Google maps or DINOLOKET are sources which can be consulted for the synopsis for the environment. The synopsis of the build environment requires the input of a single variables, for each of designated analysed areas (max 10).
The findings of COMPENSATIEBEGINSEL & EHS (n.d.) are incorporated in GENIAT and can be used in order to setup a part of the synopsis of the initial vegetation completeness. These figures are understandable for a laymen. However, eco-variables like: normative root depth, the dependency of nature on seepage, etc., need to be incorporated based upon expert judgement. The synopsis of the ecology requires the input of 7 variables, for each of analysed surfaces areas (max 10).
The synopsis of the geo-hydrological composition needs to be incorporated by an expert in the field of hydrology. Moreover, additional sources might need to be consulted by the user, for instance to determine the initial depth of the saline water interface, local groundwater regime classes, etc. The geo-hydrological setup requires the input of 44 variables, for which most are straightforward (transmissivity, aquifer thickness, etc.). Input uncertainties are not analysed within the GENIAT as explained in paragraph 5.1. Methodology.

The description above answers the following research question:

2. What data can be used in order to quantitatively analyse environmental impacts for certain geo- and eco-hydrological scenarios?

5.2.2. ASSUMPTIONS AND SIMPLIFICATIONS

After model input follow model computations. By setting up the GENIAT, choices have been made in order to integrate the interdisciplinary findings from literature into a quick scan meta-analysis. Made assumption and simplification during GENIATs setup might lead to uncertainties in numerical computing. Assumptions and simplifications are listed below. The side effect of uncertainties is that room is made for conflicting assumptions which might misleading decision making.
However, in order to provide legitimized facts for decision making, transparency is needed. It is not credible for decision making to use a single score derived by a spatially homogenous and deterministic model. This, a single score may lead to unsubstantiated bias. By dealing with uncertainties, GENIATs output becomes more credible.

(i) During initialization, it was chosen not to use expert judgement in order to approximate the impact on non-quantifiable subject, described in paragraph 3.5. Conclusion theoretical framework. It is not known to what extend the omitted subjects contribute to the total environmental impact. By neglecting subjects, the analysis might leave out significant information for the impact forecast and thereby leaving out crucial information concerning the impact on sustainability issues resulting from groundwater extraction.

(ii) In this research it is bias that groundwater extraction will lead to negative effects. However, it is possible that groundwater extraction leads to positive effects regarding sustainability. This is only partly integrated in GENIAT, but mostly not included for the eco-hydrological analysis. As was mentioned in 4.2. Forecasted impacts: interviews, the current Dutch discourse is that designating groundwater protection areas leads to an increase in nature value due to policy restrictions and environmental management. The impact of changes in anthropogenic activities due to the latter is not included in the analysis, as discussed in 3.5. Conclusion theoretical framework.

(iii) By using findings in literature, assumptions and simplifications are adopted in the GENIAT. Assumptions like for instance steady state are used in formula derivations. Steady state is based on the assumption that the continuity equation is zero, thereby neglecting spatial distribution processes. In fact, spatial distribution is a very dynamic process, not restricted by boundaries in the model grid. Moreover, a side effect of using steady state approximations is that seasonal variability can only be analysed by setting up various scenarios. For instance, the height of the precipitation lens is seasonally and locally bound and highly variable. This lens correlates with the possibility of seepage rich groundwater reaching the root zone. This highly variable and spatially distributed lens cannot be incorporated in a valid manner, partly due to the used preconditions. In addition, it is chosen to minimize spatial distribution processes and variable aspects in order to diminish combinatorial explosiveness. Also, aquifer, aquitards and initial vegetation completeness are considered homogenous and, hydraulic conductivity is considered isotropic. The analysed scenario is based on a yearly average precipitation surplus or deficit

(iv) Due to extend and nature of the used model grids, dispersion is viewed in a different manner than geo-hydrological implications resulting from groundwater extraction. A standard grid discretization has been integrated in order to simplify the input for the build environment, while still being able to analyse dispersion in a two dimensional grid. Input simplifications seemed necessary in order to minimize combinatorial explosiveness. The price is that calculations of the area sizes combined with the representative local degree of pollution have become more uncertain due to the shape of combined grids. Subsequently, it might be chosen not to calculate dispersion in a surface area, but only considered for the cross-section. However, it seems possible to combine the 2 different grids and perhaps, it might even prove valuable for the model input of phreatophytes and submerged macrophytes. Currently, input for vegetation types are 1D. In the same grid of dispersion, vegetation input can be two dimensional based on surface area. Moreover, vegetation input can become more region specific. More research is needed in order to underpin the choice in grid discretization. In the current grid-setup of GENIAT, input of spatial distribution is minimum.

The above mentioned simplifications and assumptions result in uncertainties in GENIATs output data. This data is used for the sustainability scoring system.

5.2.3. SUSTAINABILITY SCORING SYSTEM

Midpoint results are obtained as a result of GENIATs computational model. Obtained midpoint results are listed in table 3. How midpoint results are used in the sustainability scoring system is explained in paragraph 4.1.6. Sustainability scoring system. Identified impacts category are based upon the findings of Royal Haskoning (2004).

The setup of the scoring system is based on worst case (0) and best case (5) scenarios, determined in the GENIAT and partly based on findings in literature. The proposed linear relationship and the determination of worst- and base cases is based on a non-scientific approach which is not in consensus with preconditions set by Oasen N.V. Although, similar scoring systems have been proposed in literature by for instance of Chaves & Alipaz (2007) and Pandey et al. (2011), there might not be scientific support for the proposed end score of GENIAT.

GENIATs output data seems useful in order to quantify the impact on the environment resulting from groundwater extraction. Moreover, chosen aggregation and weighting schemes are underpinned by findings in the theoretical framework. However, it may not be concluded that this study answers the following research question completely, due to the fact that the proposed scoring system is not scientific based:

3. What output is relevant in order to analyse impacts and how should output be weighted, aggregated and ranked in order to build a scientific based scoring system?

This statement, combined with the uncertainty of GENIATs output, leads to the need for additional research and improvements in the setup of GENIAT. Model improvements are described in paragraph 5.3. Recommendations.

5.3. RECOMMENDATIONS

5.3.1. IMPROVING GENIAT

MODEL UNCERTAINTIES

It is recommended that the setup of the GENIAT is improved in order to provide more accurate quantitative forecasts. In addition, model uncertainties must be assessed in order to determine the model and measurements error, while there is not a single leading and correct answer in forecast analysis. Probability distributions, probability exceedance, input errors and other statistical concepts may be used to determine uncertainties. How to deal with statistically determined uncertainties in GENIAT must further be investigated.

MODEL ENHANCEMENT

Especially the eco-hydrological analysis can be enhanced by for instance incorporating the impact of soil acidification and eutrophication on vegetation completeness. Moreover, instead of deriving the impact on vegetation completeness, it might be worthwhile to calculate the impact due to groundwater extraction on vegetation value, as defined by DEMNAT. Nature value also takes into account the rareness of biotopes, as well as replaceability and completeness.

Primary, the number of dose effect functions to determine the effect on nature completeness have been constricted in order to minimize combinatorial explosiveness. However, currently it seems practicable to integrate more dose effect function in GENIAT. More specified dose effect functions relative to a certain soil-, and nature type, are available.

It seems possible to integrate dose effect functions concerning aquatic vegetation completeness in the near future due to new studies. Impact on aquatic biotopes could then also be expressed in nature value, increasing the usability of the quantitative impact forecast on aquatic vegetation.

More identified improvements are listed in annex 10. A note is that this annex does not state that the identified improvement are necessary in order to build a valid GENIAT.

5.3.2. IMPROVING LEGITIMACY

It is stated that the setup of GENIAT must be based upon legitimatized simplifications, assumptions etc. in order to provide supported input for an internationally accepted WSD. In order to gain legitimacy, it is recommended to perform a DELPHI-study by initiating constructed and transparent communication between experts. A DELPHI-study is a methodology in order to share expert opinions for hidden or undisclosed knowledge, like for instance;

- how to diminish bias integrated in GENIAT resulting from the used theoretical framework;
- how to improve the setup of the sustainability scoring system proposed in the current GENIAT;
- how to create support for or gain the knowledge to improve current assumptions and simplifications.

A DELPHI-study is conducted by carefully selecting panel member by a set of criteria. The overall procedure exist of several structured phases (optionally formed) in which brainstorms and in-depth interview are initiated either through email, meetings, telephone etc. After each round, the participants are provided with an anonymous summery in order to encourage them to critically review answers from co-participants. Ultimately, all findings are scored and ranked based on their mean or median. The DELPHI phases are stopped after reaching consent upon another set of pre-distinguished criteria (Hasson, Keeney, & McKenna, 2000).

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Figure 1

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Figure 7

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Figure 8

Van Ek, R., Witte, J. P. M., Runhaar, H., & Klijn, F. (2000). Ecological effects of water management in the Netherlands: the model DEMNAT. *Ecological Engineering*, *16*(1), 127-141.

Figure 27

Gemeente Woerden et al., (2012). “Gebiedsdossier waterwinning Woerden”. Provincie Utrecht.

Figure 28

Gemeente Woerden et al., (2012). “Gebiedsdossier waterwinning Woerden”. Provincie Utrecht.

Table 1

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Table 5

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CHAPTER 7. ANNEX

ANNEX 1: FRESH WATER RESOURCES

The main source of water on earth is saline ocean water, as depicted in figure A. Fresh water accounts for approximately 2.5 [%] of earth's water resources. 68,7 [%] of the fresh water resources are contained in glaciers. Groundwater resources account for 30,1 [%] of the freshwater resources (U.N. Water, 2006). Roughly 2 billion people use fresh groundwater every day as main resource and also agriculture is highly dependent on fresh groundwater resources (Gleeson et al, 2012). The remainder fresh water resources exist in the form of permafrost or surface and atmospheric water.

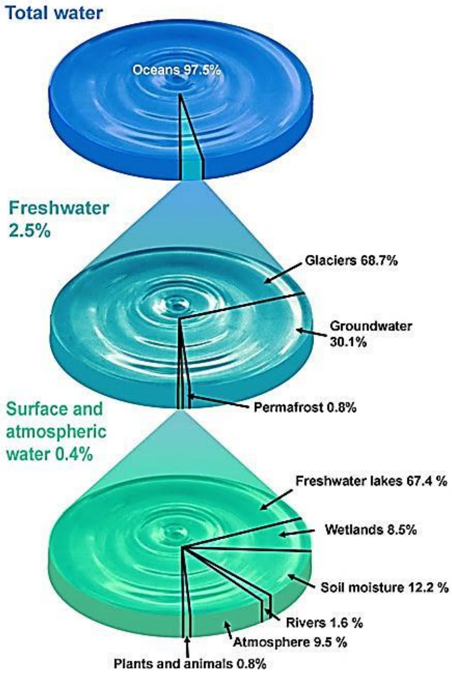

Figure A – Global distribution of the world's water resources **(U.N. Water, 2006)**.

Global groundwater depletion is increasing as estimated groundwater extraction transcends groundwater replenishment rates (Wada et al., 2010). Latest assessments using remote sensing, for instance by NASA's GRACE satellites, indicate that a third of earth main aquifers are under distress (Richey, 2014). In addition, anthropogenic groundwater contaminations are widespread and will lead to long term and significant socioeconomic impacts (Fogg & LaBolle, 2006).

Overall groundwater aquifer degradation is an unsustainable problem which threatens the resource base for a rapid socio-economic development on a widespread geographical basis. It is therefore argued that groundwater quality and quantity protection is urgently needed (Fogg & LaBolle, 2006; Gleeson et al, 2012) e.g. due to the fact that aquifer degradation resulting in higher costs for potable water treatment and for related environmental management (Loubet et al., 2014).

In the Netherlands, chemical and physical water parameters must meet the legislation in force. Standards are derived in compliance with the *Water Framework Directive (WFD)*, emanating from the European Parliament and the Council of the European Union (Ministerie van Infrastructuur en Milieu, 2009). These standard are set to safeguard overall human health while contributing to the broader EU water and health policy, which inter alia includes striving for an good ecological status in river basins (Water Framework Directive, 2000).

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ANNEX 2: OVERVIEW OF WORLDVIEWS

Rotmans (2003) made an overview of characteristics of the hierarchical- and egalitarian worldview. This overview is shown in table A and B.

Table A – Overview of the characteristics of two worldviews **(Rotmans, 2003)**.

Worldview (20th century) Hierarchical worldview	Worldview (21th century) Egalitarian worldview
• water is producible • bottom is producible • soil follows function	• water is partially producible • soil is partially producible • function follows soil
• water is the enemy: embank and drain • bottom is subordinate	• water is your friend: more space for water • soil is a partner
• drain water as soon as possible	• hold on to local water; retain
• water is a technical problem • soil is a technical problem	• water is a social problem • soil is a social problem
• water as leading principle • bottom is following	• water as an organizing principle • soil as an organizing principle

Table B – Overview of the soil and water management style of two worldviews **(Rotmans, 2003)**.

Old management model Hierarchical worldview	New management model Egalitarian worldview
• manage and control	• preventive and anticipatory
• solution oriented	• design-oriented
• monistic	• pluralistic
• plan approach	• process approach
• technocratic	• socially oriented
• integrated water policy	• integral environmental policy
• pumps, diking and draining	• retention and natural storage
• water drains accelerated	• retention of local water
• hierarchical and closed	• participatory and interactive

References:

- Rotmans, J. (2003). Transitiemanagement: Sleutel naar een Duurzame Samenleving. van Gorcum Uitgeverij.

ANNEX 3: THE AMBITION OF OASEN N.V.

Oasen N.V., one of the 11 public drinking water companies in the Netherlands, purifies and delivers potable water to about 750.000 citizens and 7.200 businesses. On a yearly basis, circa 48 billion litres of drinking water is purified and transported by 7 purifying- and 9 pumping stations (Oasen, 2013). The service area is depicted in figure B. Public health is the main responsibility of Oasen N.V. with in addition a main principle stating: 'provide drinking water in the best possible way' ("Luijt," 2013). The company is, inter alia, a manager of the fresh water supply and the surrounding environment and is aware of the changing circumstances, explained in 1.1. Context description: a changing world. Consequently, progress is made on a plan to preserve and even improve the service level of Oasen N.V., for now and in the future. Milestones in this trajectory are to become more robust and to participate in *Sustainable Development (SD)*. Oasen N.V. aims to foster innovation and SD in a business program called *'Programma Oasen Duurzaam' (POD)* (Program Oasen Sustainable). The goal of this program is:

- ***A more sustainable business operations by delivering impeccable drinking water that is best for humans and the environment*** (Zantkuijl & Schmaal, 2014)**.**

Figure B – Service area of the company Oasen N.V (**Oasen, 2013)**.

Driving forces

Direct driving forces for Oasen N.V. to participate in SD, which originated due to the described points in paragraph 1.1. A changing world, are (Zantkuijl & Schmaal, 2014):

- the societal demand for a more circular economy, resulting from the idea presented by the Club of Rome that planetary boundaries are exceeded (Meadows et al., 1972). The demands of customers are changing due to increasing environmental concerns and the increasing demand for effectiveness combined with performance (McKinsey & Company, 2011);
- the 'Bestuursakkoord Water' which is a policy document which fosters innovation in the urban water cycle (Frijns et al., 2008; Ministerie van Infrastructuur en Milieu, 2011);
- technological development, which makes it more feasible and profitable to implement innovative technology. For instance, there is a global growing interest in membrane techniques like RO due to cost reductions and efficiency improvements (Lee et al., 2011).

Sustainable development

Multiple definitions of SD have been introduced, originating from different perspectives and using different terminology. There is no consensus in the terminology used in the field of sustainability science amongst expert, organization, sectors etc. and therefore SD is classified as an umbrella term. What becomes clear from several definitions of SD is that the most terms form an interconnected system, where environmental protection, economic performance and societal welfare are driven by the political agenda, ethical values and ecological needs (Glavič & Lukman, 2007). This idea is elaborated in the concept People, Planet, Profit or PPP. The definition of the World Commission on Environment and Development, also known as the Brundtland's Commission, defined SD as *"…development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland et al., 1987). This description overlays most of the conceived definitions (Glavič & Lukman, 2007). An overview of the history, developments and the variety of perspectives of SD is described by Rogers et al. (2012).

Oasen N.V. is working towards a more sustainable business operations by striving to achieve the following points, which are elaborated in POD (Zantkuijl & Schmaal, 2014):

- stimulate the use of renewable energy and increasing energy efficiency;
- stimulate circular applications and (re)use of (raw)materials, while reducing unnecessary material and chemical consumption and usage;
- purchase more sustainable materials by paying attention to the origin and related ecological damage;
- decrease the direct environmental damage;
- initiate open dialogues with stakeholders in order to increase environmental awareness.

In addition, Oasen N.V. currently follows a short term vision concerning the exploitation of potential water resources for the drinking water supply. This vision strives for (Oasen, n.d.):

- sufficient and sustainable use of water sources with the best possible water quality;
- maintaining and improving property positions within extraction area's and the direct environment;
- a sustainable method of environmental safeguarding in synergy with natural resources and with conflicting interests in an extraction area;
- debate about potentially 'new' water sources in compliance with partners in the water supply sector;
- Riverbank filtration will be seen as main drink water source considered from the perspective of water quality, quantity, availability and reliability.

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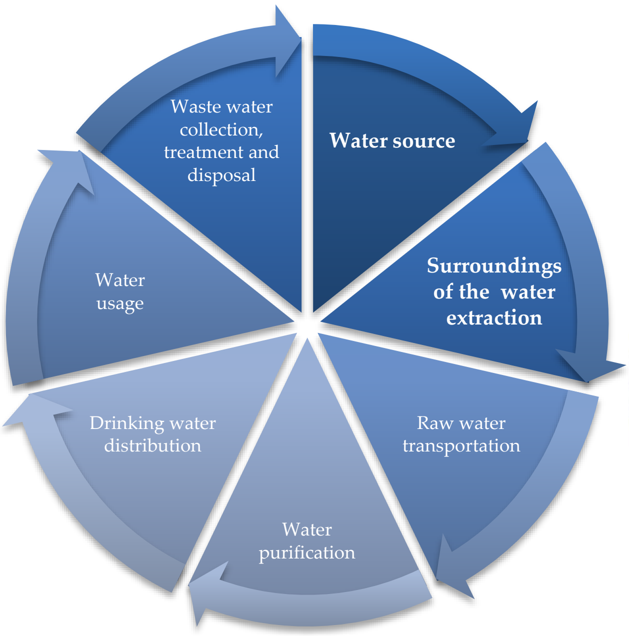
ANNEX 4: THE SCOPE OF THE WSD

Why assess a DWC instead of the ecological footprint of the company Oasen N.V.?

DWC are complex systems, were components (raw water abstraction, drinking water production, drinking water distribution, water usage, wastewater collection and treatment) are often managed by different actors (Bahri, 2012; Loubet et al., 2014). Figure C visualizes the DWC in two visualizations, while clarifying that there is a cyclical relationship between the individual components, indicating the need for a holistic approach which transcends sectorial managing. Holistic DWC management integrates the water source, water-use sectors, water services and overall water management (Loubet et al., 2014).

The cyclical relationship clarifies the ambition to create a tool that does not only quantify the impact of Oasen N.V., but also of the interrelated system. This corresponds with the egalitarian management style, described in annex 2, which concerns a more holistic environmental view. This management style is underpinned by the UN-Water, who quoted the following statement from Corcoran et al. (2010): '*It is essential that (waste)water management be considered as part of an integrated, full life cycle, eco-system-based management system that operates across all three dimensions of sustainable development (social, economic and environmental), geographical borders, and includes both freshwater and marine waters.*'



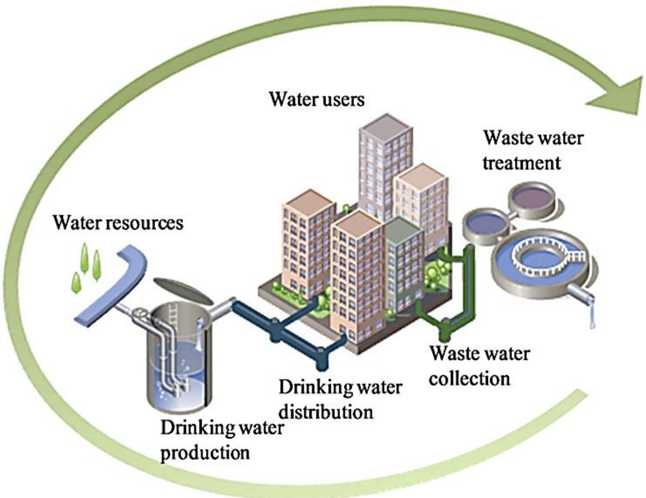


Figure C – Cyclical relationship between main components of the water cycle, referred to as DWC **(Loubet et al., 2014)**.

Related studies within the framework of WSD

An note is that there is a parallel and related study which quantifies the impact of chemical-, & energy consumption and material use for the components 'Raw water transportation' and 'Water purification', regarding sustainability issues. This study is conducted by D. Gerdes from the Utrecht University, in cooperation with Oasen N.V. and RIVM. Alongside, progress is being made with other partners and institutes to help formulating the adequate research questions and help set up the WSD to quantify the underlying sustainability matters for each block depicted in figure C. Findings of these studies will not be addressed in this report.

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ANNEX 5: CONCEPTUAL FRAMEWORK

PROCES ANALYSIS METHOD

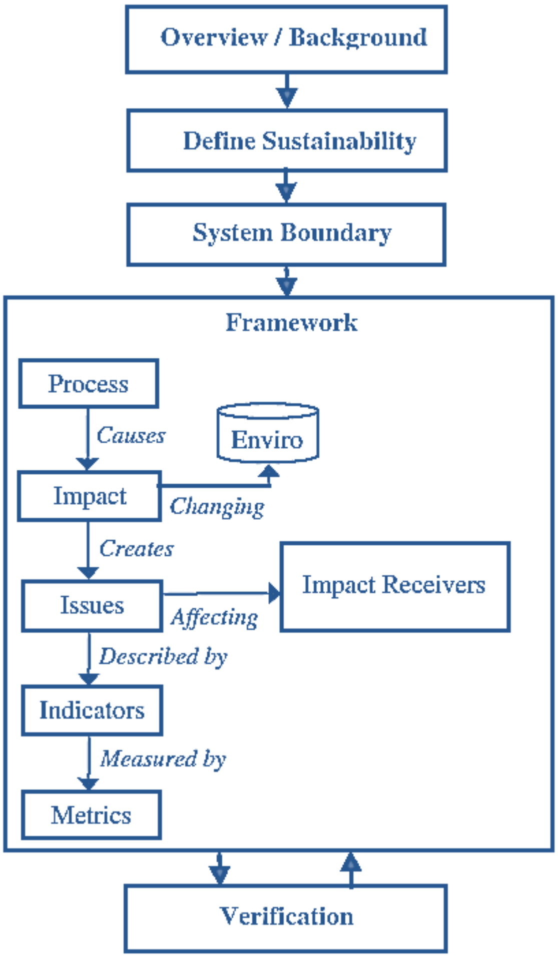

Figure D – The process analysis method flow chart, modified from **Chee Tharir & Darton (2010)** and **Etmannski & Darton (2014)**.

References:

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MAIN CONSOLTED DOCUMENTS FOR THE CONCEPTUAL MODEL

Gebiedsdossiers / area dossiers

Documents which describe important ins and outs of existing water abstraction sites will be used in order to get a sense of which environmental aspects are influenced by groundwater extraction (Wuijts, 2011).

REFLECT-methodology

In the Netherlands used to qualitatively assess the vulnerability of groundwater quality due to land functions (Van den Brink et al., 2013).

The following area dossiers have been used in this analysis:

- Gebiedsdossier Bentunepolder (Royal Haskoning B.V. et al., 2011);
- Gebiedsdossier Brakel (Royal HaskoningDHV, 2013);
- Gebiedsdossier Overijssel (Van den Brink et al., 2010);
- Gebiedsdossier Engelse Werk (Bakker et al., 2010);
- Gebiedsdossier Soestduinen (Gemeente Soest et al., 2013);
- Gebiedsdossier Veenendaal (Vergouwen et al., 2013);
- Gebiedsdossier Woerden (Gemeente Woerden et al., 2012).

The following EIAs have been used in this analysis:

- EIA Wierden (Boerefijn et al., 2009);
- EIA Twente-Achterhoek (Boerefijn, Huuskes & Bruinsma (2014);
- EIA VPC-natuurlijk duurzaam (Royal Haskoning, 2004).

The following documents have been used for the integration of the REFLECT-sub scores:

- Actualization REFLECT (Van den Brink et al., 2013);
- Handreiking (grond)waterbescherming (Royal Haskoning, 2015).

Other document that have been used for the overall analysis:

- Afweging bij het gebruik van grondwater en de ondergrond (Boers et al., 2014);
- Ecosysteemdiensten van grondwater en ondergrond (Vermooten & Lijzen, 2014).

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ANNEX 6: FORMULAS IN GENIAT

Table C – List of frequently used symbols.

Symbol	Property	Unit
β	Compressibility	$\left[\frac{s^2}{kg}\right]$
R	Distance from well to boundary condition	$[m]$
r_w	Distance of the edge of the well	$[m]$
n_e	Effective porosity	$[-]$
Q_0	Extraction rate of the well	$\left[\frac{m^2}{d}\right]$
g	Gravitational acceleration	$\left[\frac{m}{s^2}\right]$
k	Hydraulic conductivity	$\left[\frac{m}{d}\right]$
λ	Leakage factor	$[d]$
N	Precipitation rate	$\left[\frac{m}{d}\right]$
r	Radius to the well	$[m]$
ρ_f	Rho fresh water	$\left[\frac{kg}{m^3}\right]$
ρ_s	Rho salt water	$\left[\frac{kg}{m^3}\right]$
ρ_w	Rho water	$\left[\frac{kg}{m^3}\right]$
S	Storativity	$[-]$
D	Thickness aquifer	$[m]$
T	Transmissivity	$\left[\frac{m^2}{d}\right]$
c	Vertical resistance	$\left[\frac{m}{d}\right]$

CONDITIONS OF EQUATIONS

Some often used conditions for the formula derivations are:

- Steady state before extraction activities;
  - Continuity equation is zero;
  - $\Delta in - \Delta out = 0$;
  - Continuity equation is the fundamental rule underlying all changes in spatial distribution;
- The aquifer is homogenous;
  - Storativity is constant;
  - Transmissivity is constant;
- Fully penetrating well screen;
- Extraction rates (Q_0) are constant over time;
- Perfectly radial symmetry;
  - DePuit assumption.

An important note is that the user of GENIAT must deal adequately with the conditions made in formula derivation during the setup of the geo-hydrological scenario.

6.1. ANALYTICAL FORMULAS

WESSELING & WESSELING (1984)

The phreatic water table is given by

$$h(x) = h_s + (H - h_s + Nc)\left\{\tanh\left(\frac{L}{2\lambda}\right)\sinh\left(\frac{x}{\lambda}\right) - \cosh\left(\frac{x}{\lambda}\right) + 1\right\}$$

in which

$$\lambda = \sqrt{Tc} = \sqrt{kD\,c}$$

The seepage intensity is given by

$$q_s = \left(\frac{H - h_s}{c} + N\right)\frac{2\lambda}{L}\tanh\left(\frac{L}{2\lambda}\right) - N$$

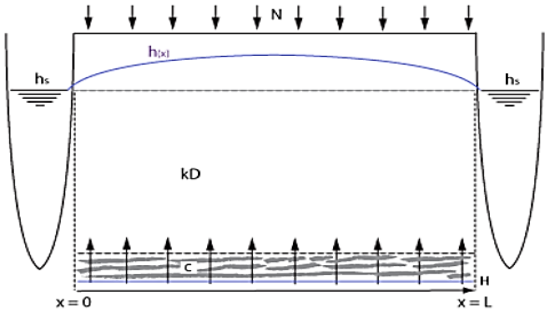

Figure E – Situation of a lot between ditches with precipitation and seepage flux **('Maas', n.d.)**.

Explanation of symbols and visualization of the situation

$h(x)$: phreatic water table $[m]$
h_s : water level $[m]$
H : artesian head $[m]$
L : distance between ditches $[m]$

Other

- Radial resistance near ditches is not taking into account.

BRAUNSFURTH & SCHNEIDER (2008)

Hydraulic head variation in the aquifer is given by

$$h(x) = h_0 - \frac{\lambda}{T}\left(c_1 e^{\frac{x}{\lambda}} - c_2 e^{-\frac{x}{\lambda}}\right)$$

in which

$$c_1 = \frac{T}{2\lambda\sinh\left(\frac{L}{\lambda}\right)}\left\{(h_a - h_0)e^{-\frac{x}{\lambda}} - (h_b - h_0)\right\}$$

$$c_2 = \frac{T}{2\lambda\sinh\left(\frac{L}{\lambda}\right)}\left\{(h_a - h_0)e^{\frac{x}{\lambda}} - (h_b - h_0)\right\}$$

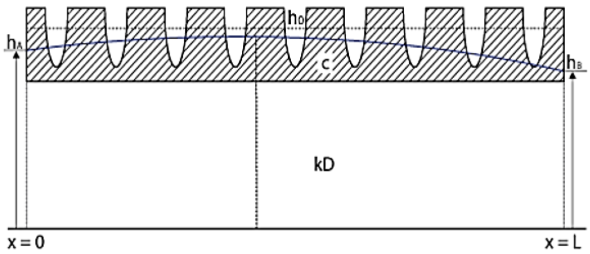

Figure F – Hydraulic head variation over a covering layer with ditches **('Maas', n.d.)**.

Explanation of symbols and visualization of the situation

x : distance between edges $[m]$
h_0 : water level in ditches $[m]$
h_a : hydraulic head at $x = 0$ $[m]$
h_b : hydraulic head $x = L$ $[m]$
L : distance between ditches $[m]$

Other

- h_0, h_a and h_b are steady boundary conditions.

BEAR (2012)

The phreatic water table is given by

$$h^2(x) = h_0^2 - \left(\frac{h_0^2 - h_L^2}{L}\right)x + \frac{N}{k}(L-x)x$$

Horizontal specific discharge is given by

$$q(x) = \frac{k}{2L}(h_0^2 - h_L^2) - N\left(\frac{L}{2} - x\right)$$

<u>Explanation of symbols and visualization of the situation</u>

x	:	distance between edges $[m]$
h_0	:	water level at $x = 0\ [m]$
h_L	:	hydraulic head $x = L\ [m]$
L	:	distance between ditches $[m]$
$q(x)$	:	specific horizontal discharge in the aquifer $[\frac{m}{d}]$

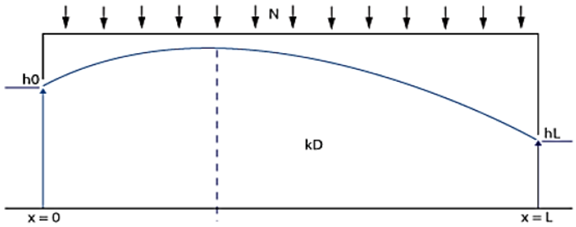

Figure G – Phreatic water level variation between ditches **('Maas', n.d.)**.

Other

- Mostly applicable for nature area's without ditches.

VERRUIJT (1970)

Drawdown in a phreatic aquifer with boundary conditions is given by

$$h(r)^2 = h_0^2 + \frac{N}{2k}(R^2 - r^2) + \frac{Q_0}{\pi k} ln\left(\frac{r}{R}\right)$$

<u>Explanation of symbols and visualization of the situation</u>

$h(r)$	:	phreatic groundwater level $[m]$
h_0	:	hydraulic head on boundary condition $[m]$

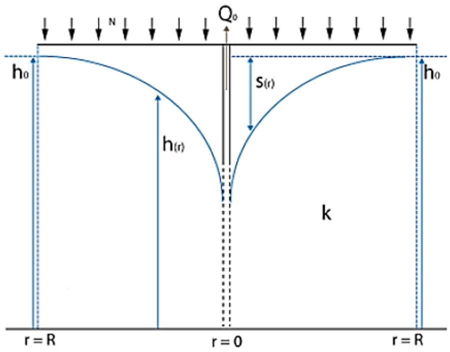

Figure H – Drawdown in a phreatic aquifer with boundary conditions **('Maas', n.d.)**.

Drawdown in a confined aquifer with boundary conditions is given by

$$\varphi(r) - \varphi_0 = \frac{Q_0}{2\pi T} \ln\left(\frac{r}{R}\right)$$

<u>Explanation of symbols and visualization of the situation</u>

$\varphi(r)$	:	hydraulic head in the aquifer $[m]$
φ_0	:	hydraulic head at boundary condition $[m]$

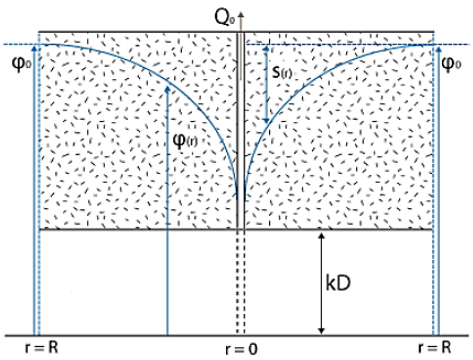

Figure I – Drawdown in a confined aquifer with boundary conditions **('Maas', n.d.)**.

THEIS (1935)

Drawdown as a function of time in a confined aquifer without boundary conditions is given by

$$s(u^2) = \frac{Q_0}{4\pi T} W_{(u^2)}$$

In which

$$u^2 = \frac{Sr^2}{4Tt}$$

And

$$S = \rho g n_e \beta D$$

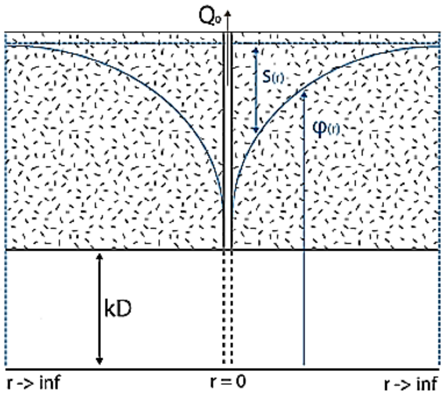

Figure J – Extraction in a confined aquifer (**'Maas', n.d.**).

Explanation of symbols and visualization of the situation

$s(u^2)$: drawdown in aquifer $[m]$

Other

- 'W' indicates the Theis well function.
  A simplified approximation is $W(u) = \ln\frac{0{,}562}{u}$, when $u < 0{,}1$.

DE VRIES (1974)

Travel time to a well in a phreatic aquifer is given by

$$t(r) = n_e \sqrt{\frac{\pi}{2kQ_0}} \left[r_i^2 g(r_i) - r^2 g(r_i) + \frac{r_w^2\sqrt{\pi}}{2C}\left[erfi\big(g(r_i)\big) - erfi\big(g(r)\big)\right]\right]$$

in which

$$g(r) = \sqrt{\ln\left(C\frac{r^2}{r_w^2}\right)}$$

$$erfi(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{t^2}dt$$

and

$$\ln C = \frac{2\pi k h_w^2}{Q_0}$$

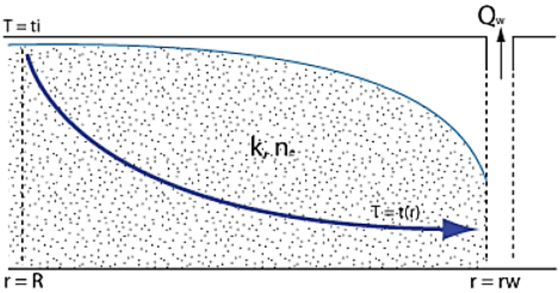

Figure K – Travel time to a well in a phreatic aquifer (**'Maas', n.d.**).

Explanation of symbols and visualization of the situation

$h(r)$: phreatic groundwater level $[m]$
$h(R)$: hydraulic head on boundary condition $[m]$
h_w : hydraulic head directly next to the well $[m]$
r_i : distance from well to particle $[m]$

Travel time to a groundwater well in a confined aquifer is given by

$$t_1 - t_2 = \frac{n_e D}{N}\ln\left(\frac{x_2}{x_1}\right)$$

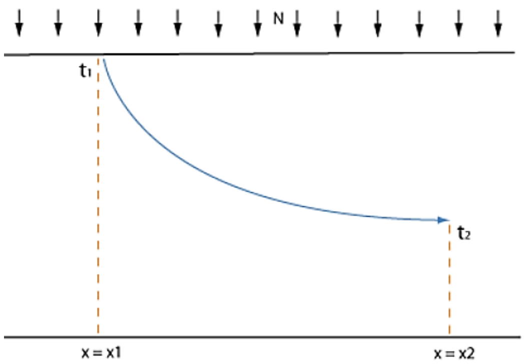

Figure L – Age of water as a function of depth in a confined aquifer (**'Maas', n.d.**).

Other

- May also be used to calculate vertical travel times.

MEINARDI (1994)

Age of water in as a function of depth is given by

$$t(z) = \frac{\theta D}{N} \ln\left(\frac{D}{D-z}\right)$$

<u>Explanation of symbols and visualization of the situation</u>

t_1 : moment of particle departure at x_1 $[d]$
t_2 : moment of particle arrivle at x_2 $[d]$
x_1 : infiltration point of a particle $[m]$
$z(t)$: depth of a water particle $[m]$
N : replenishment rate $\left[\frac{m}{d}\right]$
θ : porosity $[-]$

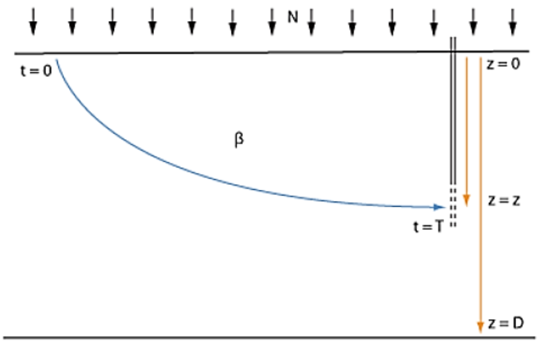

Figure M – Age of water as a function of depth in a phreatic aquifer **('Maas', n.d.)**.

DAGAN & BEAR (1968)

Steady state solution for upconing of the saline water interface beneath a pumping well is given by

$$\eta = \frac{\rho_f * Q_0}{2\pi D k(\rho_s - \rho_f)} * \frac{1}{\left[1 + \left(\frac{r}{D}\right)^2\right]^{\frac{1}{2}}}$$

<u>Explanation of symbols</u>

η : upconing of saline interface $[m]$

Other

- As described by Rushton (2003), in steady state and based on the Gyyben-Herzburg principle;
- Applicable on layered aquifers, but in GENIAT also used for approximations in phreatic situations;
- Assumes a sharp interface.

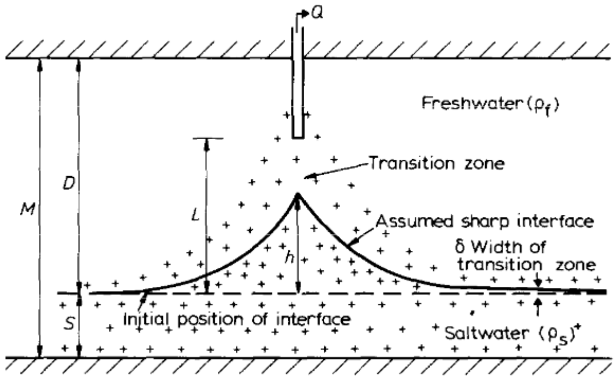

Figure N – Steady state solution for upconing of the saline water interface beneath a pumping well **(Chandler & McWhorter, 1975)**.

DARCY'S LAW (WHITAKER, 1986)

Change in seepage flux through a confined layer is given by

$$q_v = \frac{\varphi_{aquif} - \varphi_{avg}}{c}$$

<u>Explanation of symbols</u>

q_v : seepage flux though clay layer $[m]$
φ_{aquif} : artesian head $[m]$
φ_{avg} : hydraulic head $[m]$

CHAPUIS EN CHESNEAUX (2006)

An indication of the width of the sphere of influence is given by

$$R = r_w e^{\pi k(h_r^2 - h_w^2)/Q_w}$$

Explanation of symbols

$h(r)$: phreatic groundwater level $[m]$

h_w : hydraulic head directly next to the well $[m]$

THERZAGI (1925)

Consolidation of a dry layer is given by

$$Z_z = \frac{d}{C} \ln \frac{\bar{\sigma}_{k,after}}{\sigma_{k,before}}$$

in which

$$\sigma_k = \sigma_t - \sigma_w$$

Explanation of symbols

Z_z : consolidation $[m]$

C : coefficient of consolidation $[-]$

σ_t : total stress $[\rho g h]$

σ_w : fluid stress $[\rho g h]$

σ_k : effective stress $[\rho g h]$

HOOGLAND, VAN DEN AKKER, & BRUS (2012).

Oxidation of the peat layer is given by

$$\Delta h = h_{dry} * \left(1 - e^{(-V_{ox} * \Delta t)}\right)$$

Explanation of symbols

Δh : subsidence due to peat oxidation $[m]$

h_{dry} : thickness of peat above groundwater level $[m]$

V_{ox} : oxidation rate $\left[\frac{\frac{m}{y}}{h_{dry}}\right]$

Δt : time above water level $[y]$

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6.2. MULTILAYER FORMULA SIMPLIFICATION

It is deliberately chosen not to incorporate multilayer formulas in GENIAT due to the limited timeframe of the overall research. Multilayer formulas are needed to assess the lowering of piezometric levels due to groundwater extraction beneath various confining layers. This delimitation makes is necessary to work with input from other hydrological models.

In case there is no data available concerning the hydrological situation, but there is knowledge about the geological composition of the area, GENIAT is able to roughly estimate the piezometric surface in case of deep groundwater extraction.

In formula 6.1 it is assumed that the seepage flux is fully discharged via the ditch and it is assumed that there is no precipitation (Bot, 2011):

$$h_{average} = \frac{\lambda}{\lambda + c}(\varphi_{deep} - \varphi_{ditch}) \qquad (6.1)$$

h_{avg}	:	average groundwater level $[m]$
λ	:	leakage factor $[d]$
c	:	vertical resistance$[m]$
φ_{deep}	:	artesian head $[m]$
φ_{deep}	:	water level in ditch $[m]$

Formula 6.1 is not used to determine the groundwater level in a situation with drawdown. Instead, the formula is used as shown in formula 6.2 to approximate an attenuation factor (dempingsfactor), as a result of the geo-hydrological situation.

$$attenuation\ factor = \frac{1}{\frac{\gamma_l}{\gamma_l + c}(\varphi_{deep} - \varphi_{ditch})} \qquad (6.2)$$

The attenuation effect is used to approximate the drawdown inflicted by deep groundwater extraction, beneath several clay layers. The local drawdown calculated by Theis (1935) or Verruijt (1970) is divided with the attenuation factor.

This methodology is used in paragraph 4.4. Case Kamerik, in scenario B and scenario C.

Reference:

- Bot, B., (2011) Grondwater zakboekje. Rotterdam, The Netherlands. Bot Raadgevend Ingenieurs.

ANNEX 7: DOSE EFFECT FUNCTION DEMNAT

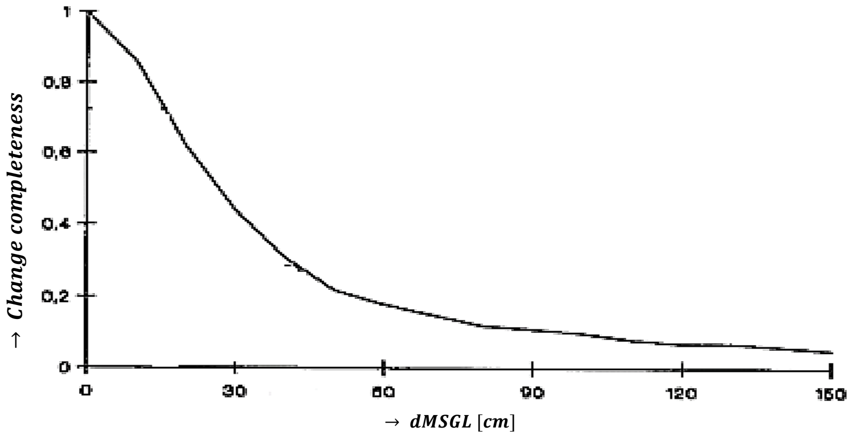


Figure M – Description of the empirical relationship between a change in MSGL and terrestrial vegetation completeness **(Van Ek et al., 2000)**.

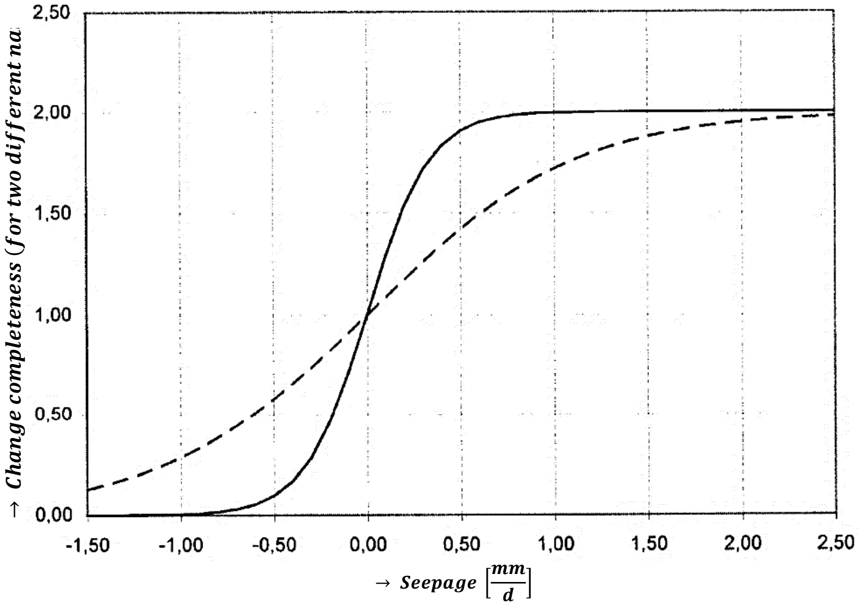


Figure O – Description of the empirical relationship between a change in upward seepage flux and terrestrial vegetation completeness **(Van Ek & Bos, 1997).**

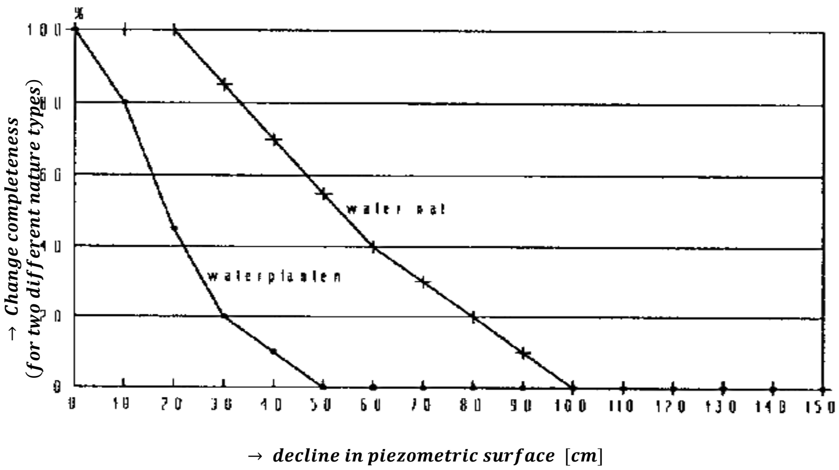


Figure P – Description of the empirical relationship between a change in water levels [cm] and terrestrial vegetation completeness in case of a low geographical context **(Van Ek & Bos, 1997).**

|

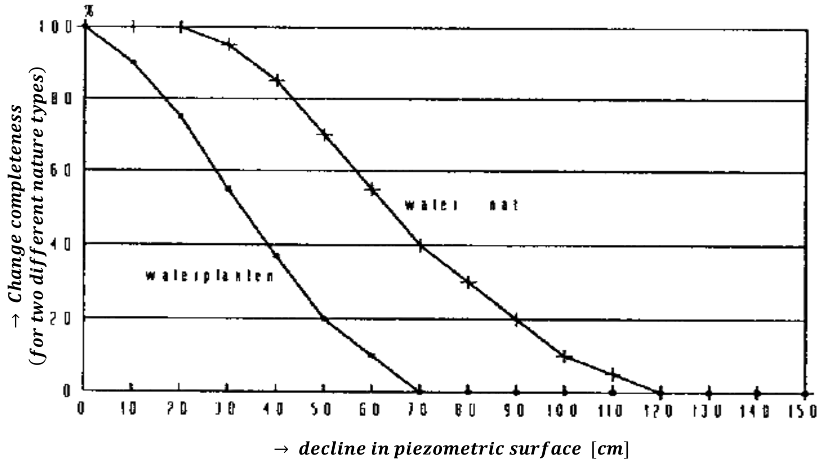


Figure Q – Description of the empirical relationship between a change in water levels $[cm]$ and terrestrial vegetation completeness in case of a low geographical context **(Van Ek & Bos, 1997).**

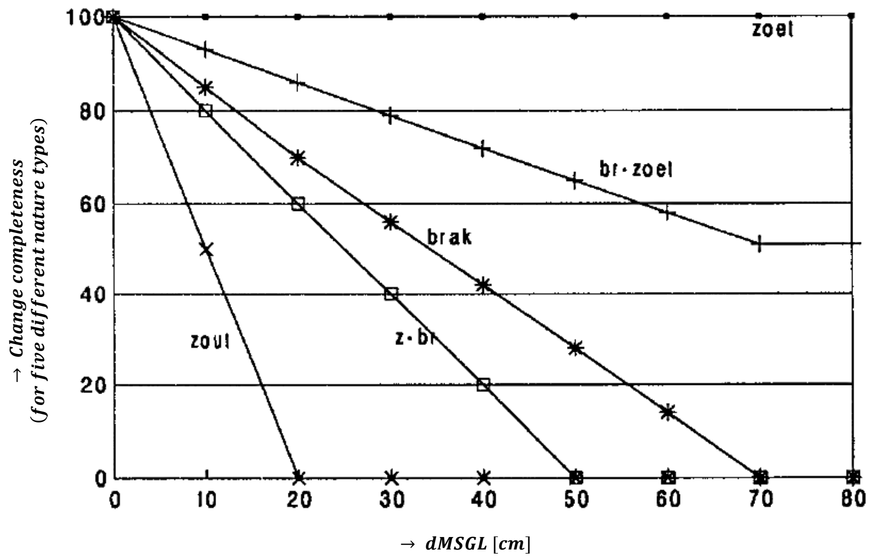


Figure R – Description of the empirical relationship between a change in MSGL, freshening and terrestrial vegetation completeness based upon the salinity dependency phreatophytes **(Van Ek & Bos, 1997)**.

References:

- Ek, R. V., & Bos, H. (1997). Dosis-effect-module DEMNAT-2.1. *RIZA*.
- Van Ek, R., Witte, J. P. M., Runhaar, H., & Klijn, F. (2000). Ecological effects of water management in the Netherlands: the model DEMNAT. *Ecological Engineering*, 16(1), 127-141

ANNEX 8: SENSITIVITY ANALYSIS

8.1. SENSITIVITY OF THE SCENARIO PHREATIC

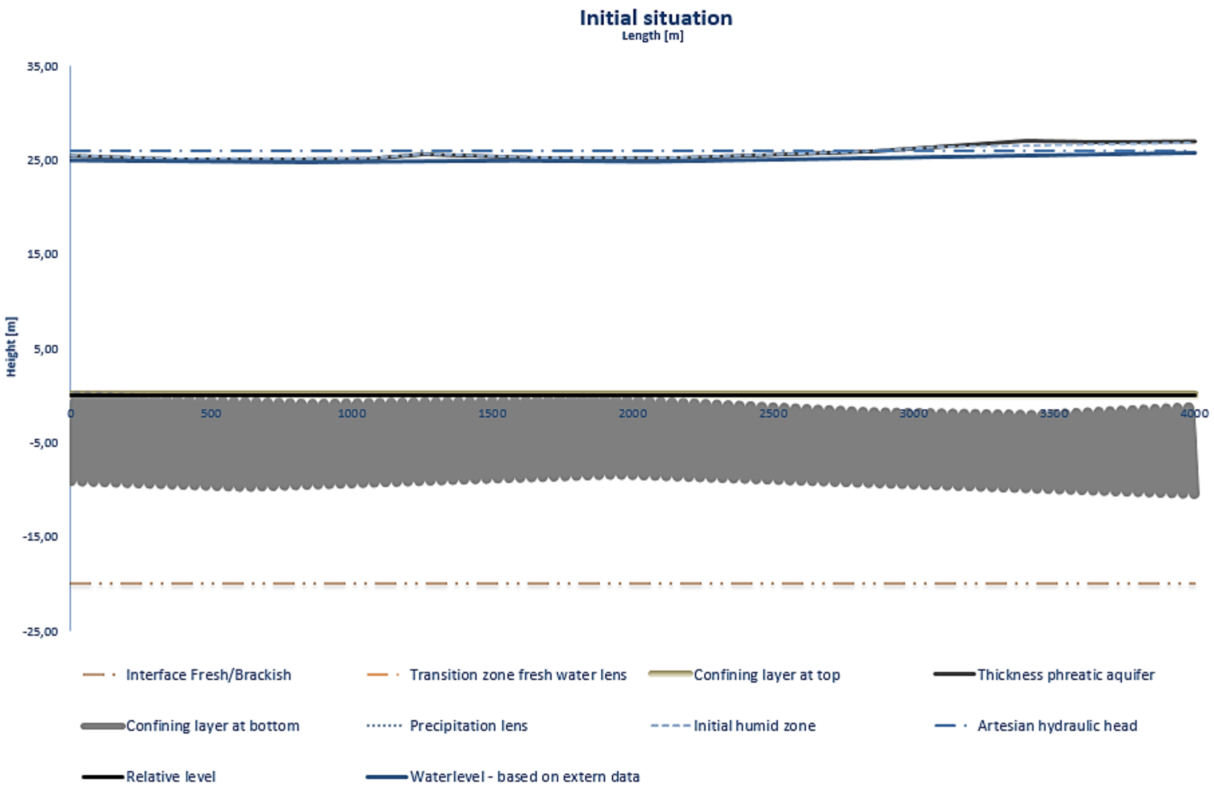


Figure S – Geo-hydrological situation for the scenario 'phreatic'.

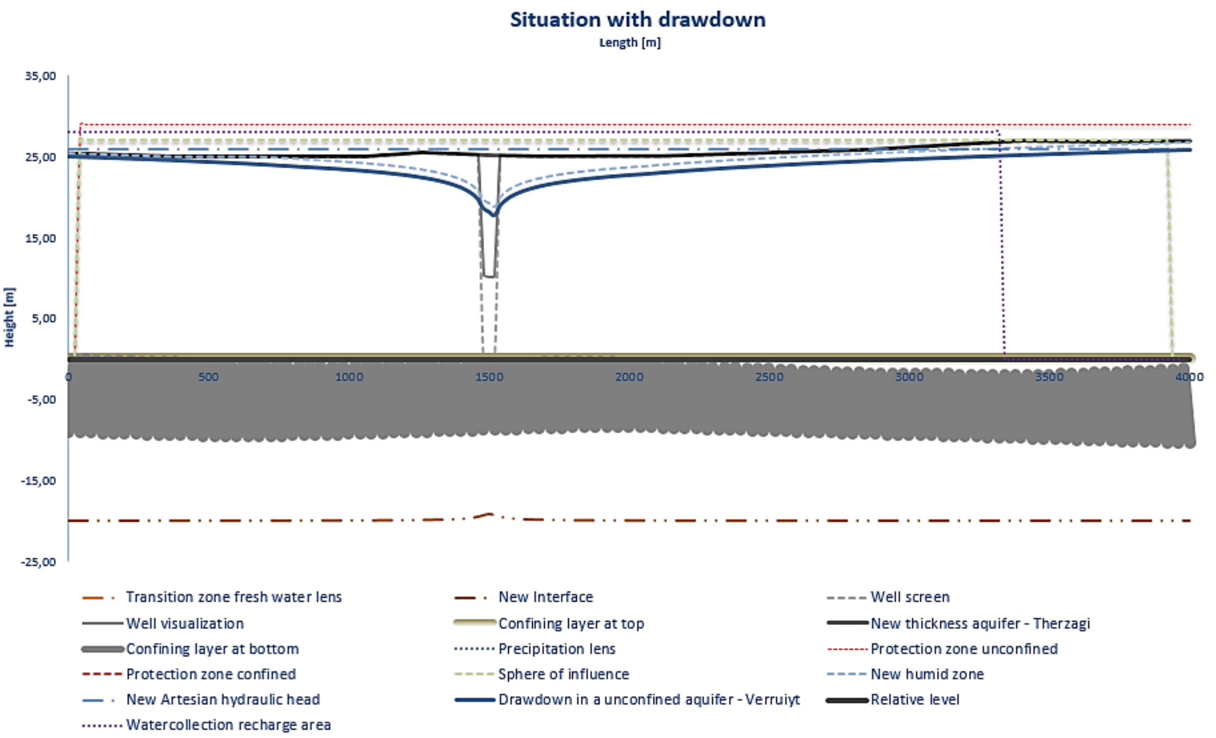


Figure T – Geo-hydrological situation in case of groundwater extraction in the scenario 'phreatic'.

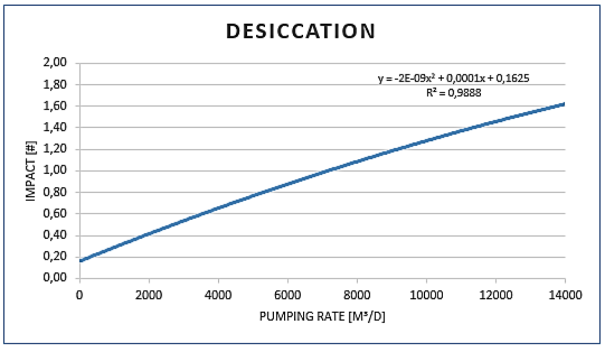


Figure U – Aggregated result of the variables below.

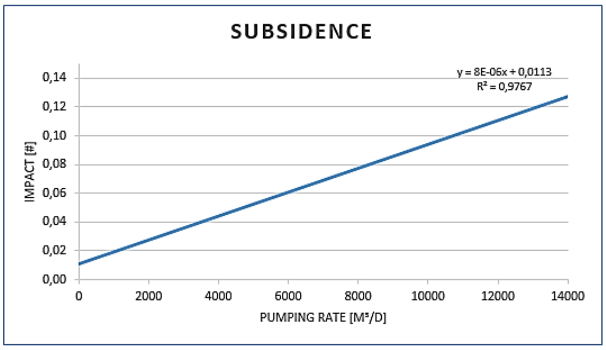


Figure V – Aggregated result of the variables below.

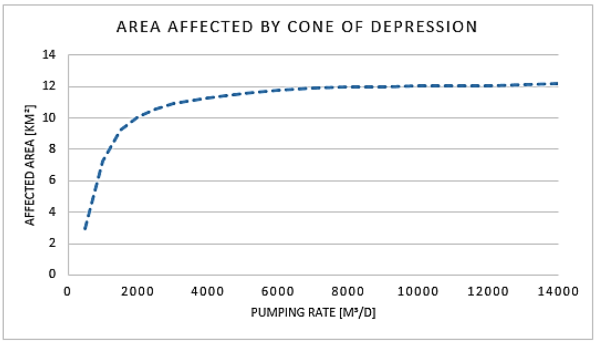


Figure W – Pumping rate VS area affected by cone of depression.

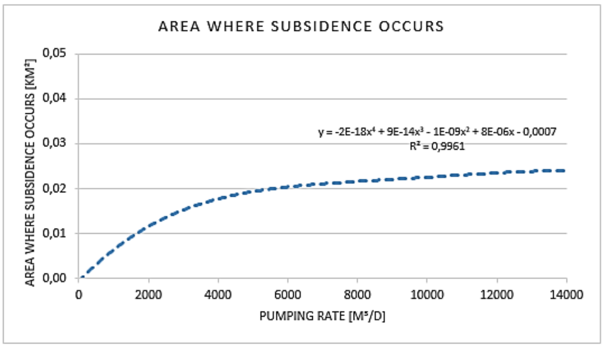


Figure X – Pumping rate VS area affected by subsidence.

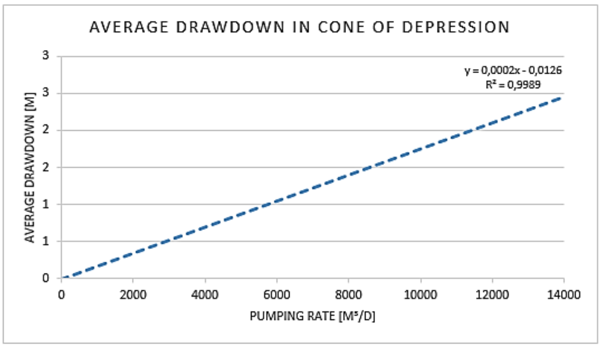


Figure Y – Pumping rate VS average drawdown in cone of depression.

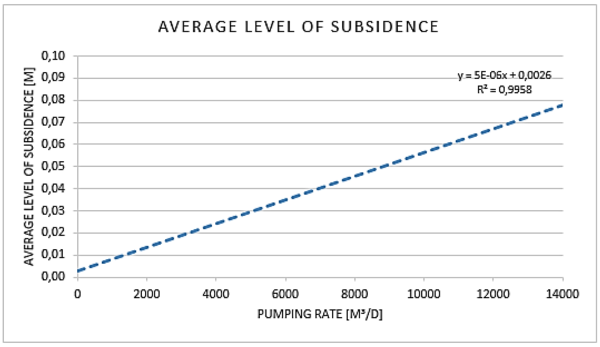


Figure Z – Pumping rate VS average subsidence in affected area.

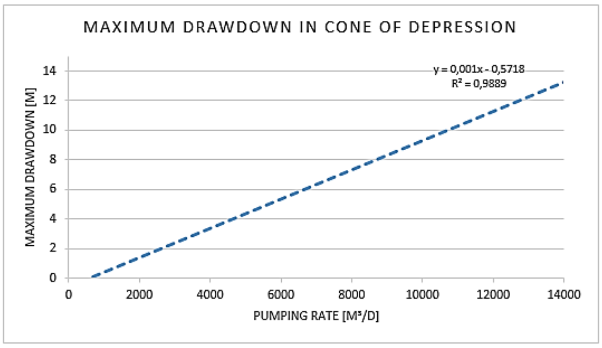


Figure AA – Pumping rate VS maximum drawdown in cone of depression.

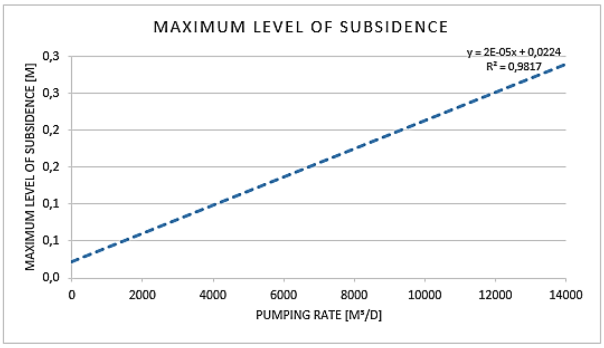


Figure AB – Pumping rate VS maximum subsidence in affected area.

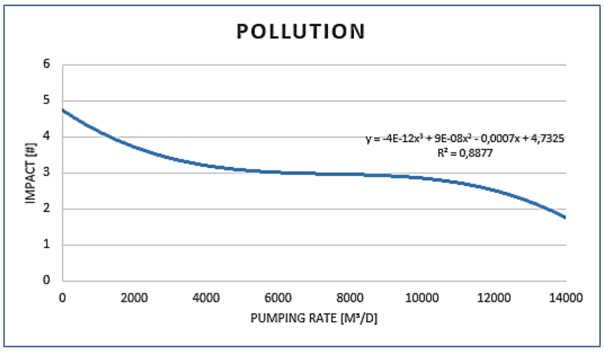


Figure AC – Pumping rate VS dispersion of pollution, expressed in the scoring system.

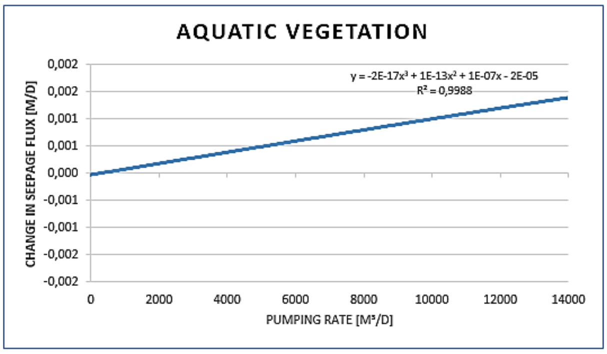


Figure AD – Pumping rate VS change in seepage flux.

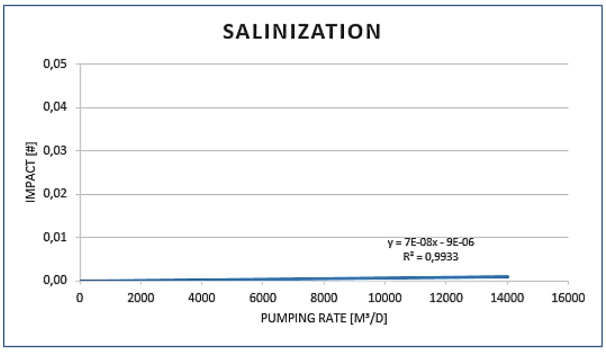


Figure AE – Pumping rate VS salinized volume of groundwater.

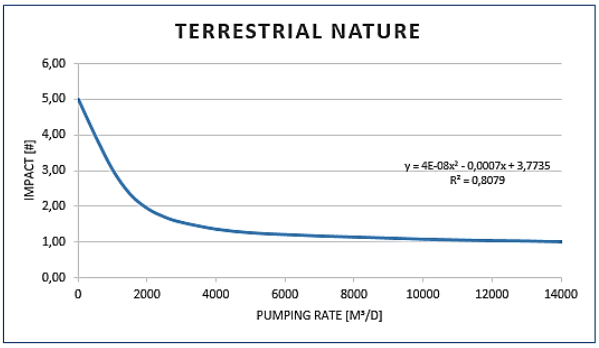


Figure AF – Pumping rate VS stress on phreatophytic vegetation, expressed in the scoring system.

The following explanation is given for the figures above:

- the **higher** the trend line indicating **desiccation** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **salinization** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **subsidence** score, the more negative the forecasted influence;

- the **lower** the trend line indicating **pollution**, the more negative the forecasted influence;
- the **lower** the trend line indicating **aquatic vegetation** score, the more negative the forecasted influence;
- the **lower** the trend line indicating **terrestrial vegetation** score, the more negative the forecasted influence.

8.2. SENSITIVITY OF THE SCENARIO SHALLOW

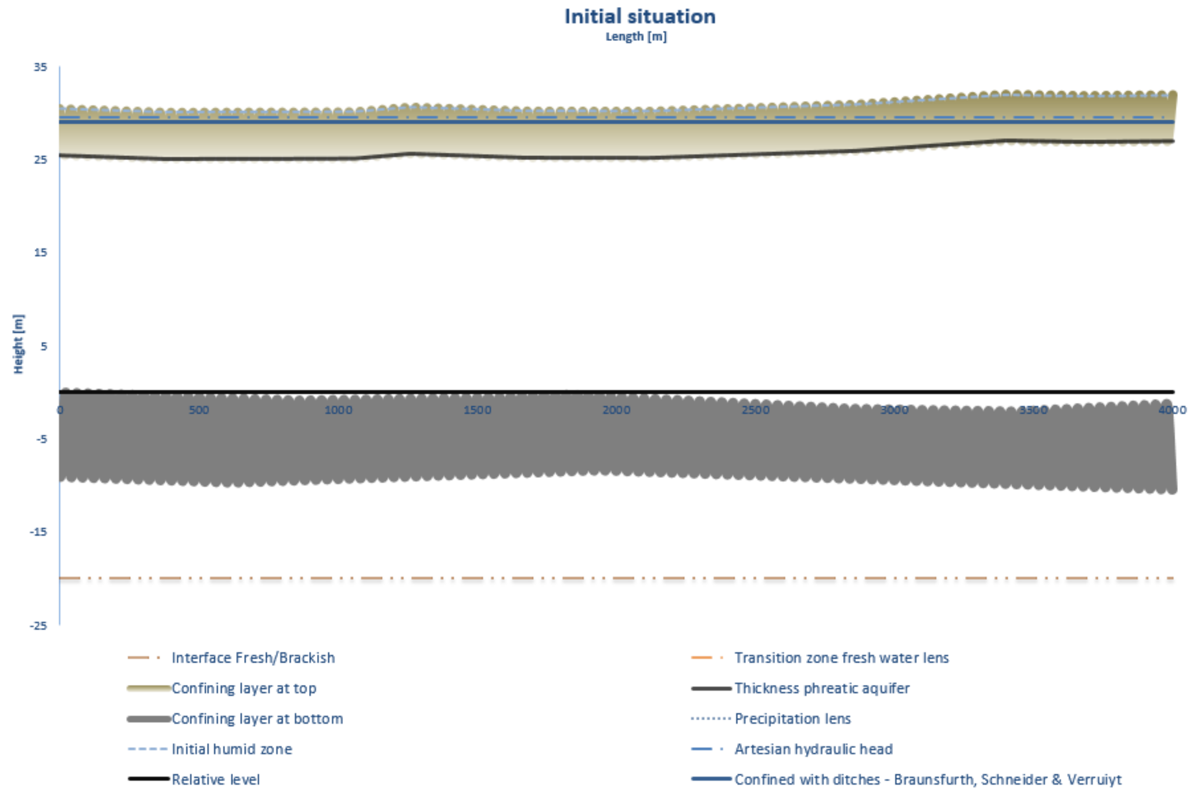


Figure AG – Geo-hydrological situation for the scenario 'shallow'.

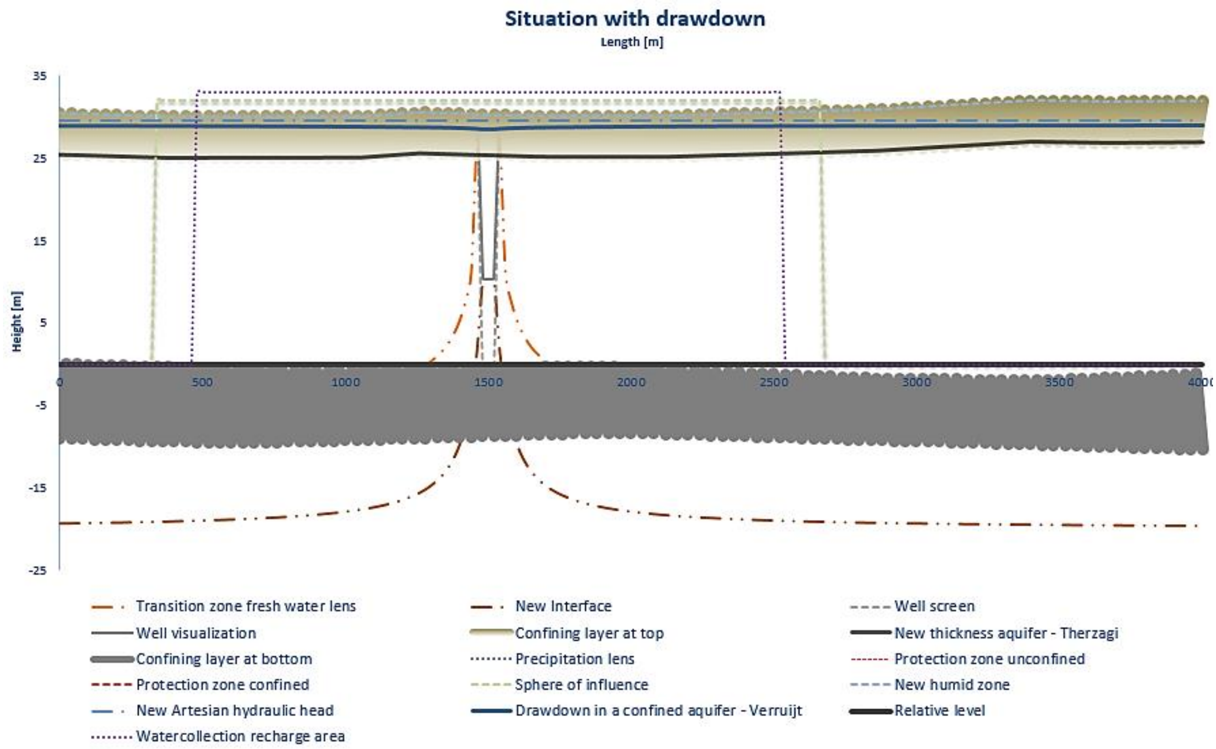


Figure AH – Geo-hydrological situation in case of groundwater extraction in the scenario 'shallow'. In this scenario is chosen that the clay layers does not affect the upconing in order to determine the sensitivity of the impact category 'salinization'. This is not a realistic assumption.

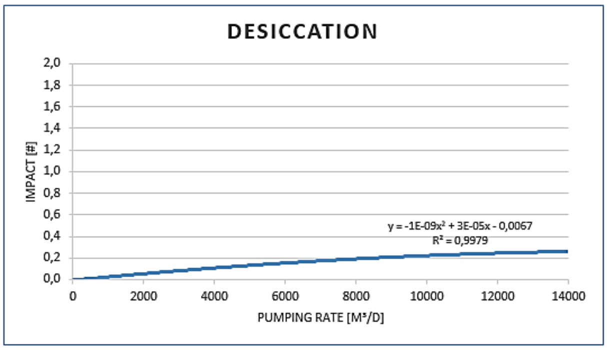


Figure AI – Aggregated result of the variables below.

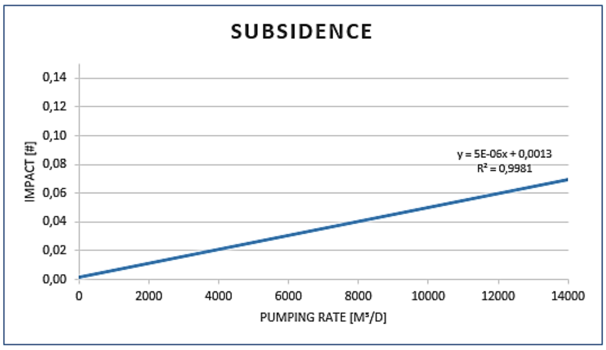


Figure AJ – Aggregated result of the variables below.

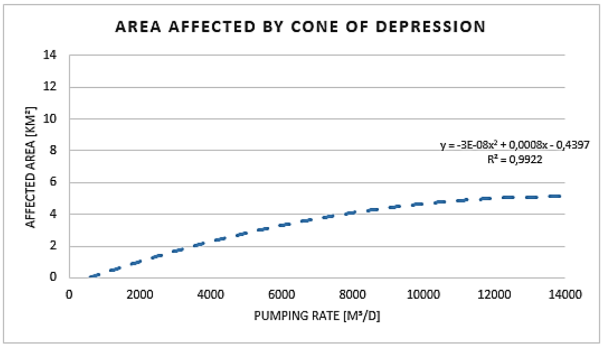


Figure AK – Pumping rate VS area affected by cone of depression**.**

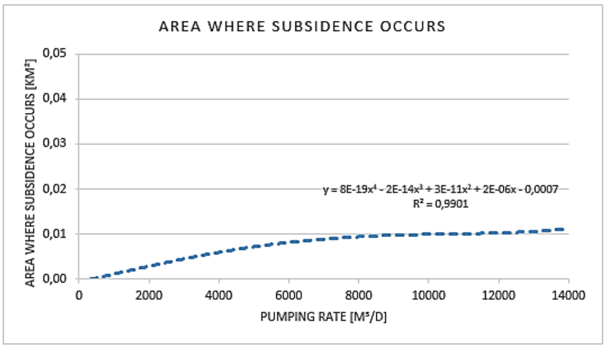


Figure AL – Pumping rate VS area affected by subsidence.

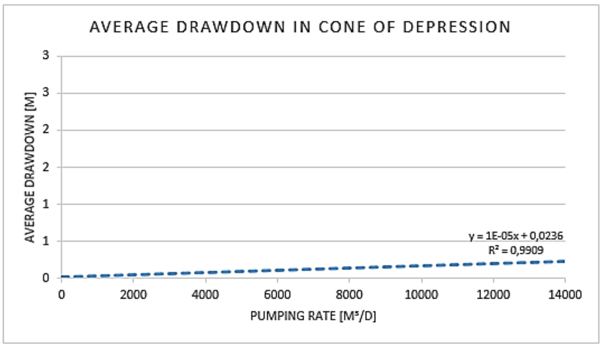


Figure AM – Pumping rate VS average drawdown in cone of depression.

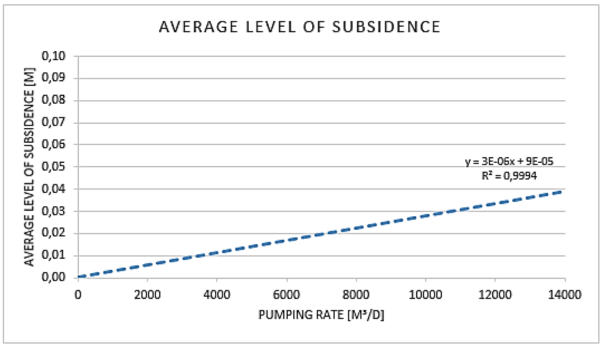


Figure AN – Pumping rate VS average subsidence in affected area.

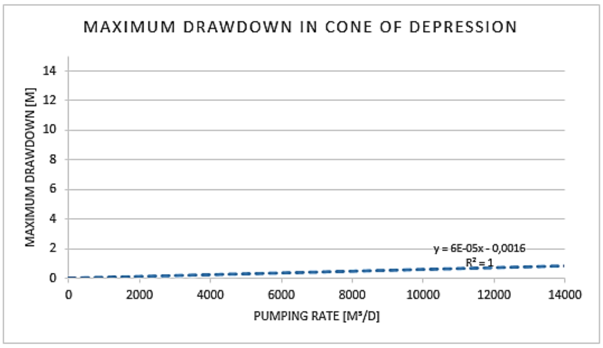


Figure AO – Pumping rate VS maximum drawdown in cone of depression.

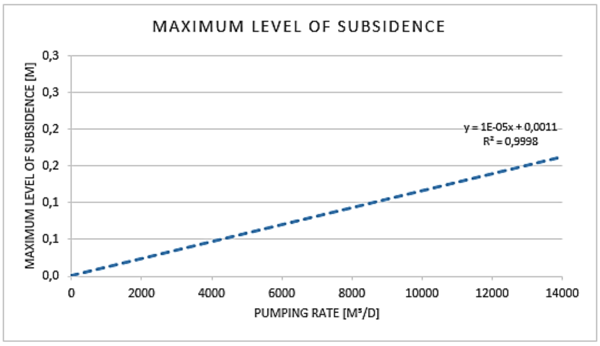


Figure AP – Pumping rate VS maximum subsidence in affected area**.**

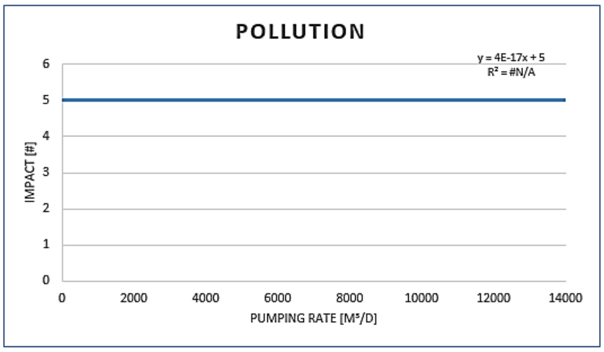


Figure AQ – Pumping rate VS dispersion of pollution, expressed in the scoring system**.**

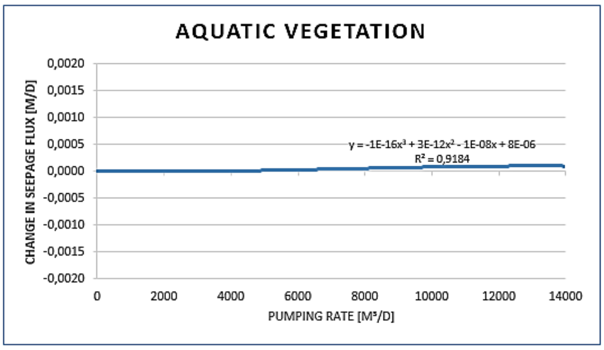


Figure AR – Pumping rate VS change in seepage flux.

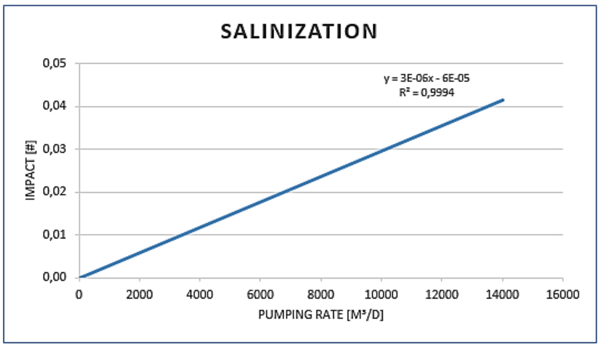


Figure AS – Pumping rate VS salinized volume of groundwater.

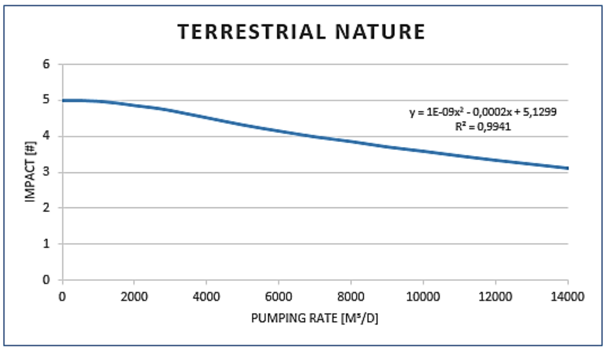


Figure AT – Pumping rate VS stress on phreatophytic vegetation, expressed in the scoring system.

The following explanation is given for the figures above:

- the **higher** the trend line indicating **desiccation** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **salinization** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **subsidence** score, the more negative the forecasted influence;

- the **lower** the trend line indicating **pollution**, the more negative the forecasted influence;
- the **lower** the trend line indicating **aquatic vegetation** score, the more negative the forecasted influence;
- the **lower** the trend line indicating **terrestrial vegetation** score, the more negative the forecasted influence.

8.3. SENSITIVITY OF THE SCENARIO DEEP

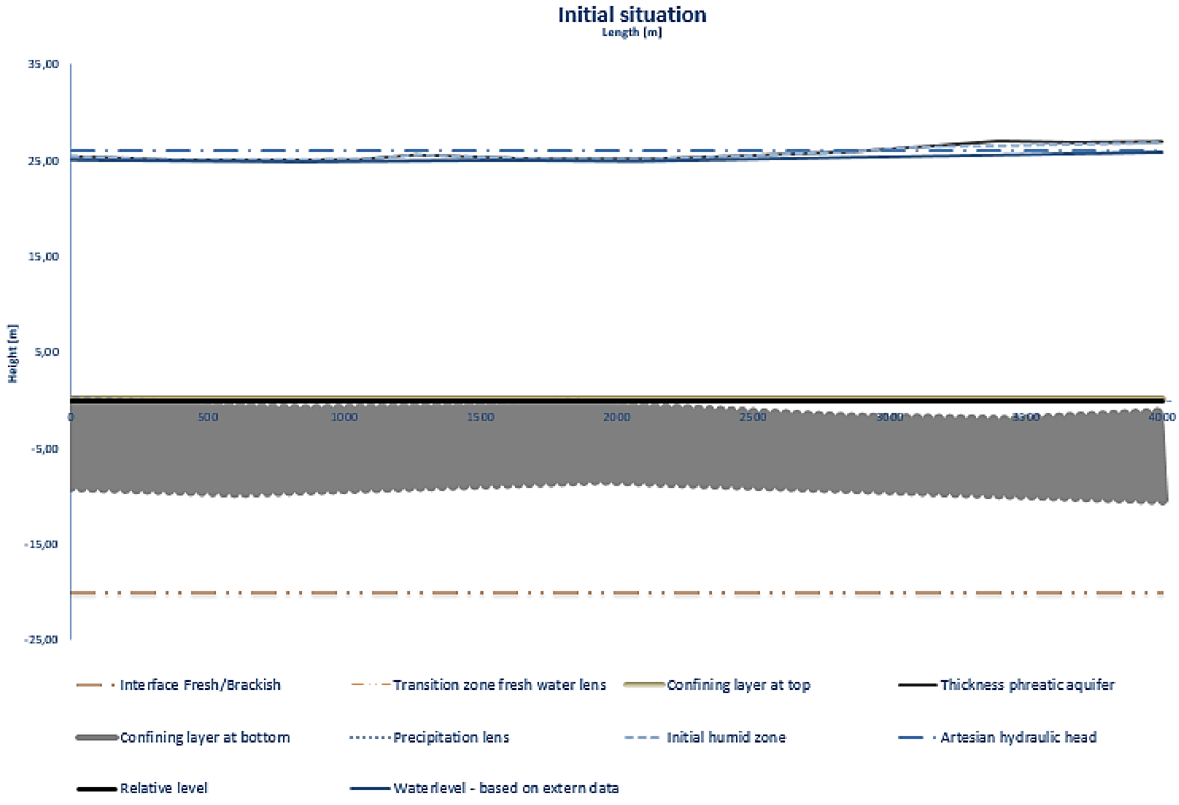


Figure AU – Geo-hydrological situation for the scenario 'deep'.

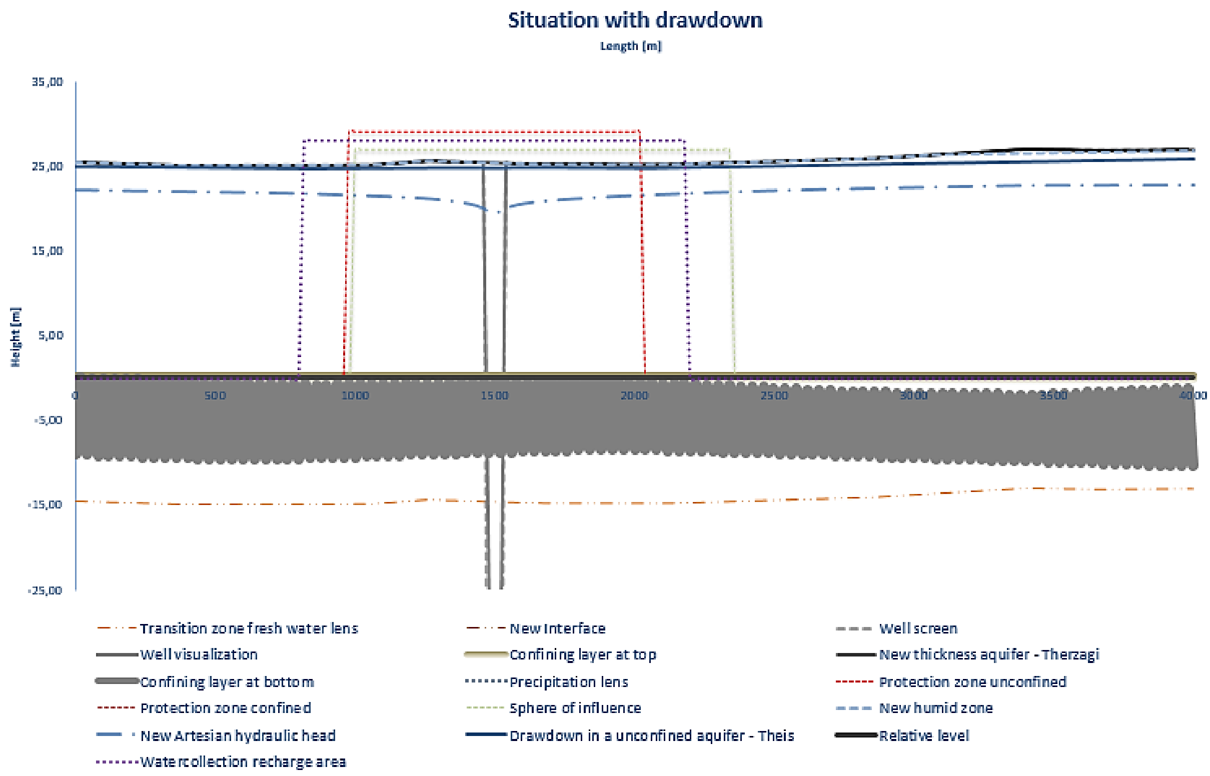


Figure AV – Geo-hydrological situation in case of groundwater extraction in the scenario 'deep'.

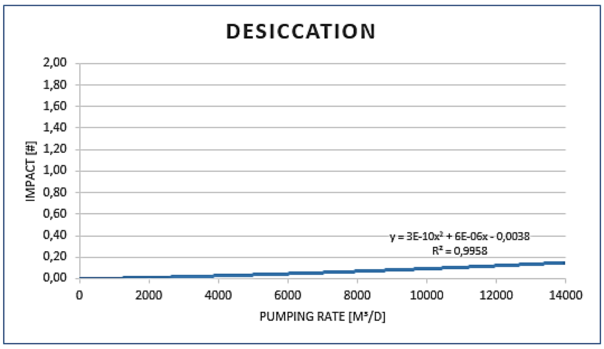


Figure AW – Aggregated result of the variables below.

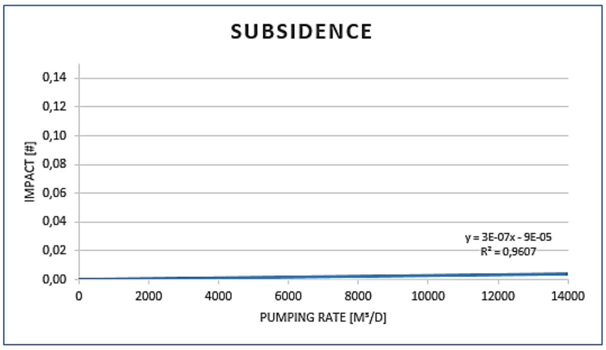


Figure AX – Aggregated result of the variables below.

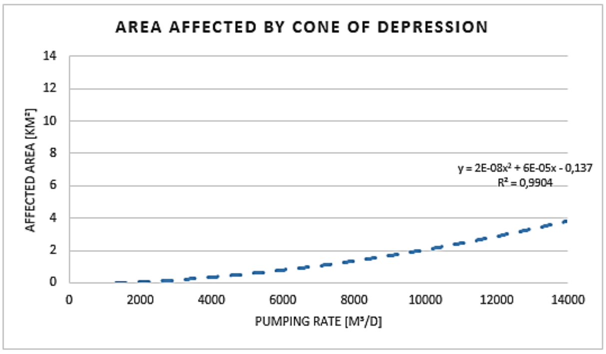


Figure AY – Pumping rate VS area affected by cone of depression.

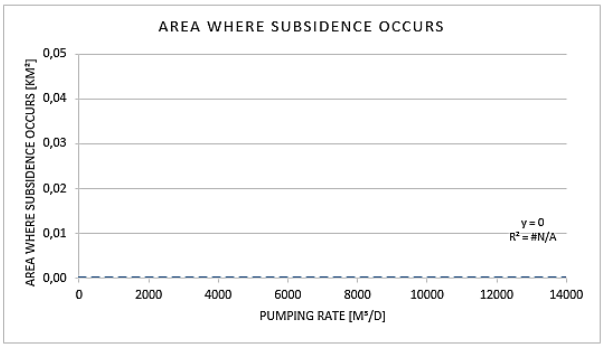


Figure AZ – Pumping rate VS area affected by subsidence.

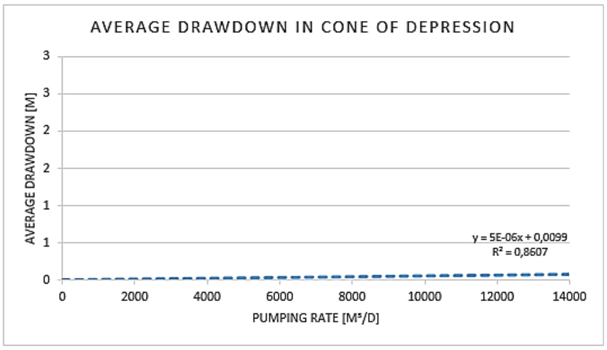


Figure BA – Pumping rate VS average drawdown in cone of depression.

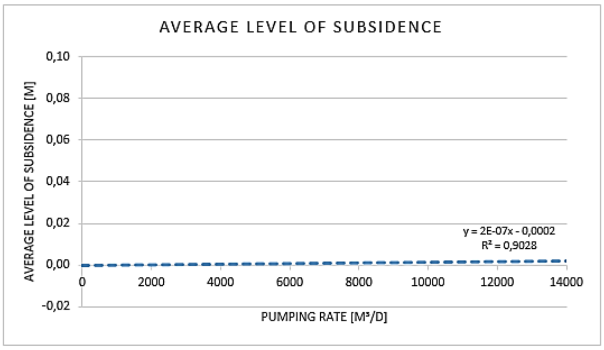


Figure BB – Pumping rate VS average subsidence in affected area.

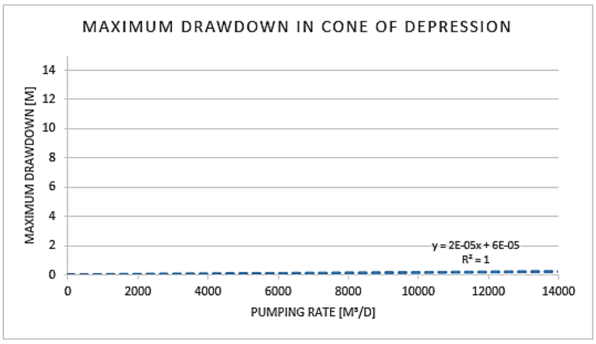


Figure BC – Pumping rate VS maximum drawdown in cone of depression.

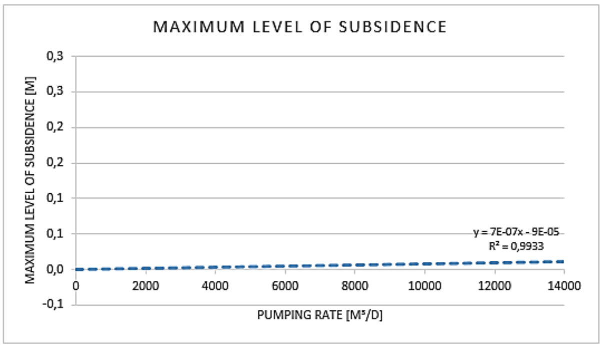


Figure BD – Pumping rate VS maximum subsidence in affected area.

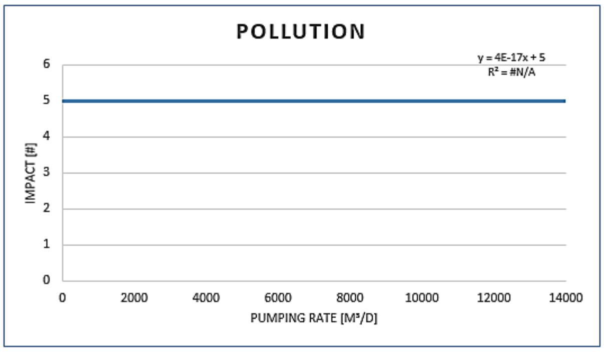


Figure BE – Pumping rate VS dispersion of pollution, expressed in the scoring system.

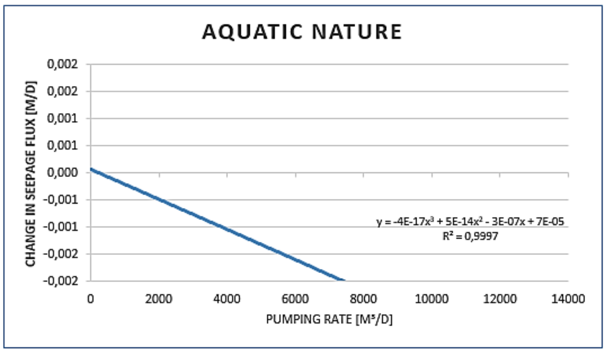


Figure BF – Pumping rate VS change in seepage flux.

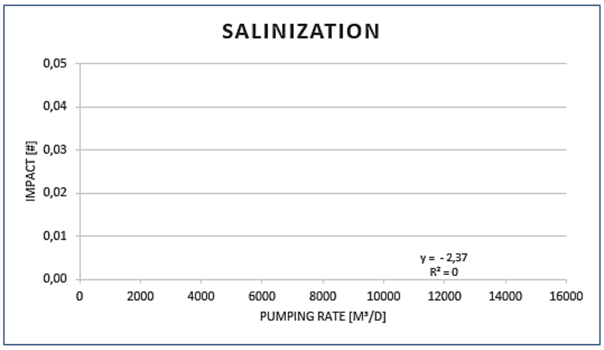


Figure BG – Pumping rate VS salinized volume of groundwater.

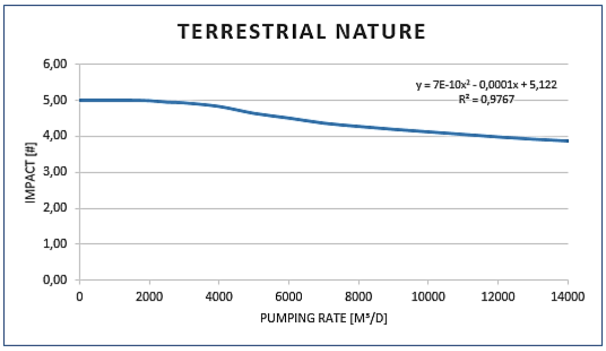


Figure BH – Pumping rate VS stress on phreatophytic vegetation, expressed in the scoring system.

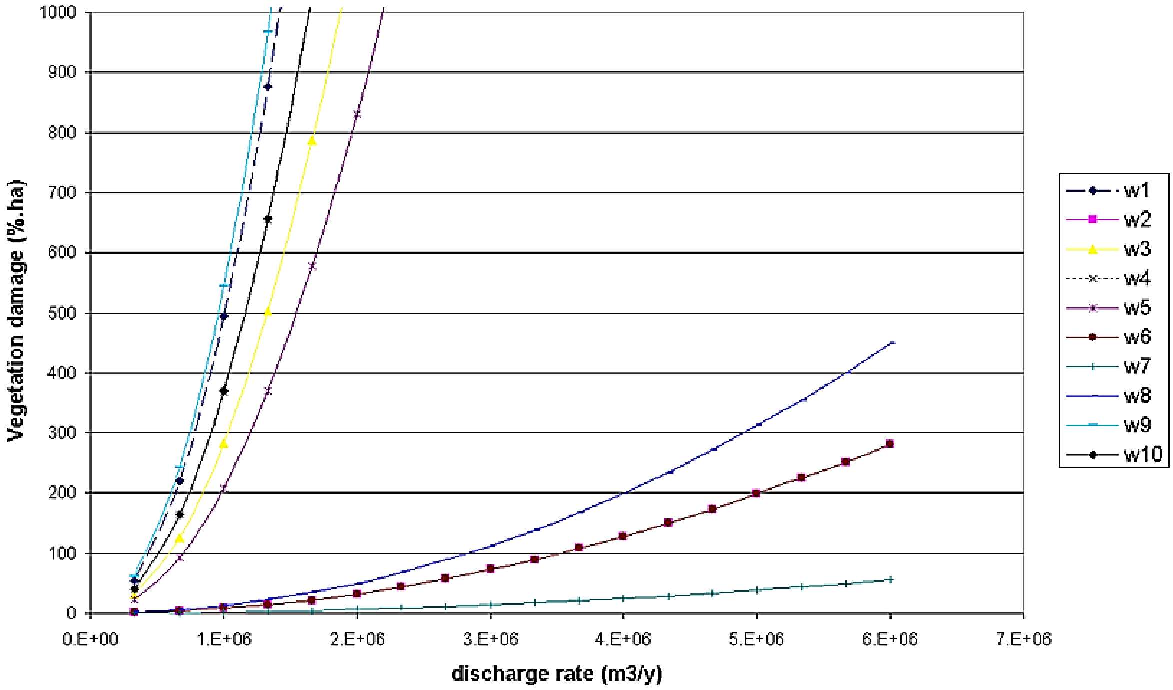
The following explanation is given for the figures above:

- the **higher** the trend line indicating **desiccation** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **salinization** score, the more negative the forecasted influence;
- the **higher** the trend line indicating **subsidence** score, the more negative the forecasted influence;

- the **lower** the trend line indicating **pollution**, the more negative the forecasted influence;
- the **lower** the trend line indicating **aquatic vegetation** score, the more negative the forecasted influence;
- the **lower** the trend line indicating **terrestrial vegetation** score, the more negative the forecasted influence.

8.4. PARETO-OPTIMAL SOULTION

Found by Vink & Schot (2002), using a genetic algorithm optimisation method in a search for a more effective management of drinking water production. Adverse impact of drawdown on phreatophytes was analysed by a nonlinear impact model, using a distributed approach of drawdown and fictitious, location-specific data on vulnerability to lowering of piezometric surface and eco-value. Their findings for the relation between drawdown and vegetation damage $\%.ha$ is depicted in figure BI.



Well	w1	w2	w3	w4	w5	w6	w7	w8	w9	w10
Use of deep groundwater	y	n	y	n	y	n	n	n	n	n

Figure BI - Vegetation damage versus pumping rate

The trend lines indicating the sensitivity of the GENIAT for phreatophytic stress are the result of dose effect functions and the findings of Zelm et al. (2010). These trend lines comparable with the findings of Vink & Schot (2002) in figure BI.

ANNEX 9: CROSS-SECTION KAMERIK

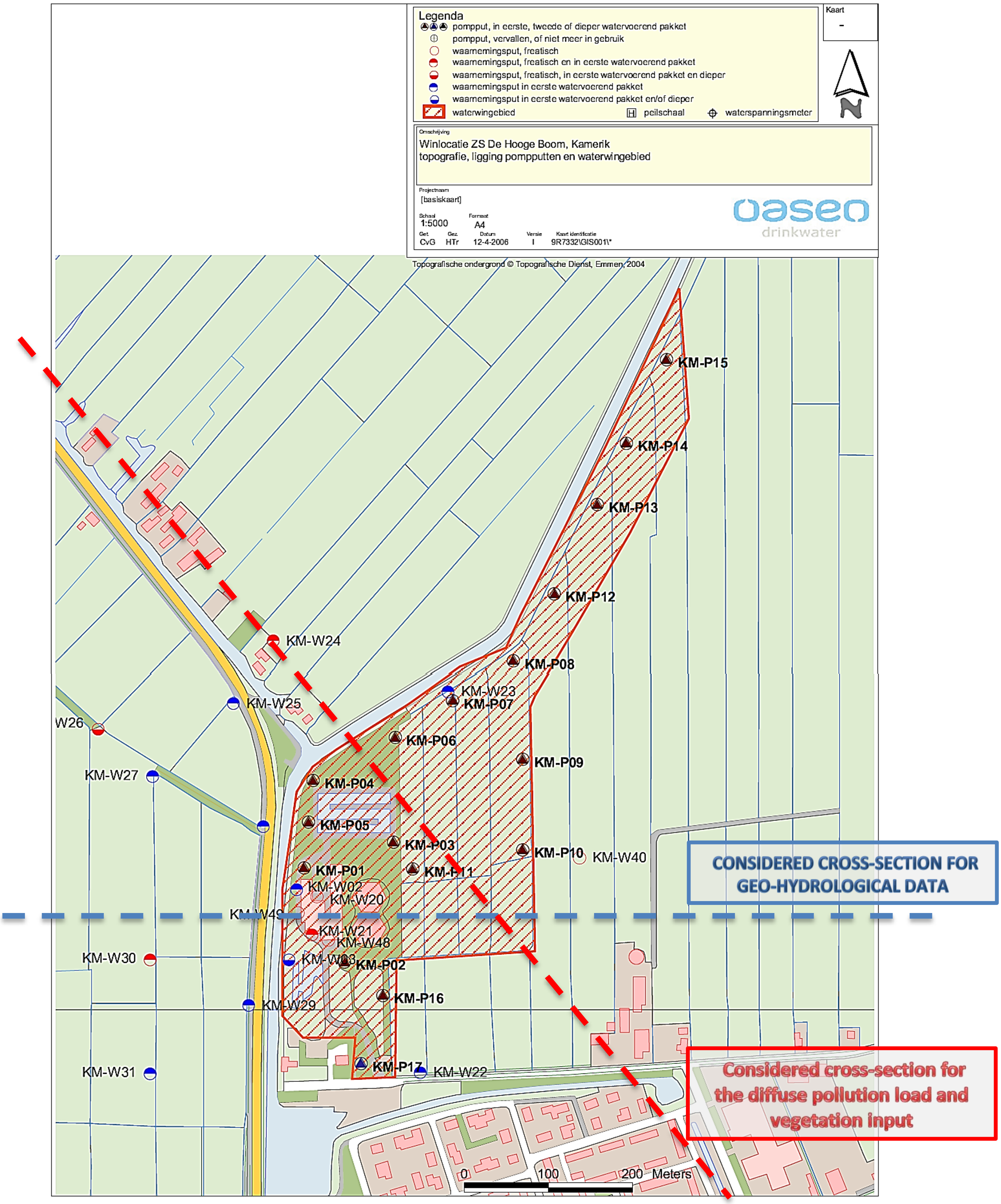


Figure BJ – Considered cross-sections for scenario Kamerik. It is chosen to use the cross-section with the most diffuse pollution sources for the land use synopsis.

ANNEX 10: IDENTIFIED MODEL IMPROVEMENTS

IMPACT ANALYSIS: GEO-HYDROLOGY

- Travel time of groundwater, indicating the age of extracted raw water:
  - Can be improved by means of the findings of Kovar et al. (2005).

IMPACT ANALYSIS: VEGETATION

- Evaluate the possibility and arising pros and cons of enabling a more sophisticated standard grid discretization:
  - The more sophisticated gird must integrate subsurface geo-hydrological changes with aboveground changes approached by its corresponding surface area;
  - This grid would make it possible to implement more local vegetation types, therefore taking more into account the spatially distributed vegetation types.

TERRESTRIAL VEGETATION

- Incorporate the acidification of soils relative to the soil type and the related impact on phreatophytes:
  - According to the findings of Van Ek & Bos (1997) and Van Ek et al. (2000).
- Incorporate dose-effect functions related to certain soil types and related to more specific vegetation types:
  - According to the used method in DEMNAT 3.0.
- Incorporate an analysis, indicating the initial and new 'attendance of vegetation types':
  - Based upon the findings of Van Ek & Bos (1997) and Van Ek et al. (2000).
- Determine the impact on nature value, as defined by DEMNAT, instead of vegetation completeness:
  - Based upon the findings of Van Ek & Bos (1997) and Van Ek et al. (2000).
- Incorporate the effect of salinized upward seepage fluxes and the impact on vegetation types:
  - Based upon related dose effect functions, which are partly determined by Van Ek & Bos (1997).

AQUATIC VEGETATION

- Monitor developments which could help quantify initial vegetation completeness or value:
  - Establish contact with for instance Hoop et al. (2015).
- Include an numerical determination of surface base flow, and the impact on it due to groundwater extraction:
  - Based upon the findings of Lange (2001) and Kemen, Riskens & Charles (2014).
- Incorporate the effect of salinized upward seepage fluxes and the impact on vegetation types:
  - Based upon related dose effect functions, which need to be determined.

IMPACT ANALYSIS: BUILD ENVIRONMENT

- Evaluate the possibility and arising pros and cons of enabling a more sophisticated standard grid discretization:
  - The more sophisticated gird must integrate subsurface geo-hydrological changes with sub-soil changes approached by its corresponding surface area;
  - This grid would make it possible to analyse more the local degree of dispersion of diffuse pollution, therefore taking more into account the spatially distributed land use functions.

In additions, by means of a DELPHI-study, other possible improvement can be identified. A note is that this annex does not state that the identified improvement are necessary in order to build a valid GENIAT.

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