GIMA

Geographical Information Management and Applications

*Master's Thesis*

# Exploring 3D functionalities: A research into software that support the spatial analysis and visualisation of 3D subsurface data

*I.J. van den Meiracker*

antea group

Universiteit Utrecht

TU Delft

University of Twente.

Wageningen UR

*Final Thesis—February 2019*

Author: I.J. van den Meiracker

Supervisors: E. Verbree & J.A. Linders

Responsible Professor: P.J.M. van Oosterom

University: Delft University of Technology

**MASTER'S THESIS**

# Exploring 3D functionalities: A research into software that support the spatial analysis and visualisation of 3D subsurface data

*by*

I.J. van den Meiracker

A thesis submitted in the fulfilment of the requirements for the degree of Master of Science, in the field of Geographical Information Management and Applications, Faculty of Geosciences

February 28, 2019

This master's thesis is commissioned by Utrecht University, University of Wageningen, University of Twente and Delft University of Technology, as part of the Geographical Information Management and Applications (GIMA) master program

This thesis is fulfilled in collaboration with Delft University of Technology and Antea Nederland BV (Antea Group)



**Author**
I.J. van den Meiracker
Ingevdmeiracker@hotmail.com
UU student number: 4073649

**Responsible Professor**
Prof. dr. ir. P.J.M. van Oosterom
Delft University of Technology

**Supervisors**
Ir. E. Verbree
Delft University of Technology

Ir. J.A. Linders
Antea Group

**Citation**
van den Meiracker, I.J. (2019). *Exploring 3D functionalities: A research into software that support the spatial analysis and visualisation of 3D subsurface data* (Master's Thesis, Delft University of Technology, The Netherlands).

An electronic version of this thesis is available at http://repository.tudelft.nl/ and http://studenttheses.library.uu.nl/

# PREFACE

This thesis research is submitted to fulfil the university master program of Geographical Information Management and Applications (GIMA) and to obtain the degree of Master of Science. It is the result of six months research in co-operation with Delft University of Technology and Antea Group Nederland.

GIMA offered me the connection between two personal interests: societal/environmental issues and technical/computational solutions. During this master, I have strongly developed my technical skills in the field of Geographic Information Systems and (3D) spatial data. I have always been driven to carry out work that matters. Antea Group has given me the opportunity to actively participate in the company with my academic research. It overjoyed me to see that the outcomes of my research resulted in many interest from my colleagues.

I am grateful to my daily supervisor at Antea Group: Jim Linders. Thanks for showing me around within the company and introducing me to new people. Additionally, to argue and think about the research approach and the practical relevance together. I also want to thank Jasper Holten for the guidance and participation in the project and for the possibilities to promote the interesting subject and myself within Antea Group.

Special thanks go out to supervisor Edward Verbree for all assistance and support during the whole research process. I have really appreciated all useful tips and quickly responded feedback. After a meeting, I was encouraged to critically reflect on the work made so far and I gained new perspectives and inspirations to think about. I would like to thank Professor Peter van Oosterom for providing appropriate feedback, asking questions and for reading and assessing my final work. Furthermore, gratitude to Reinder Reindersma from TNO for assistance regarding subsurface related concepts and definitions.

Last but not least I would like to thank my family and friends for supporting and motivating me during the past months. In particular Stefan Dirven for all support, advice and feedback at any time. Without your help I would never have been as proud of the end result as I am now.

Inge van den Meiracker
Capelle aan den IJsel
February, 2019

# ABSTRACT


The need for three-dimensional (3D) spatial information is rapidly increasing nowadays, because it provides more spatial insights, more precise and objective representations of real world phenomenon, better interpretation of spatial relations and it improves the communication between experts and non-experts. Especially within the soil sciences, 3D representations can be an added value since the subsurface cannot be directly observed, and are therefore the solution to visualise and view the subsurface in its spatial context. Geographical Information Systems (GIS) are suitable software to create these 3D subsurface representations, because of the ability to process spatial data, to operate with large scope of features, to perform spatial analyses and by its locational precision. However, subsurface data is still frequently visualised by means of traditional 2D representations, due to a shortage of spatial subsurface data, time-consuming and complex 3D functionalities and limitations in current 3D GIS software packages.

This research aims to explore 3D functionalities within software packages that support 3D subsurface data. Five GIS packages are evaluated and assessed by means of a Multiple-Criteria Analysis (MCA) to assess the suitability on the support of 3D subsurface data. In addition, subsurface data of a case area is analysed and visualised, with the aim to generate a comprehensible 3D subsurface representation that includes real-world complexity. An extensive review of relevant literature studies is the starting point for the determination of the criteria and requirements included in the MCA. The map use cube, in which different user types, dimensions, purposes and goals of GIS are identified, forms the general framework to evaluate, compare and classify the GIS software packages.

In order to select a suitable software package to support 3D subsurface data predefined criteria and requirements must be met. For this research five main-criteria are defined based on the literature framework, expert judgements and stakeholder requirements. The requirements on which the software are evaluated and assessed relate to functionality, usability, reliability, vendor and cost criteria. The MCA resulted in Leapfrog Works being the most suitable GIS software to support 3D subsurface data. Leapfrog Works includes a user-friendly environment as well as advanced subsurface-related functionalities. In addition, the software offers certain desired requirements, such as interactive online upload and share options, the management of large data files, prioritisation of executive tasks and a large user platform. Herewith, Leapfrog Works is suitable for both advanced users desired to generate extended and reliable subsurface representations, as for basic users who can comprehensibly and interactively view and move the 3D output.

Leapfrog Works is looked into in-depth where desires are highlighted, among which the time dimension, real time data processing and database management. In addition, a number of cases are demonstrated where 3D subsurface representations are applicable to, including the monitoring of contaminated groundwater and smart planning of civil engineering designs. A 3D subsurface representation is provided with the purpose to include real-world complexity. This is done by adding different types of subsurface data inputs, creating both numerical and geological models, adding surrounding objects and civil engineering designs. The 3D subsurface representation is illustrated in Figure 1.

From the research it can be concluded, regardless of the fact that the subsurface is not directly observable, that suitable GIS software is developed to process and support 3D subsurface data in order to create comprehensible and realistic outputs. However, each GIS software package includes its own focus on user types, dimensions and purposes causing a specific place within the map use cube. These different software identities substantiate the importance of conducting anticipatory research into the suitability of a software package. This research provides a generic approach to identify and assess GIS software packages on suitability based on predefined criteria. The research proves that reliable 3D subsurface representations can be created in GIS software that are of added value for multiple common cases and can be comprehensible for different types of users. It therefore tackles the challenge of representing the subsurface in 3D and offers new insights into the movement towards 3D functionalities within GIS software.

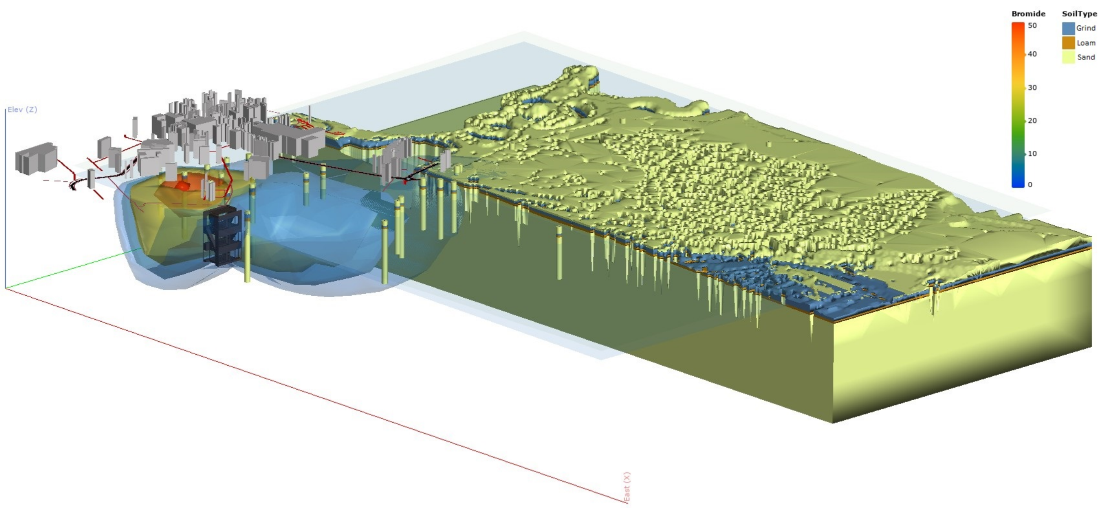



**Figure 1:** 3D subsurface representation of the case area

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ABBREVIATIONS

| | |
|---|---|
| 2D | Two-Dimensional |
| 2.5D | Two-and-a-Half-Dimensional |
| 3D | Three-Dimensional |
| 4D | Four-Dimensional |
| ARGIS | Augmented Reality Geographical Information System |
| AHN | Current Height of The Netherlands *Actueel Hoogtebestand Nederland* |
| AHP | Analytic hierarchy process |
| AR | Augmented Reality |
| BIS | Soil Information System *Bodem Informatie Systeem* |
| BRO | Key Register of the Subsurface *Basisregistratie Ondergrond* |
| CPT | Cone Penetration Test |
| CSG | Constructive Solid Geometry |
| CSM | Conventional Soil Mapping |
| DEM | Digital Elevation Model |
| DGM | Digital Geological Model |
| DINO | Data and Information Dutch Subsurface *Data en Informatie Nederlandse Ondergrond* |
| DSM | Digital Soil Mapping |
| ERT | Electrical Resistivity Tomography |
| Esri | Environmental Systems Research Institute |
| FOSS | Free and Open Source Software |

| | |
|---|---|
| GDN | Geological Survey of the Netherlands *Geologische Dienst Nederland* |
| GIMA | Geographical Information Management and Applications |
| GIS | Geographic Information System |
| GPI | Global Polynomial Interpolation |
| GPR | Ground Penetrating Radar |
| GPS | Global Positioning System |
| GSW | Geospatial Service Web |
| IDW | Inverse Distance Weighting |
| LPI | Local Polynomial Interpolation |
| MCA | Multiple-Criteria Analysis |
| MCDM | Multiple-Criteria Decision Making |
| NAP | Normal Amsterdam Level *Normaal Amsterdams Peil* |
| PDOK | Public Services on the Map *Publieke Dienstverlening Op de Kaart* |
| QGIS | Quantum GIS |
| RBF | Radial Basis Functions |
| RIVM | National Institute for Health and Environment *Rijksinstituut voor Volksgezondheid en Milieu* |
| RTD | Real-Time Data |
| SIKB | Foundation Infrastructure, quality assurance, Soil management *Stichting Infrastructuur Kwaliteitsborging Bodembeheer* |
| StiBoKa | Dutch Soil Survey Institute *Stichting voor bodemkartering* |
| TIN | Triangulated Irregular Network |
| TNO | Dutch Organisation for Applied Scientific Research *Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek* |
| UML | Unified Modeling Language |
| VBA | Visual Basic for Applications |
| VES | Vertical Electrical Sounding |
| VR | Virtual Reality |
| VRGIS | Virtual Reality Geographical Information System |
| WMS | Web Map Service |
| XML | Extensible Markup Language |

# GLOSSARY

| | |
|---|---|
| Aquifer | Permeable unconfined soil layer |
| Aquitard | Impermeable confined soil layer |
| Black box | A system or object of which its internal working is unknown and therefore only is observed as input and output |
| Drilling | The boring of a hole or tunnel, according to different methods, into the Earth's surface. This can take place for different depths and purposes, including soil samples and structure |
| Conventional Soil mapping | Methodology to generate soil maps that strongly relies on extensive soil surveys (CSM) |
| Digital Soil Mapping | Methodology to generate soil maps that focuses on computational advanced and digital spatial analyses (DSM) |
| Edaphology | Study of the interaction of soils with living organisms, especially plant materials |
| Electrical Resistivity Tomography | A geophysical technique for imaging soil structures from electrical resistivity measurements made at the ground level or by electrodes in one or more boreholes (ERT) |
| Ground level | Indication of the height of the Earth's surface compared to national zero level. The ground level referred to in this study are the heights of the AHN relative to the NAP |
| Groundwater flow | The groundwater flow is the displacement of groundwater through the soil |
| Groundwater level | The groundwater level is the height of the water in a monitoring well, or where the groundwater would be when the soil is excavated |
| Lithology | The physical characteristics of a rock, including colour, composition, and texture |

| | |
|---|---|
| Monitoring well | A tube placed in a drilling with one or more filters at a known depth in order to monitor and determine for instance the quantity, quality and rise or fall of the groundwater |
| Pedology | the study of the formation, chemistry, morphology and classification of the soil |
| Probing | The determination of the bearing capacity of the soil by pressing a rod with a conical tip into the ground and thereby reducing the mechanical resistance of the soil. Also referred to as CPT |
| Pseudo-section | Cross-section of the resistivity of the soil, obtained by ERT measurements |
| Real-time data | Data that are immediately visible after the measurements and therefore suitable for monitoring and tracking |
| Sanitation | The process of clearing an area from soil contamination |
| Software metric | A standard of measure of software characteristics which are quantifiable or countable |
| Soil contamination | Soil where substances or materials have been introduced by humans that do not naturally occur in the soil or groundwater and lead or can lead to damage of the ecosystem |
| Soil science | Study of the soil as a natural resource of the Earth (pedology) and its relations with soil-dependent uses (edaphology) |
| Soil type | Taxonomic units of geological material from which the soil is built up, such as clay, sand, gravel etc., and its properties |
| Spatial interpolation | Analysis method to estimate values at unobserved locations in geographic space based on values at observed locations |
| Subsurface data | The subsurface data referred to in this study contains the information from the ground level to about 50 meters deep below surface. The subsurface data will mainly focus on groundwater, soil types/structures and concentrations of contaminated soil |
| Surface-based representation | 3D object of vector features, generated by bounding vertexes, lines, polygons and polyhedrons |
| Volume-based representation | 3D object of raster features, mainly practised by voxels |

CHAPTER 1

# INTRODUCTION

## 1.1 Background

### 1.1.1 General

The need for three-dimensional (3D) information is rapidly increasing. More and more areas of expertise are making steps from two-dimensional (2D) imagery and techniques towards 3D. It proves that the area of interest progresses significantly when 3D functions are offered on the market (Zlatanova et al., 2012). Also in geosciences 3D models and visualisations are widely used by scientists and experts to construct conceptual and qualitative representations of the earth's (sub)surface (Raska, 2017). A 3D representation is a closer approximation to the physical manifestation in comparison to 2D. Due to the enriched spatial insight that 3D offers, it is a strong verification for spatial data. 3D developments are therefore functional and of great use in Geographic Information Systems (GIS).

GIS provide locational precision which allows the examination of the environment, both natural and built. This makes it possible to carry out spatial analyses and to explore and investigate the surroundings (Richards-Rissetto, 2017). GIS proves, among other types of software systems processing spatial data, to be the most sophisticated system because of the ability to operate with a large scope of objects, relationships and the means to perform spatial analyses (Zlatanova et al., 2012). Due to the large amount of spatial data that is being processed in GIS, 3D techniques are an asset to the current functionalities.

An area of expertise of the geosciences where many GIS software packages and tools are used is soil science. Understanding both above and below ground levels of the earth is meaningful for multiple applications within the geosciences (Raska, 2017). In the real world, geologic structures exist in three-dimensional space. However, they are commonly analysed and presented on paper or in GIS in two-dimensional space. Investigating these geologic structures more in line with the real world will provide more spatial insight and would therefore be an enrichment to the current developments. 3D techniques can offer a solution to visualise the earth in a more realistic spatial manner (Poggio and Gimona, 2017).

A combination of GIS software packages, 3D techniques and convenient databases will allow scientists to build geological 3D models and representations. Examining alternative methods and identifying constraints in the data gaps and the research and modelling process will remain an important direction and area of interest in the current geospatial world (Raska, 2017).

### 1.1.2 Antea Group

Antea Group is an internationally operating engineering and consultancy firm. Through a combination of strategic thinking, multidisciplinary knowledge, technical expertise and pragmatic action they offer effective and sustainable answers to the challenges of their clients. Antea Group features among others a large sector focused on soil services in which various branches within the soil sciences are active. Examples include soil research and advice, soil and cultural techniques, soil remediation, archaeology and soil protection. Within these different services Antea Group responds to innovative GIS software packages and tools regarding geo-information.

The usability of 3D functionalities are also noticed by Antea Group and are being taken into account in various projects. Certainly for the (sub)surface 3D images can be an added value for both contractor and client. A project has been set up by Antea Group to discover the possibilities with GIS to support subsurface data three-dimensionally. The purpose here is to analyse and visualise the subsurface information in 3D that includes real-world complexity to provide better spatial insights. The research of this master's thesis is aiming to be a support for this project by selecting suitable a GIS software that supports 3D subsurface data and thereby presenting a visualisation that aligns with the three-dimensional world of which the subsurface is part of.

## 1.2 Problem Statement

The subsurface cannot and is not directly observed. In comparison with the surface much less data is available about the subsurface which makes the modelling and visualisation very challenging. Except drill holes, scientists and geologists use alternative methods and techniques to examine and interpret the subsurface (Raska, 2017). Cross-sections and 2D maps of the top and bottom of the strata are traditional ways of representing the geological subsurface. This 2D view of the subsurface may be useful for a first interpretation but lacks the spatial insight, complexity and reality that 3D visualisations can provide. Antea Group also noticed in practice that 2D representations of the subsurface are difficult to interpret for many people. In 2D views it is challenging to orientate on a specified subsurface area and it is difficult to imagine the situation in a 3D space.

Accurate 3D models improve the interpretation of geological measurements. In addition, it can be used as means of revealing potential inconsistencies in current used tables, cross-sections and 2D representations (Poggio and Gimona, 2017). Carrell (2014) even argues that the ability to three-dimensionally view, zoom, rotate, pan and fly through subsurface data is vital in order to accurately understand geological relations, structures and phenomena. Besides better interpretation and understanding of subsurface data, it also improves the communication and sharing of subsurface data for both professionals and experts as the general public, customers and stakeholders (Raska, 2017).

Creating a 3D representation of subsurface data, for example groundwater levels, is challenging for various reasons. The lack of spatial data of certain subsurface areas makes it almost impossible to create a qualitatively reliable subsurface model. Despite the fact that improvements have been made in computational facilities, subsurface data sets and tools, these techniques are often very time consuming and only feasible and understandable for experts (Poggio and Gimona, 2017). In addition, subsurface data of different formats and sources are often integrated by geologists in order to research the subsurface. Raska (2017) even argues that consequently there is no one software product that is able to efficiently store, manipulate and publish sufficient and accurate subsurface information. Many different GIS packages are developed that are suitable for different dimensions, proposes and users. It is therefore important that it is explored and considered which GIS packages are suitable to support 3D subsurface data.

The extent to which 3D developments and techniques are currently used in soil science is limited. Subsurface data is still frequently exchanged by means of tables, cross-sections and 2D maps. Despite the fact that the modelling of subsurface data in 3D is beneficial, it still causes obstacles. The current developments involve a set of challenges which are still in anticipation to be even properly determined (Herrador et al., 2016). It can therefore be stated that stagnations and obstacles occur in the field of 3D GIS developments in order to represent the subsurface in an insightful, comprehensive and efficient way despite its high desirability. Because as Herrador et al. (2016) argue:

*"Since our environment is 3D, the obtained geoknowledge must be in 3D."*

### 1.2.1 Research Questions

After the definition of the problem statement of this study, the following main research question is formulated to tackle the problem:

*Which software package is suitable to support 3D subsurface data when exploring its 3D functionalities, purposes and dimensions;*
*and to what extent is the generated output able to provide a comprehensible 3D subsurface representation that includes real-world complexity?*

To address the main question several sub-questions need to be answered:

- What is subsurface data and how is it visualised?
- How is the subsurface data of the Netherlands stored and mapped?
- What is 3D spatial data and how does it differ from 2D spatial data?
- Which criteria should be taken into account when selecting a suitable GIS software package to support 3D subsurface data?
- Which software packages are suitable to support 3D subsurface data?
- For which applications can the 3D subsurface representations be useful?
- Which real-world components can be included and represented by the 3D subsurface output?

### 1.2.2 Research Objectives

The research objectives serve as a guideline for the implementation of the research and the definition of the achievements of the study. The first objective is to select a suitable software package that meets pre-defined criteria in order to support 3D subsurface data. This is done by exploring the included 3D functionalities and by assessing and evaluating the software's purpose and user types. The second objective is to actually analyse and visualise the subsurface data in 3D with the aid of the selected software. Here, the aim is to provide an comprehensible subsurface representation that includes real-world complexity, in order for basic users to understand. Because of the two objectives the research is both scientifically as pragmatically embedded: scientifically by means of the literature-based assessment framework, criteria and requirements and pragmatically by the software selection and its practical application.

The ultimate objective and research goal of stakeholder Antea Group is to work towards a package to visualise, share and interpret subsurface information in 3D. The aim here is to improve the imaging towards the consultants about the subsurface related project locations. This improved imaging and interpretation of the subsurface information can consequently be more clearly shared and advised to clients and other stakeholders. The research objective for stakeholder Antea Group is to provide a well-considered choice of GIS software and to create a thought-out foundation for the creation and implementation of this package.

### 1.2.3 Research Boundaries

The research boundaries indicate the scope of the study and delineate the subject:

- The research will not substantively include surface data, data of above ground, unless this information contains direct consequences on the subsurface data

- The subsurface data that is used in this research belongs to a case area. This data set is only used to present the capabilities and functionalities of the software. No substantive conclusions or recommendations will be provided about the subsurface of the specific case study area

- This research is performed within the master level context of GIMA. Therefore, the research contains a theoretical embedding and hence includes a comprehensive theoretical framework

- Since this research is performed within the context of GIMA and Antea Group. A possible software solution will be within the limits of these organisations. As a result, the output will more likely rely on GIS infrastructures, rather than a mathematical software package

- Because the emphasis of the research is on the development of a GIS output supporting 3D subsurface data and because of time and resources restrictions, only the most relevant criteria for this research will be included in the software evaluation and not all possible criteria that can be found in literature

- Implementing the output within projects of Antea Group is not part of the research

### 1.2.4 Challenges

The scope of this research, which is indicated by the research boundaries, is part of a larger ongoing investigation towards the subsurface, as posed by Culshaw (2005). The value of this investigation and research topic has only increased since then due to new computational developments in software and data acquisition. The research questions and objectives that are drawn up for this master thesis put flesh on to the bone of and contribute to some overall challenges of this larger investigation:

- *Representation* challenge: covers the way of finding expressions to represent the geological environment of the subsurface and its infinite complexity using the capacity of innovative technological developments
- *Data* challenge: covers the respond to the expansion of the collection and archiving of subsurface data, the respond to the refinement of subsurface data and the respond to the need of complex spatial analysis
- *Cognition* challenge: covers the understanding between digital and cognitive representations of the observed subsurface
- *Discover* challenge: covers the discovering towards ways of analysing and visualising the differences between the real situation and the computational representation
- *Provider's* challenge: covers the level of responsibility of the geoscientist, as spatial data provider, towards the requirement to be customer-oriented
- *User's* challenge: covers the level of responsibility of the geoscientist, as model and information provider, towards the requirements to be both purpose-oriented and user-oriented

## 1.3 Relevance

### 1.3.1 Scientific Relevance

Geological structures and processes have been frequently examined and researched by scientists and geologists. Data and results are nowadays still frequently presented in a two-dimensional way, as mentioned in the problem statement. Despite that 3D functionalities are increasingly being developed and applied in different software and GIS environments, this is not widely used in soil science (Poggio and Gimona, 2017). The few information available and not being able to observe the subsurface directly makes it challenging to apply 3D functionalities.

Despite the fact that the supply for 3D functionalities applicable for subsurface data is not very wide, the demand has raised. Wong and Ellul (2017) examined the usefulness to produce and visualise certain domains in 3D. These domains included among others roads, buildings, trees, bridges, but also underground features. The result of this research indicates that underground features were declared as the second highest domain to be produced and visualised in 3D regarding usefulness. Wong and Ellul (2017) emphasise that 3D developments in the geo-information field, particular in the subsurface domain, can be of great use.

The objective for this research is to select a suitable GIS software package that supports the spatial analysis and visualisation of subsurface data in 3D. In addition to the selection, the subsurface data will actually be analysed and visualised in 3D with the aim to include real-world complexity. Since the developments towards 3D functionalities, GIS software and soil science are still developing, and will remain in development, this research will devote to this scientific evolution. The scientific motive of this research is to provide insights into 3D GIS functionalities and to contribute to the inventory of useful GIS software applicable for 3D analyses and visualisations within the subsurface domain. In addition, a generic method is provided to recognise and identify GIS software dimensions and user types, and to assess its suitability for a particular purpose.

### 1.3.2 Practical Relevance

When performing research it is of great use to take into account both the scientific and practical relevance. Something that is confirmed in literature does not automatically arrange well in practise, and vice versa. Antea Group as stakeholder is, in contrast to the findings from the literature, practically involved with GIS software, subsurface data and 3D developments. From the practical point of view they discover problems or difficulties, instead of through lacks in and recommendations from the literature.

Direct practical motive here is the arrangement of the project by Antea Group and the demand towards 3D subsurface data. This research is relevant for stakeholder Antea Group, because it offers insights and solutions for the processing of their soil surveys and subsurface data. By researching GIS software and included 3D functionalities there will be eventually less obstacles in the creation of a 3D representation of subsurface areas. It is relevant because Antea Group has noticed that non-experts are struggling with drawing conclusions and interpreting 2D maps, cross-sections and tables. This results in both advantages for the contractor and the client because the subsurface information can be better spatially investigated and understood. The ability to view, zoom, rotate, and fly through borehole data in three dimensions is vital to understand geological relations in the subsurface, especially for non-experts (Carrell, 2014).

In addition to more spatial insight and better representation of subsurface data, this research also benefits other sectors. Infrastructural, industrial and environmental sectors, where spatial data is also widely used, can profit from improved 3D representations. Therefore, findings from this research can be applied to other sectors, which broadens the practical relevance for multidimensional operating companies such as Antea Group.

## 1.4 Research Strategy

A conceptual model of the research scope is provided in Figure 1.1. Here, three different research stages are identified: the problem and theory delineation, the Multiple-Criteria Analysis (MCA) and the in-depth phase. The problem statement together with the research objectives and questions are defined in the introduction, forming the essence and scope of the research. The first stage also includes the theoretical framework covering background information, current knowledge and developments. It includes theoretical and methodological contributions to relevant topics regarding the assessment framework of the map use cube, the (Dutch) subsurface and its soils, GIS principles, 3D functionalities and representations.

Hereafter follows the methodology. The methodology includes the part in which the method behind the evaluation and scoring of GIS software packages is established and explained, in order to select a suitable GIS software. The inputs of the MCA, the different GIS software alternatives and their scores and weights, are defined and demarcated by means of literature findings, software metrics, stakeholder criteria and expert judgements. The MCA ultimately results in a ranking of the software packages on suitability to analyse and visualise the subsurface in 3D.

After the analysis the best scoring software and its capacity will be examined in the third research stage: the in-depth. Here, the generated output is optimised and desires are investigated in-depth. The in-depth is included in the research strategy in order to broaden the knowledge about the software and generate an comprehensible output that concerns real-world complexity. The in-depth phase is an important research stage because these goals play a crucial role in providing answers to the research questions and to meet the research objectives.

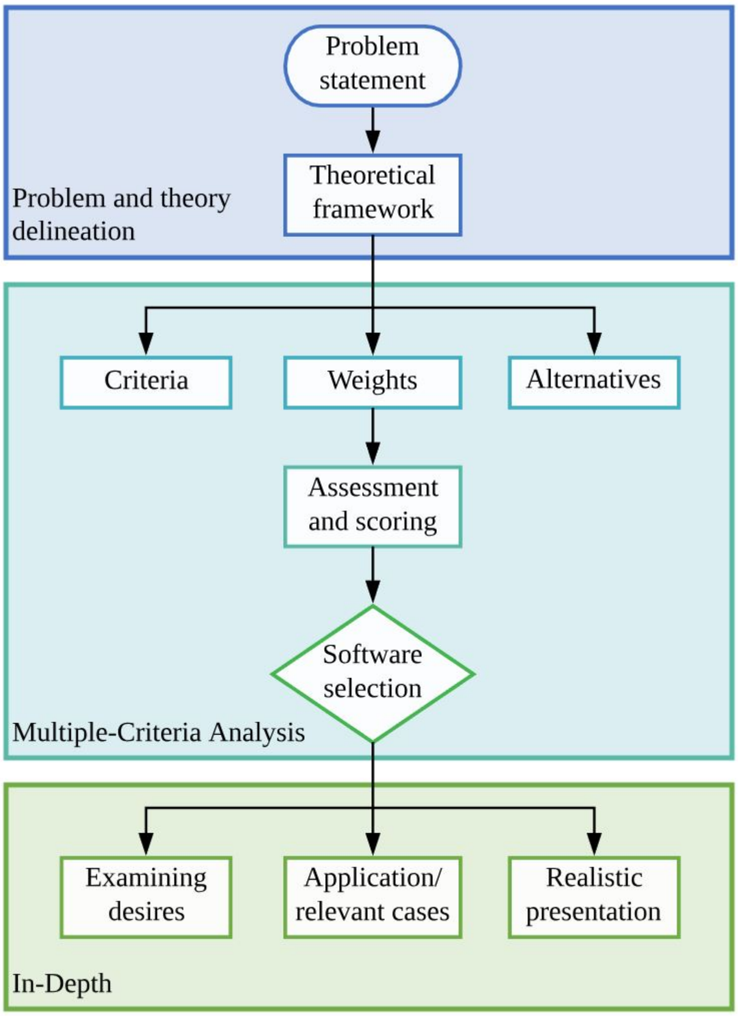



**Figure 1.1:** Conceptual model

## 1.5 Report Structure

The report structure is given as follows. Chapter 1 contains the introduction to the research providing the problem statement, research questions, objectives, boundaries and relevance. Chapter 2 involves the theoretical framework in which substantive theories, concepts and developments are defined. The chapter starts with the assessment framework of the map use cube and its importance regarding selecting suitable software for a particular purpose. Hereafter, relevant topics relating to the subsurface and its soils, GIS environments and 3D functionalities are discussed, that largely form the basis and input for the MCA. Chapter 3 includes the methodology for the evaluation and selection of the software alternatives. Here, the MCA inputs are operationalised, which are the criteria, the scores and the weights. The software packages are evaluated and scored which ultimately results in a software ranking on suitability. Chapter 4 includes the results of the MCA from which the best scoring software comes forward. The best scoring software is selected for further investigation. This is done in Chapter 5, where the selected software is looked into in-depth. Not yet discussed desires are discussed and it is aimed to provide a comprehensible 3D representation of the subsurface that includes real-world complexity. Finally, Chapter 6 provides answers to the research questions, draws conclusions about the research and the results, discusses the research process and provides recommendations for further research.

CHAPTER 2

# THEORETICAL FRAMEWORK

This chapter addresses and discusses information and findings from relevant literature studies, that together constitute the background, scope and embedding of the research and are the base for the methodology and research process. It starts with the map use cube theory that is used as overall assessment framework during the evaluation of the GIS software. Hereafter, key concepts of GIS software, 3D functionalities and the (Dutch) subsurface and its soils are discussed and defined for this research.

## 2.1 Map Use Cube Assessment Framework

The demand for specific computer software packages has strongly increased over the past years. Software firms respond to this demand by designing packages that meet the organisation's requirements (Jadhav and Sonar, 2009). As a result of this development many different types of software packages for different applications are available on the market. It is important that applicable software is selected for the right purposes and users. Selecting improper software may result in wrong strategic decisions and subsequent deterioration of the economic condition of the organisation (Jadhav and Sonar, 2009). Incorrectly selecting software often results in risks related to high expenses, consuming significant quantities of organisation's budgets. Therefore, this section addresses the importance of selecting software based on a conscious choice, by means of a theory that identifies and classifies the differences between GIS software: the map use cube.

### 2.1.1 Selecting GIS software

Selecting the right software is generally a complex and exhausting process. It is a complicated task to elect a software package that consists of predefined conditions and requirements. It resulted in scientists investigating ways to select and assess software (Eldrandaly, 2007; Jadhav and Sonar, 2009; Jamwal, 2010; Pacheco-Cardenas, 2018). This scientific literature contributes to the method for establishing and defining software requirements, testing the available software packages and ultimately selecting one.

Geo-information and associated GIS software to process this spatial data is a promising branch of information systems with considerable success in the past decades (Eldrandaly, 2007). Developers extended the number of geographic software packages and tools.

Due to the increased capability of the software, the prices of advanced GIS software packages has increased. On the other hand, due to the growing demands and innovative initiatives more accessible GIS software is developed, which has even led to free software such as QGIS. All these new software are built to meet different user requirements and to run on different hardware platforms (Eldrandaly, 2007).

Creating or building a new product in GIS is for many organisations a major expenditure. Selecting the right GIS software can be crucial for the success of such an investment. The existence of various criteria and requirements and because several decision-makers pertain to the project, the decisions involve multiple dimensions. These dimensions can for example concern costs, quality and technology. The solution process becomes therefore very complex. In order to select a suitable GIS software certain functional demands and requirements need to be defined and delineated. In addition, it is important to examine for what purpose the GIS software is used and by whom to make a deliberate choice. An underlying theory to examine and classify the GIS use and its users is discussed in the next subsection.

### 2.1.2 Map Use Cube

Past and present computational and technological developments led to an increasing diversity in data, data acquisition, data processing and versatility in the software that process spatial data. This is not only happening for certain specifications, but takes place in and between different fields including the subsurface and geographical information domain. The diversity in the geo-information domain resulted in many different ways to use, analyse and visualise spatial data. This is done in different software, for different audiences and for different objectives or purposes. The importance of GIS software and appropriate selection for a particular research or purpose has been raised in the previous subsection. However, GIS software is not self-containing. The software, users, audience and objectives are all connected to a broader context. A theory that supports this broader context is the map use cube.

The map use cube was first introduced by MacEachren in 1994. MacEachren discussed maps as something more than just visualisations. Maps and spatial information are a means of communication between user and audience that can take place at different levels and for different purposes (MacEachren and Kraak, 1997). MacEachren recorded this coherence and context of software, maps and data in a cube as shown in Figure 2.1. The map use cube consists of three dimensions: the user dimension, ranging from private (expert) to public (non-expert); the knowledge dimension, ranging from the known to the unknown information that is presented; and the level of interactivity between humans and maps (MacEachren and Kraak, 1997; Elzakker, 2004; Neset et al., 2016). MacEachren and Kraak (1997) indicate that strategies must differ for the application and design of visual displays and display systems to support map use. They defined four goals or purposes that all have a different place in the cube: explore, analyse, synthesise and present. The explore goal relates to examining unknown and often raw data. In order to do so, exploration functions are required to explore the spatial data, identify relations among variables and to look at the data from different perspectives. On the other side, the viewing goal transfers spatial insights of known data to the public (MacEachren and Kraak, 1997). Because these goals are different according to the three dimensions, different strategies are needed to support map use (Elzakker, 2004).

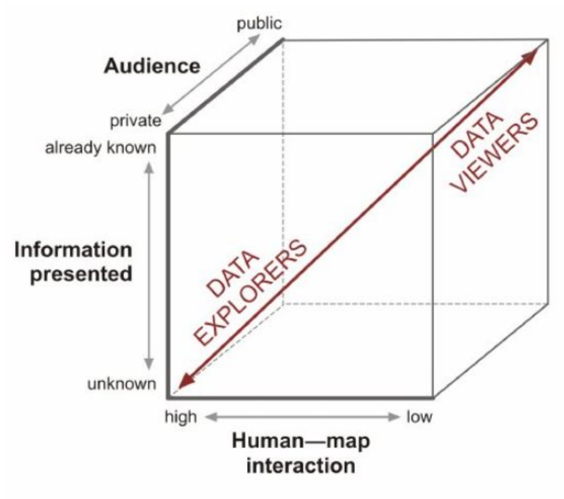



**Figure 2.1:** Map use cube
*Source:* Neset et al. (2016)

The map use cube is a theoretical approach for critical analysis. For this research it is a useful tool when evaluating the GIS software. GIS software packages also contain different dimensions. For example, there are software that include advanced tools in the field of analysis and (explorative) visualisation, and software are developed that are more focused on presenting spatial data. GIS software therefore consist of a certain software environment that can be placed in the map use cube. GIS packages that are suitable for data viewers will mostly be more public, contain few analysis functionalities and show already unravelled data. Examples of this are GIS viewers or GIS web services, such as the PDOK viewer and DINOloket. GIS software that can be placed in the opposite side of the cube, such as ArcGIS, will contain more analysis and visualisation functionalities in order to investigate unknown and raw data. These different environments and dimensions are important when selecting software, in order to match the capabilities of the software with the goal and use of the researcher.

### 2.1.3 GIS User Types

So it emerged that it is important to make an informed choice for the selection and purchase of a GIS software package. GIS software contain different dimensions and perspectives and when these do not match the requirements or criteria it can result in undesirable outcomes. The dimensions or perspectives that a GIS includes or offers puts the software at a certain place in the map use cube. These dimensions and perspectives are nearly associated and connected to different types of users. User types indicate the user's capability and their needs and requirements.

Aitken and Michel (1995) already started the discussion about GIS users playing different roles. They refuted the dichotomous view on users either being experts who use GIS, or being actors whom the experts invent to serve. Their paper seek to find a solution to define and connect the academic, the practitioner and the client, in a way that all actors involved in the production and consumption of GIS have ownership and value in the creation of geoknowledge. Four user types for strategic planning are defined and shown in Figure 2.2: information specialist, preparer of policy, policy decision-maker and interested citizen (Aitken and Michel, 1995).

| Type of user | Information demand | User demand | Type of GIS | Development |
|---|---|---|---|---|
| Information specialist | Raw data | Analysis<br>Flexibility | Large<br>Flexible | Links to other packages |
| Preparer of policy | Raw data and pre-treated data (information) | Analysis<br>Good accessibility | Compact<br>Manageable | Macro languages<br>Interfaces to other packages |
| Policy decision-maker | Strategic information | Good accessibility to users<br>Weighting and optimization models | "Small and beautiful" | User-friendly interface<br>Key information |
| Interested citizen | Information | Good accessibility to users | "Small and beautiful" | User-friendly interface |

**Figure 2.2:** User types
*Source:* Aitken and Michel (1995)

When looking at the table columns a strong agreement can be observed with the map use cube. The information specialist demanding raw data, analyses and flexibility corresponds to the data explorer of the cube. Interested citizens demanding information, good accessibility and user-friendliness complement the data viewers of the cube. This shows the cooperation between GIS dimensions and user types. In the subsequent period, several studies are conducted on GIS users in which user types are identified. More general categories are defined, such as GIS professional versus layman, expert versus non-expert and producer versus consumer. In addition, some studies thoroughly elaborated user classes, such as Boone County GIS (2008) who classified GIS users in: system administrators, application programmers, data managers, data editors/technicians, user support personnel, power users, casual users and public users, all using GIS software but on different levels and for different purposes.

Esri, as dominant global vendor of GIS software products, determined five user types (Esri, 2018e,f; Gerrow-Wilcox, 2018; Kachelriess, 2018). The user types reflect identities and capabilities that are tailored to the needs of users. The five types include: viewer, editor, field worker, creator and GIS professional. Viewers view items, data and maps that are made and shared by other users. Editors view and edit items, data and maps, but cannot analyse, create or share them. Field workers are able to view and edit data, by means of apps and devices to which access can be obtained in the field. Creators have all the capabilities of the Viewer, Editor, and Field Worker user types, plus the ability to create content by means of spatial analyses and tools, administer the organisation and share content for use (Esri, 2018e,f). The GIS professional user type is designed for users who need the full package of GIS capabilities to create (web)maps, perform in-depth spatial analysis, use multiple functionalities and leverage the advanced tools.

Wikle and Fagin (2015) and Hong (2016) look into user types in-depth and discuss the skills and requirements that belong to a user type. They both made a distinction between technical/hard skills and general/soft skills. Technical or hard skills include analysis, modelling, cartography, visualisation, data processing, software development and management, and are acquired through education, training, and/or experience (Wikle and Fagin, 2015; Hong, 2016). General or soft skills include analytic, management, personal and social skill categories, and are transfer-able across job types and employment levels.

The user type skills can be linked to the taxonomy of Bloom, which is a hierarchical model of skills ranging from low to high (Adams, 2015). In Figures 2.3 and 2.4 the knowledge-based and action-based hierarchical models are shown. The Knowledge-based hierarchy is focused on the cognitive domain, while the Action-based domain includes psycho motor skills or the ability to use a tool or instrument. The hierarchies and skills of Knowledge-based and Action-based respectively match the soft and hard user type skills within a certain extent. When moving up in the hierarchy the complexity of the skills increase. For instance, the cognitive skill Remember requires the recall or retrieve of previous learned information, while the cognitive skill Create involves the creation of a structure or pattern from diverse elements, containing a more complex process.

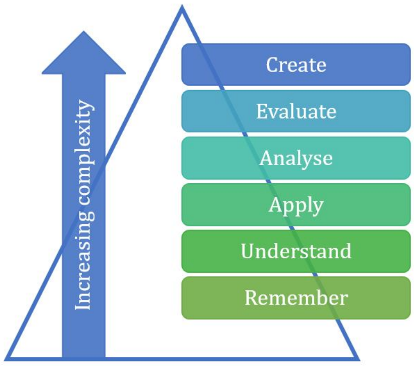



**Figure 2.3:** Knowledge-based skills

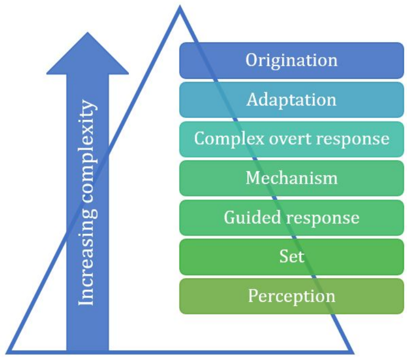



**Figure 2.4:** Action-based skills

The taxonomy of Bloom can be associated to a certain extent to the five user types defined by Esri. The user types can also be categorised hierarchically in terms of required skills and complexity. A viewer observes and views the information that is provided by an output or map. On the other side of the hierarchy, a GIS professional performs complex spatial analyses using advanced tools whereby well-considered choices must be made. This is a more complex task and therefore requires different soft and hard skills.

### 2.1.4 Discussion

The map use cube identifies GIS users and corresponding practice. It provides a convenient assessment framework to classify, label and asses GIS software products during evaluation research. In addition, the framework allows for follow-up research, even applicable for other areas of expertise. It is a useful tool when evaluating GIS software and offers a fundamentally adequate approach to make a deliberately choice. In this research the GIS software are therefore evaluated likewise during the MCA on the different user types, its dimensions and its place in the map use cube.

## 2.2 GIS Principles

The importance of investigating and identifying the dimension, purpose and goal of GIS software and hereafter selecting a suitable software is raised in the previous section. To do this it is important that the operation of GIS software packages, and specifically for this research the 3D operation and capacity related to subsurface data, is understood and known. This section therefore discusses GIS principles relating to vector and raster data, measurement scales and levels, soil properties, black boxes and point clouds. The subsections substantiate the importance of specific soil related 3D functionalities in order to realistically represent the subsurface.

### 2.2.1 2D Vector and Raster Data

The advent of digital practice and the use of computers in the early 1990s resulted in the digitising of subsurface data and the digitally storage of accompanying (meta)data and information. The technology to interpret subsurface information has developed in a way that manual processes of interpretation and analysing have been replaced with the advancements of GIS technologies (Paterson et al., 2015). GIS are able to maintain and process data about spatial phenomena. The tools available in GIS have the ability to analyse the spatial data and thereby gain knowledge about the environment around us (Zlatanova et al., 2012). Capturing, structuring, manipulating, analysing and presenting spatial data are the main functions of GIS.

Because of deficiencies of the current developed systems dealing with 3D, the data are often spread across different systems. For instance, one system is used to store and one to analyse 3D data, as embedded in the map use cube. Spreading over different software eventually results in additional time, effort and money. Even though the 3D GIS technologies are still under development it consists of great value. 3D advancements are one of the most remarkable current developments and improvements in GIS. To understand 3D GIS and its complexity, 2D features are discussed as first.

In GIS data models can generally be categorised into two types: vector data and raster data. Vector data contains points, lines and polygon features, while raster data is represented by cells, pixels and squares. Vector lines and polygons are sequences of point data. Raster data does not contain any point features according to geometric terms but raster cells. In Figure 2.5 the characteristics of raster and vector data are shown.

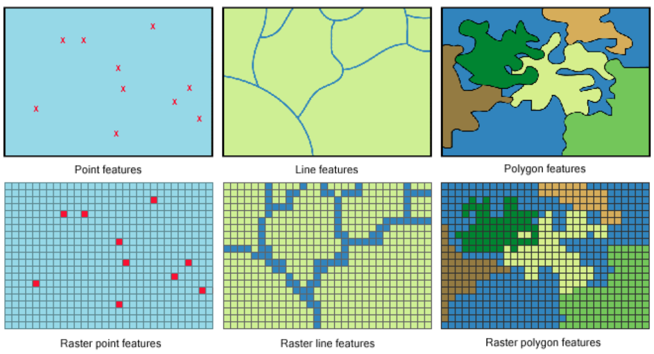



**Figure 2.5:** Vector and raster data
*Source:* Humboldt State University (2018)

In order to create surfaces or areas new data points must be predicted or constructed. Spatial interpolation consists of the estimation of property values of unsampled sites within an area covered by existing values (Heywood et al., 2011). The estimation of the values creates a degree of uncertainty. This limitation must be considered by researchers and data analysts when drawing conclusions. Because subsurface data consists of fixed point values obtained by soil surveys, spatial interpolation is a suitable method to estimate the unknown areas between these point values. Different methods to perform interpolation are discussed in Appendix A.

Subsurface data contain different types of features and properties. This can consist of both raster and vector data. Underground pipes and cables will most likely consist of vector data, while certain soil layers and contamination cover raster data. Difficulties can arise when these data are both utilised and visualised. There are several methods and tools to convert vector to raster and vice versa, and to combine vector and raster data, including merging, extraction and overlays. However, during these conversions data may be transformed or lost. This must be kept in mind by the user when performing these actions while analysing and visualising subsurface features.

### 2.2.2 Measurement Scales and Levels

Data can be classified in discrete and continuous data to present spatial elements. Discrete data illustrate thematic or categorical information in which the values represent a predefined class with a finite number of possibilities (USDA, 2017). The data lack numerical meaning because of the models are typically nominal, ordinal or binary. An example of a discrete data variable is soil types or classes, shown in Figure 2.6. Discrete representations have traditionally been used in soil mapping to visualise different soil types of an area. Discrete representations in a raster provide a simplified display of the classes. In the subsurface domain this means that it is assumed that the subsurface occurs in constant demarcated classes (USDA, 2017). The accuracy of the soil classes is linked to the level of detail of the classes. When there is sufficient survey data available the soil classes can be well-defined resulting in site-specific interpretations. Broadly defined soil classes may help bridge the gap from Conventional Soil Mapping (CSM) to Digital Soil Mapping (DSM) and are most suitable when survey data is limited.

In continuous data the values have a numerical meaning and illustrate a continuum, as indicated in Figure 2.7. Continuous variables allow for any value over a continuous range, while discrete variables only consist of a fixed amount of predefined values (USDA, 2017). Therefore, continuous variables also include numerical meanings. Continuous subsurface models are able to realistically illustrate the natural continuity of the soil properties compared to discrete subsurface models. Theoretically the boundaries of the classes are eliminated in continuous subsurface models. Practically the cell size and the accuracy that is used determine the continuity. Forecasts of subsurface processes are typically generated with a continuous data model. Continuous models are often applied in DSM, including soil attributes as curvature, slope gradient and solar radiation (Heywood et al., 2011).

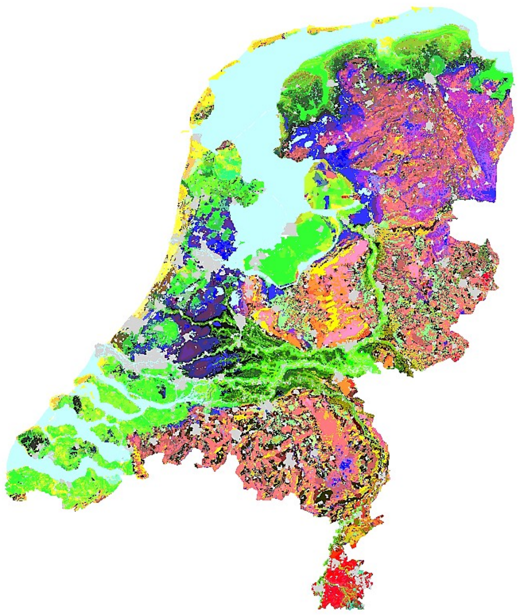


**Figure 2.6:** Soil types (BRO)

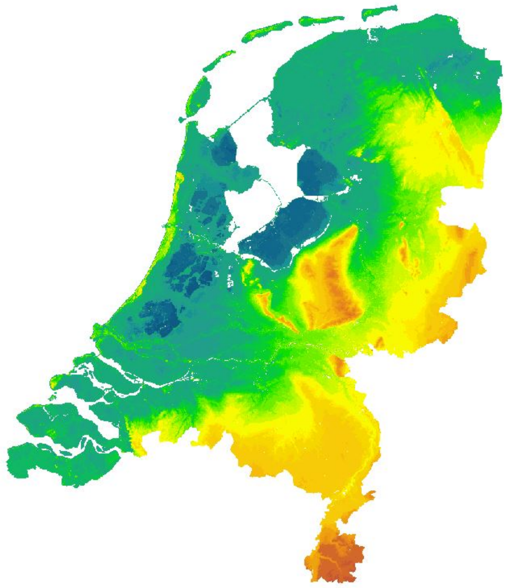


**Figure 2.7:** Ground level height (AHN)

### 2.2.3 3D Vector and Raster Data

A shift takes place in GIS software from 2D to 3D data and outputs. Van Leusen and Van Gessel (2016) mentioned that for a long time, in GIS parlance, outputs were created in two-and-a-half-dimension or 2.5D. 2.5D perspectives are 2D graphical projections used to cause images or scenes to simulate the appearance of being 3D when in fact it is still 2D (Becker et al., 2012). According to Van Leusen and Van Gessel (2016) 3D GIS represents both layers, features and objects and their spatial relationships in 3D.

In 3D GIS the distinction between vector and raster remains. Vector features receive multiple z-values per distinct x and y coordinate. Raster features adopt z-values for every pixel or grid cell, which results in volumetric cells called voxels (Berry, 2007). Zlatanova et al. (2016) argues that vector features represent the boundary of an object, while voxels represent the interior. In literature, a major distinction is made in the modelling of 3D objects and phenomena between Surface-based and Volume-based representations (Zlatanova et al., 2012). 3D vector and raster features are respectively examples of Surface-based and Volume-based representations.

In addition to these different representations vector data is appropriate for modelling 3D homogeneous and discrete objects and raster data fits for modelling of continuous phenomena with properties of a continuous variation (Zlatanova et al., 2012). In Figure 2.8 the representations of volumes and surfaces are shown.

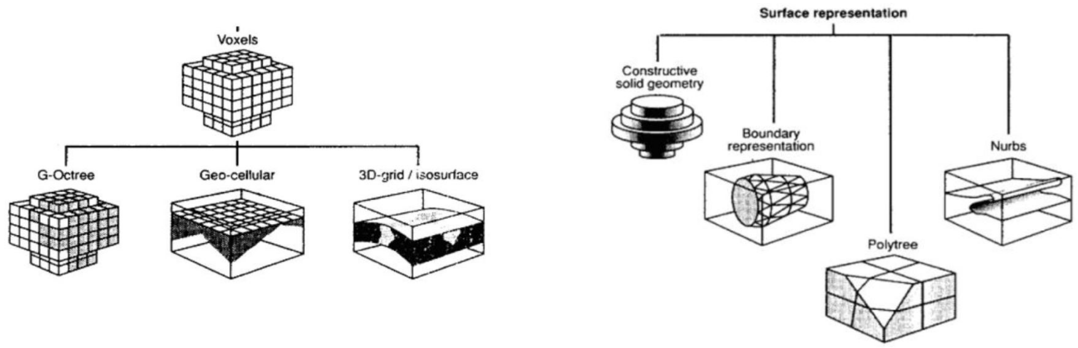



**Figure 2.8:** Voxel and surface representation
*Source:* Zlatanova et al. (2012)

Volume-based representations, mainly practised by voxels, comprehend a regular space division. Because of this regularity the modelling and their management is relatively simple as it is easy to compute the volume (Zlatanova et al., 2012). However, high-resolution voxel data results in large volumes of data and the output is cubic and rough which results in unrealistic visualisations. Boundaries do not exist in voxel representations (Zlatanova et al., 2016). The thin place were the voxels touch is a notion of the boundary. This thin touch implies that the size of the voxels is smaller than the size of the actual represented 3D object. Alternatively, the 3D objects have to be exaggerated, or voxelised, to the size of the voxel. Geometric accuracy and semantics must be taken into account during voxelisation.

Surface-based representations are generated by means of 3D vector features. Constructive Solid Geometry (CSG), an example of Surface-based representation, uses spheres, cubes and cylinders to abstract 3D objects (Becker et al., 2012). This results in very realistic outputs and visualisations. However, because of this reality the 3D objects and their relationship may become very complex. Boundary representations, indicated in Figure 2.8, are common to model discrete real-world objects and design models. The objects are generated by bounding vertexes, lines, polygons and polyhedrons organised in data structures (Zlatanova et al., 2012). Simple outputs are created by means of planar faces and straight edges, while more complex models include curved surfaces and edges. Just as CSG, boundary representations provide realistic visualisations, but it is very complex.

Van Leusen and Van Gessel (2016) discuss some challenges that arise during Today's 3D modelling within GIS, especially in the field of geology and archaeology. These difficulties have to do with scale, resolution and quality. Geologists and archaeologists tend to be interested in a wide range of spatial scales, causing wide ranges of resolutions from geological to individual scales. GIS software supporting 3D data and functionalities should efficiently deal with these scale differences (Van Leusen and Van Gessel, 2016). Besides, the quality of the data may be challenging when data is missing or consists a degree of uncertainty. GIS software should allow data absence and uncertainty and should be able to create hypothetical or prediction models.

Different conclusions are drawn in the literature about the importance and presence of vector and raster based 3D objects in GIS software. Zlatanova et al. (2012) argue that vector boundary representations of 3D objects form the basis in most GIS for information exchange, despite the greater complexity.

Van Leusen and Van Gessel (2016) state on the other hand that with the current techniques 3D vector representations require considerable simplification of the complex layers and features in order to provide representations. Performing relevant analyses becomes very difficult by these simplifications. Therefore Van Leusen and Van Gessel (2016) indicate, for the time being, to see the most opportunities in 3D Volume-based representations in GIS. Because of this, it is interesting to examine in this study what types of 3D representations are included or provided by the different GIS software that are evaluated, in order to see whether there is a certain emphasis on raster or vector representations or that some 3D representations are not supported at all. In addition, it is relevant to investigate if there are differences in scale, resolution and quality between Surface- and Volume-based representations within the GIS software.

### 2.2.4 Point Clouds

In addition to the distinction between vector, representing objects, and raster, representing grids, a third representation or direction has occurred. Point clouds are data sets consisting of thousands of individual points and include advantages of both vector and raster. The individual points may be positioned to represent an object, but can also be positioned in a grid form. When obtaining point clouds both height (z) and coordinates (x,y) are recorded, resulting in the possibility to calculate heights of a specific area. As a result, point clouds are three-dimensional causing numerous 3D spatial analyses and functionalities to be applicable to the generated point data. Point clouds in combination with surface photography can construct realistic landscape models (Heywood et al., 2011).

Drainage models, soil subsidence tracking, tunnels and viaducts measuring, vegetation analyses, mutation signalling, volume calculating and feature extracting are examples of potential point cloud operations (Ali-Sisto and Packalen, 2017). When it comes to the subsurface and its soils the number of applications is somewhat limited. The surface and ground level can be measured with the aid of scanners, as shown in Figure 2.10. This allows a point cloud to be obtained that shows the earth's surface and any objects and heights. Subsurface scanning is not possible, therefore actual below ground point clouds cannot be obtained by scanning methods. Point clouds can however be obtained manually by executing and entering many soil surveys.

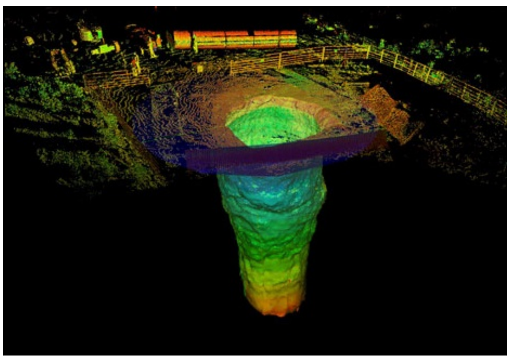


**Figure 2.9:** 3D mine shaft
*Source:* Geoterra (2018)

**Figure 2.10:** 3D tunnel scanning
*Source:* Hoovering Solutions (2017)

Point clouds of the subsurface can be generated by means of the available or measured subsurface data. Subsurface data contain a lot of information, including x, y, z values. The CLORPT and SCORPAN models that are discussed in Subsection 2.3.4 are examples of subsurface data point clouds, as it contains information about environmental factors at a certain point in space and time. Since the measured points contain a lot of soil variables, such as soil structure, climate, organisms, relief, parent material, age and location, the point data can be referred to as a nD PointCloud. The nD PointCloud is announced by Liu et al. (2018) for the handling of massive multi-dimensional point cloud data sets. These point clouds represent space, time and added information such as the soil variables. The nD PointCloud data structure is dedicated for smartly and flexibly managing and organising the information of large point clouds, which is suitable for large quantity subsurface data with multiple variables.

### 2.2.5 GIS Soil Properties

As will come clear from the SCORPAN function in Subsection 2.3.4, there are many variables that affect the subsurface and its formation. Therefore, the support of both Volume-based representations, Surface-based representation and point clouds, corresponding to the differences in soil types and formations increases the reliability of the output. Additionally, the reliability increases if the user has the ability to enter area specific soil properties during the creation of the 3D representations.

Factors are defined that influence soil formation, including parent material, climate, topography, time and biological factors (McBratney et al., 2003; Brevik et al., 2016; USDA, 2017). Because the subsurface and its layers can form in different ways based on different factors, this should be included within GIS packages in order to be able to generate a matching representation. The output of a subsurface area becomes therefore more realistic and reliable when variables of these factors can be entered or included within the GIS software.

The contact surfaces between different soil types indicate the versatility of soil formations. Brevik et al. (2016) and Seequent (2017) indicate different internal structures of soil formations, based on Surface- and Volume representations. Deposits, erosions, intrusions, veins, vein systems and stratigraphic sequences are different types of contact surfaces between soil types that together reconstruct a subsurface area. Figure 2.11 shows the difference of layer D entered as deposit or erosion layer, referring to the chronology or age of the soil layer. This shows that soil variables significantly affect and influence the output of the subsurface area, and therefore demonstrates that the subsurface can be more truthfully represented if GIS software support the input of these soil parameters.

In addition to age and chronology, examples of other advantageous soil properties to be set within GIS are: trend values indicating horizontal or vertical relationships of soil layers; pH-values; hydrological properties regarding conductivity, permeability, water content and pressure head; height or relief; soil types and lithologies. Additionally, the GIS software should provide some internal properties in order to create a more reliable output. These properties can refer to the resolution of the output (e.g. size of the voxel or triangle), number of interpolation methods, support of data type representations (e.g. Surface- and Volume-based) and the range of supported data formats.

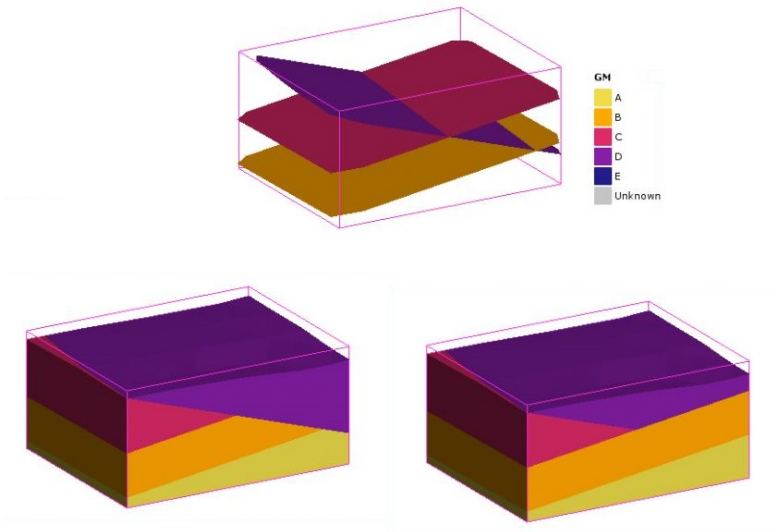



**Figure 2.11:** 3D soil formation
*Source:* Seequent (2017)

### 2.2.6 Black Box

GIS are complex software systems where data is processed and outputs are generated. Spatial data are fed in and maps with information come out. The GIS software, and its range of analyses, functions and tools, stands in the middle of the in- and output. The operation of or within GIS may sometimes be unknown or incomprehensible to the users. In this way, the system or object is viewed in terms of its input and output where there is no indication or knowledge about the internal working. This is referred to a black box.

Black boxes are abstract concepts and can include almost anything. Poore (2003) argues that GIS are black boxes. GIS has evolved into a commercial universality product for a wide range of users (Poore, 2003). As a result, the actual concept and knowledge about the internal operation has shifted to the background and is often unknown. The risk here is that mistakes can be made during black box operations without this is being known or recognised. The precision of GIS software, coupled with the ability to perform complex analyses and calculate spatial statistics for research and guidance reinforces this. Outputs and results that are generated with a black box whereby no critical consideration are made can be become subject to suspicion (Vaughan, 2014).

Poore (2003) therefore ask the question: 'Are current geographical information systems truly generic?' One may wonder whether GIS is universal if the output only has value if the internal operation of the software is understood and known by the user. Poore (2003) dismisses the commonly accepted idea of GIS serving as a universal toolkit that can easily be understand by a wide range of users and can be integrated within different disciplines, because of the black box. However, Vaughan (2014) supplements this by indicating the differences between the wide range of GIS software being developed. For example, open source GIS provide more insights of the operation within the black box through which the end results can be better examined and verified. In closed systems the operations within the black box are hidden making it impossible to view the source or to modify and track down exactly why these results were generated.

Kvamme (2018) addresses the main issue related to the black boxes of current GIS software. In order to achieve desired outputs very complex spatial data manipulations and operations need to be applied. To do this correctly, complete understanding of needed algorithms and operations and their sequences and consequences is required. However, performing such operations with GIS software does not requisite knowledge of complicated computer scripts, languages or codes, as would be required using common programming solutions such as Python, MatLab or R language (Kvamme, 2018). This is due to the graphical user interface of GIS software that is constructed through 'drag and drop' operations. True knowledge about the algorithms and internal working behind these drag and drop operations is essential in understanding and creating reliable outcomes.

As a GIS user it is therefore of great importance to understand the process between the entered input and received output. Otherwise, the output cannot be critically considered resulting in an output of decreased value. Attention must be paid to the presence of a black box and its internal working when investigating, evaluating and using GIS software. Sequentially, it is an advantage if GIS software provides insight into the black box.

## 2.3 The Subsurface

This research focuses on the subsurface domain. However, the subsurface is a large concept that also crosses the boundaries of other domains. Therefore, in addition to providing background information, this section contains the scope of the subsurface domain and defines its meaning for this research.

### 2.3.1 Soil Science

The earth's subsurface is the support of life. The subsurface is a mixture of organic material, gases, minerals, organisms and liquids and is an essential medium for nature and human beings. Plant growth, water storage, supply and purification are important natural functions of the subsurface. People use the subsurface environment for living and building (Verruijt, 2017). Geological related studies started to be conducted as a result of natural incidents, including landslides, earthquakes and volcanic eruptions, and human incidents, such as failures of foundations.

Soil research mainly takes place in the outermost layer of the earth, the pedosphere. The pedosphere can be seen as the skin of the earth and is composed by different soil types. The pedosphere is connected to all other earth spheres, which is shown in Figure 2.12. The pedosphere is the foundation of the critical zone. This zone is an environment around the surface where complex interactions take place between rock, soil, water, air and living organisms (Lin, 2010). These interactions determine life sustaining and environmental resources and regulate the natural environment. The subsurface is the central point of the critical zone where the atmosphere, biosphere, hydrosphere, and lithosphere cross.

Because the area of the pedosphere is the intersection between the other spheres, causing complex interactions to occur, it is challenging, but very useful to investigate the subsurface. The challenge lies in the processes of the atmosphere, biosphere, hydrosphere, and lithosphere converging at the pedosphere, which is shown in Figure 2.12.

Bouma (2009) emphasises that consequently soil research involves scientist, stakeholders, policy-makers and politicians from a variety of specialties. That is why soil science researches often cover a wide variety of disciplines. This complexity is, however, an important reason why soil research is needed.

Soil science is generally divided into pedology and edaphology. Pedology is the study of the formation, chemistry, morphology and classification of the soil, while edaphology includes the interaction of soils with living organisms, especially plant materials. Within these two main directions many specialisations are developed. The diversity of the directions within the soil science relate to the multiple disciplines concerned.

The pedosphere is an earth layer that is easily and extensively impacted by people. These human activities have a relatively larger impact on the pedosphere in contrast to the other spheres of the earth. For instance, the atmosphere is able to intermix, the hydrosphere can rapidly move along the landscape, the biosphere is divided into individual entities which can avoid undesirable environmental changes and the lithosphere manages to escape rapid human and biological perturbations (Lin, 2010). The subsurface of the pedosphere is relatively immobile and firmly set. The subsurface is therefore fated to encounter, react and process environmental changes. Climatic, biotic and human interactive forcings will inevitably lead to transformation of the subsurface (Wilding and Lin, 2006). Monitoring and investigating the subsurface and its soils is accordingly an excellent and useful assessment of the environment. Each soil layer and component is a 'reminder' from a time in the past and the current biosphere-geosphere dynamics.

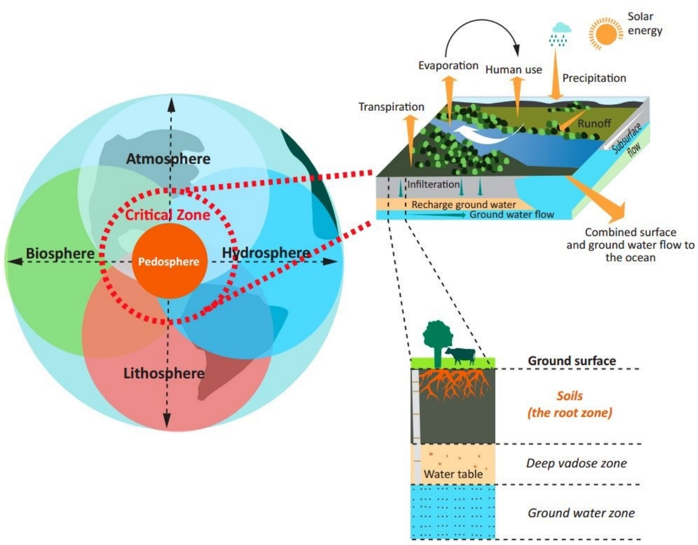



**Figure 2.12:** Critical zone
*Source:* Wilding and Lin (2006)

### 2.3.2 Subsurface Data

In order to carry out all studies and disciplines that relate to science, it is fundamental that there is sufficient and qualitatively correct information about the subsurface. Despite this relevance and importance of subsurface data there is scarcity subsurface information of sufficient quality, especially at the resolution required for environmental modelling (Poggio and Gimona, 2017).

Complications occur in terms of obtaining accurate subsurface data. As first, the subsurface cannot be directly observed in comparison to the surface (Raska, 2017). Aboveground data can easily be accessed by topo-cadastral maps and digital elevation models or be obtained via surveys. It takes more effort to obtain subsurface data, especially at a refined level of detail (Paterson et al., 2015). The only possibility to observe the subsurface is through measurements. If no measurements are taken in a certain area, no actual descriptions or conclusions about the subsurface can be drawn.

Despite the fact that it takes more effort to collect subsurface data, it is necessary for researchers to feature enough accurate data in order to draw legitimate conclusions (McCarthy and Graniero, 2006). Large volumes of subsurface data can however be difficult to administer. Performing analyses even harder. Discovering spatial patterns in the subsurface is nearly impossible from only viewing tabular data. The procedure of geologists manually overlaying paper maps is despite the possibly reliable result very time-consuming. Computer software taking over display and visualisation techniques saves the user time and effort.

Evolution in the fields of information technology, satellite imagery, digital elevation models and geostatistics resulted in the development of new soil survey techniques (Paterson et al., 2015). In the 1980s this led to the emerging of Digital Soil Mapping (DSM), including collecting, creating and assimilating spatial subsurface data through the usage of survey and laboratory observational methodologies combined with subsurface inference systems. DSM extensively operates with technological advances, such as remote sensing, GPS and field scanners, and computational advances, including data mining, DEMs and GIS.

As mentioned, this research is focused on subsurface data and its processing and visualising in GIS. Since the subsurface covers a large area and multiple disciplines there is no single unambiguous definition of the subsurface and its soils. The concepts of subsurface and soil may vary in meaning and application for different instances. To avoid ambiguity, the terms subsurface and soil are defined as used in this research, according to the independent Dutch research bodies TNO and Alterra. The data used in this study contains depths of up to 50 meters in the subsurface measured from the ground level. Therefore, the deeper earth mantles are excluded and will not be referred to. When subsurface data is mentioned, the information of the area to about 50 meters under the earth's surface is meant. When the term soil is used only the top few meters of the subsurface is indicated. Soil types signify the taxonomic units and its properties of soil categories. For the ground level the heights of the AHN (the current heights of the Netherlands) relative to the NAP (Normal Amsterdam Level) will be maintained.

### 2.3.3 Soil Survey Techniques

There are various methods for examining the subsurface and obtaining subsurface data. Examples of soil researches are: field research, laboratory research, foundation control, construction guidance, monitoring and consulting. In this section some fieldwork techniques will be discussed, since these are methods to obtain subsurface data.

Cone Penetration Testing (CPT), also referred to as probing, is the determination of the bearing capacity of the ground by pressing a rod into the ground and thereby reducing the mechanical resistance of the subsurface (Rowell, 2014). Probings are carried out by a probing vehicle, usually a heavy 6x6 truck or a vehicle on caterpillar tracks, as shown in Figure 2.13. A hydraulic press is included in the probing trolley that presses the probing rods into the ground. The weight of the probing trolley provides the reaction force and the oil pressure in the hydraulic press is a measure of the cone resistance. Modern electronic versions now exist which can determine the cone resistance and the adhesive on the ground.

In addition to probing, drilling is performed to obtain information about the subsurface. Soil drilling or boreholes are used for different purposes and depths. Manual, pulse, stitch and rotation drilling are some examples. Although manual drilling only go up to 10 meters deep, pulse drilling can reach 100 meters deep. The boreholes are used to place infrastructural and material objects, but also for obtaining soil samples in soil research. The choice for a drilling technique is dominated by environmental aspects, quality requirements, safety and labour related aspects, above and below ground infrastructure, depth of drilling to be reached, soil conditions, experiences and costs.

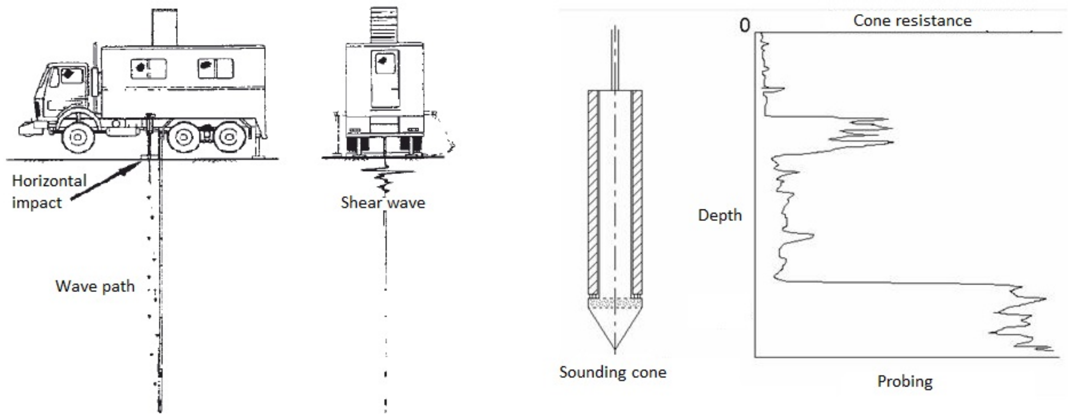



**Figure 2.13:** Probing technique and output
*Source:* Bouwbedrijf Lichtenberg (2016)

When performing soil research the soil composition, groundwater levels and soil quality are often examined. Soil composition can be obtained through the observations during the soil drilling and the analysis of these soil samples in a laboratory. Monitoring wells with filters are placed to monitor and determine the quantity, quality and rise or fall of the groundwater. The length of a monitoring well can vary from one to hundreds meters deep and contains a perforation at the bottom of the tube (USDA, 2017). The monitoring well is placed in the drilled hole and the remaining space in the hole is filled with soil. This soil varies from dense clay to sand or gravel. The inserted soil surrounding the filter must be permeable so that it is connected to the groundwater, which is shown in Figure 2.14.

Drilling and soil samples are fairly traditional methods to examine the subsurface beneath the surface. Advanced techniques are developed to supplement these more traditional techniques of subsurface exploration and investigation (Lopez, 2017). Examples are ground radar and (shallow) seismic.

Geo-electric research additionally includes more advanced methods for imaging the subsurface. The purpose of this research method is to measure the resistivity distribution of the subsurface (Samouëlian et al., 2005). Various geological parameters affect the subsurface resistivity including the mineralogy, the composition of the pore fluids, the state of weathering and porosity and the degree of saturation of the materials (G-tec, 2018). The research supplies are a battery, two flow electrodes and two potential electrodes. Electric currents that are artificially-generated are supplied to the subsurface where after potential differences can be measured. These potential difference patterns provide insides on soil structures and their electrical properties (Samouëlian et al., 2005).

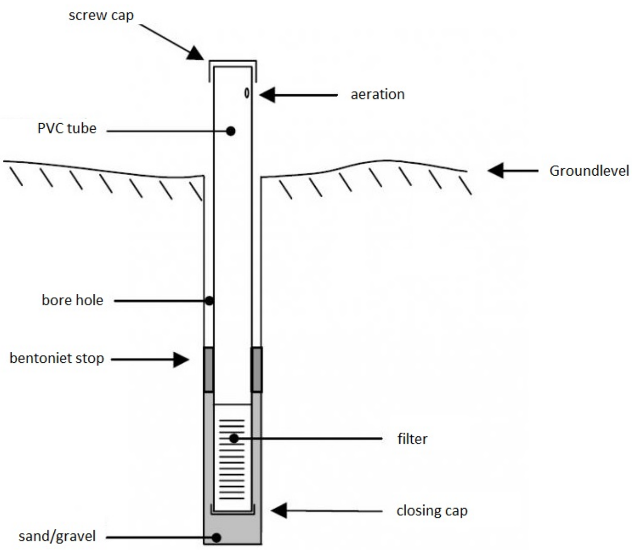



**Figure 2.14:** Monitoring well
*Source:* Ecopedia (2018)

Within the geo-electrical measurements, a distinction is made between Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT). VES measurements are delivered along a horizontal line from the surface and provide a 1D model in the centre of the measurement setup (Zarroca et al., 2011). A VES measurement has a fixed centre point. The position of the outer current electrodes is increasingly widened during the VES. The further the outer current electrodes are apart, the deeper the range of the measurement into the subsurface. However, this deeper range in the ground leads to a reduced level of detail. The most frequently used applications of VES measurements are: determining the groundwater depth, generating (hydro) geological profiles combined with boring data and assessing the electrical resistance of the subsurface. A typical output of a VES measurement can be seen in Figure 2.15. Here the resistivity of the subsurface of the measured points is graphically shown in 1D.

Another method to map the electrical resistivity of the subsurface is ERT (Zarroca et al., 2011). In contrast to VES, ERT provides a 2D image of the resistivity distribution of the subsurface, both laterally and in depth. ERT is applied more often because the 2D result provides better insights. Examples of applications of the ERT method are: time lapse monitoring of saltwater intrusion dynamics, localising contaminant plumes and indicating their motions, estimating depth and thickness of landfills, exploring waste sites and detecting underground cavities (Zarroca et al., 2011; G-tec, 2018).

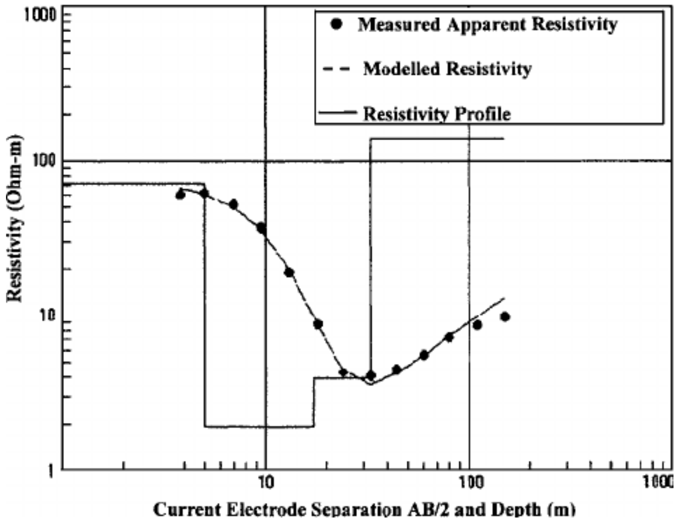



**Figure 2.15:** Typical output of VES measurement
*Source:* Rinaldi et al. (2006)

ERT is executed by means of a cable to which different electrodes are installed. The measurement is carried out by multi-channel acquisition system which can be programmed. It is indicated for each electrode whether it is passive or active by a series of relays using an acquisition geometry protocol (G-tec, 2018). In Figure 2.16 a typical setup for an ERT measurement is shown. The green dots represent the measured apparent resistivity and are plotted in the middle of each set op electrodes. The depth of the measurements relate to the range between the electrodes. This range of space between the electrodes ($a$) can be setup with different arrays. The most common are the Wenner, the Schlumberger, pole-pole, the pole-dipole and the dipole-dipole array, presented in Figure 2.17. The choice for an array depends on the research requirements and location characteristics, including the desired depth, resolution, topography, and horizontal and vertical structures (G-tec, 2018).

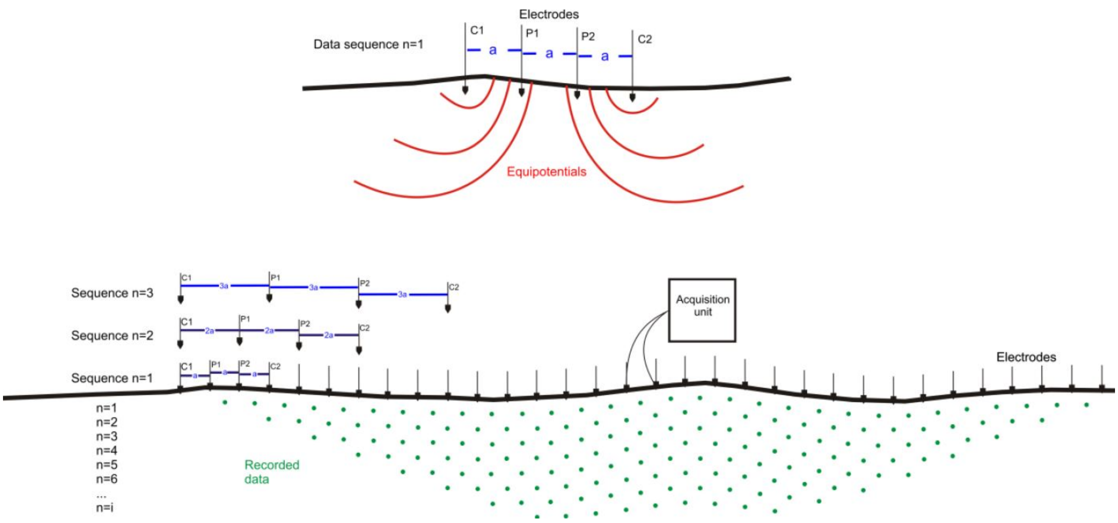



**Figure 2.16:** Typical setup for an ERT survey
*Source:* G-tec (2018)

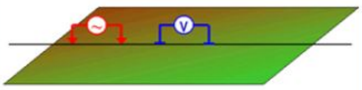
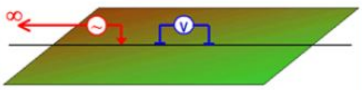
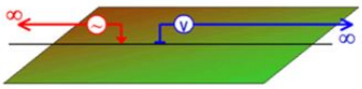
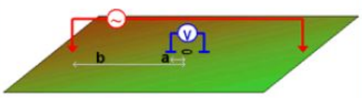
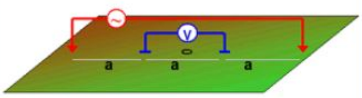
| Protocol | | Description | Approx. depth of penetration/resolution |
|---|---|---|---|
|  | **Dipole-dipole** | Most common profiling configuration. Several potential measurements are taken for each transmitter station. | Depth of penetration >2 x (distance V1-V2)<br>resolution: 0.5 x (distance V1-V2) |
|  | **Pole-dipole** | Compared to dipole - dipole, more efficient (move only one source electrode), deeper penetration, but slightly lower spatial resolution. | Depth of penetration > 2.5 x (distance V1-V2)<br>Resolution: 0.5 x (distance V1-V2) |
|  | **Pole-pole** | Compared to pole - dipole, more efficient, deeper penetration, but lower spatial resolution. | Depth of penetration >2.5x (distance between V1-I1)<br>Resolution: 0.5 x (distance between V1-I1) |
|  | **Schlumberger sounding** | Distance "a" is on the order of one tenth of distance "b" | Depth of penetration >(distance between I1-I2)/8<br>Resolution: poor |
|  | **Wenner sounding** | The three spacing between electrodes are kept equal for all measurements | Depth of penetration(distance between I1-I2)/8<br>Resolution: depending on lateral shift |

**Figure 2.17:** Different arrays of ERT
*Source:* G-tec (2018)

The 2D output of an ERT measurement is visualised as a contoured map, shown in Figure 2.18. An output like this is called a pseudosection. The pseudosection is imported into a numerical modelling program in which the electrical resistivity distribution can be calculated (G-tec, 2018). The elevation of the ground level strongly influences the output of the ERT. Accordingly, the ground level heights must also be measured during the survey and will be considered and processed during the modelling process.

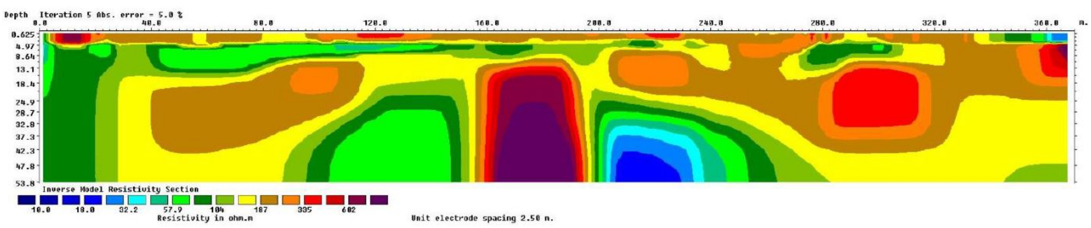


**Figure 2.18:** Pseudosection
*Source:* G-tec (2018)

### 2.3.4 Soil Mapping

The data from the soil fieldwork surveys are first largely processed in tables. The tabular data contain a variety of information about the monitoring wells, coordinates, groundwater levels, soil structure, analysis samples, filters and other soil characteristics. These tables are useful because all data is gathered here. However, displaying data in a tabular form is often not very clear, especially if the table contains large quantities of units and measurements. Therefore, subsurface data is often represented schematically, for example by means of cross-sections. A cross-section, or soil profile, is a vertical representation of the subsurface. The different soil layers, also called soil horizons, become visible through a cross-section representation as can be seen in Figure 2.19.

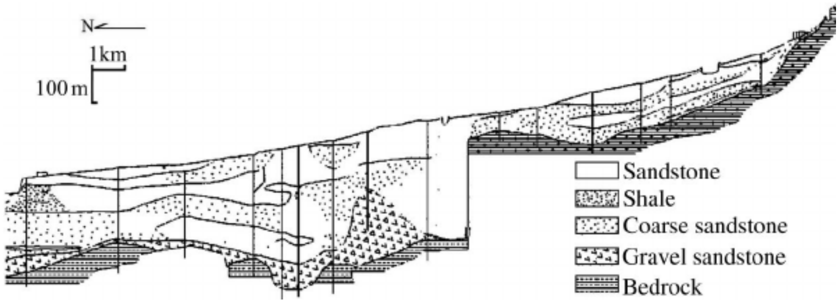



**Figure 2.19:** Cross-section
*Source:* Yu et al. (2012)

Another method to visualise subsurface data two-dimensionally is by generating soil maps. In Figure 2.20 a traditional soil map is shown, indicating productivity of soils in Nigeria. In the literature a distinction is made between Conventional Soil Mapping (CSM) and Digital Soil Mapping (DSM) (Yang et al., 2011; Kempen et al., 2012; USDA, 2017). CSM are generally produced by means of free survey. This kind of survey method encompasses the researcher or soil geometrician to use a subsurface model to select suitable measurement locations (Kempen et al., 2012). Landscape items, aerial photos, topographical maps, DEMs and past experiences in similar areas are used to create the soil maps. In addition intensive fieldwork is required to obtain subsurface data (Yang et al., 2011). CSM results in a soil type map and a subsurface database containing information on the map unit composition, soil profile descriptions and map unit interpretations (Kempen et al., 2012). Conventional soil maps are useful for general purposes.

Opposite to this are digital soil maps that are often generated for more specific use. The important difference is that DSM uses quantitative inference models to provide prospects of soil classes and properties in a raster format (USDA, 2017). CSM is based on a qualitative model, resulting in criticisms questioning the reproducibility and certainty of the maps (Kempen et al., 2012). DSM offers solutions to these shortcomings because the prediction model can be stored and thereafter ran again. However, the availability of (up-to-date) subsurface data and environmental data layers determine the success of DSM.

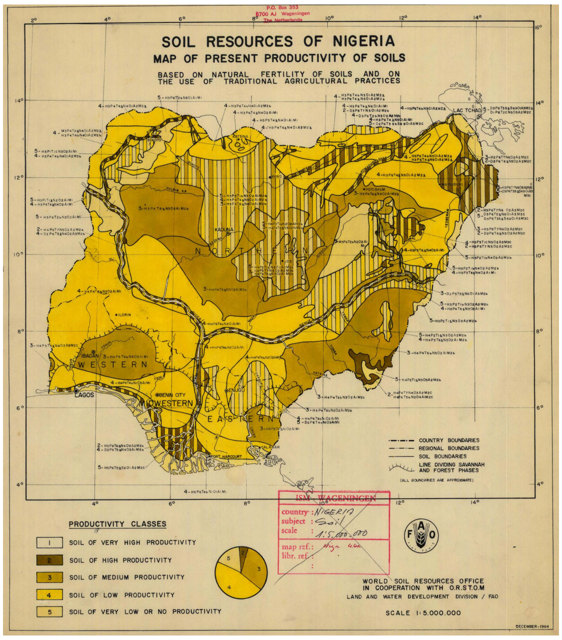



**Figure 2.20:** Traditional soil map
*Source:* ESDAC (2019)

Soil mapping is scientifically founded in a conceptual model of H. Jenny in 1941 assuming that soils ($S$) on a landscape are a function of five environmental factors: climate ($cl$), organisms ($o$), relief ($r$), parent material ($p$) and time ($t$):

$$S = f(cl, o, r, p, t) \tag{2.1}$$

This model referred to as CLOPRT is usefully applied in CSM, but it is not quantitative nor spatially explicit (USDA, 2017). A new model has developed by McBratney et al. (2003) to present soils and related environmental factors in a quantitative expression and spatial context. Here, the soil classes ($S_c$) or soil attributes ($S_a$) are an empirical quantitative function of seven environmental factors at a certain point in time and space: soil ($s$), climate ($c$), organisms ($o$), relief ($r$), parent material ($p$), age ($a$), and spatial location ($n$):

$$S_{c,a} = f(s, c, o, r, p, a, n) \tag{2.2}$$

The SCORPAN model fits DSM (USDA, 2017). These two models indicate the difference between the qualitative CSM and the quantitative DSM.

### 2.3.5 Subsurface Data Dependency

Information about soil types and groundwater is essential when investigation soil contamination. Groundwater is water beneath the Earth's surface located in pore spaces in unconsolidated geologic materials and bedrock fractures. The water is often supplemented by precipitation that has percolated the surface or by water bodies. Groundwater can flow both upwards and downwards due to differences in pressure levels caused by different soil layers and structures.

In Figure 2.21 a visual representation is outlined of a groundwater flow situation explaining the flow direction. The figure shows aquifers which are geological formations consisting of unconfined soil material like sand or permeable bedrock. The aquifers allow water seepage. Confined soil material like clay form sealing layers through which the water can hardly pass, referred to as aquitards. In Figure 2.21 a confining soil layer (aquitard) is situated above an unconfined layer (aquifer) causing an increased pressure in the unconfined layer. When a well or borehole is placed that reaches this layer the water level within the well will rise above the aquifer with the increased pressure. This is represented by the rightmost well in the figure and is called an Artesian well. When the water in the well rises to an elevation above the Earth's surface due to the high pressure the well will overflow. This is an Flowing Artesian well and is presented in the figure by the leftmost well.

If the subsurface is polluted in a certain area it is important to know how the groundwater flows to predict in which direction the contamination will move. Therefore it is essential to measure and examine which soil materials the subsurface consists of in that area. This allows wells to be placed at the most useful and critical locations to measure concentrations.

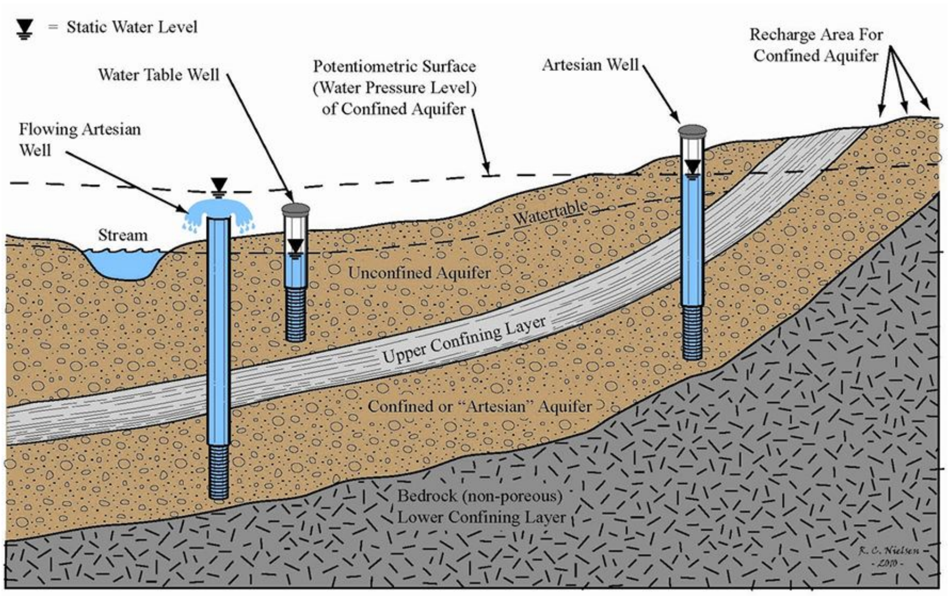



**Figure 2.21:** Groundwater flow
*Source:* MDH (2018)

### 2.3.6 The Subsurface in a Broader Context

In the beginning of this chapter it is mentioned that the top layer of the Earth, the pedosphere, is a complex area that interacts with and depends on all the other spheres. Soil research consequently involves scientists, stakeholders, policy-makers and politicians from a variety of disciplines. Soil science related disciplines are for instance agricultural science, anthropology, environmental science, physical geography, geology, atmospheric sciences and hydrology. Because of this variety of disciplines, carrying out the above mentioned soil surveys and digital soil mapping is not a self-containing process. It can therefore be stated that soil science is part of a broader environmental context that must be considered when research or proceedings are carried out.

In addition, when looking at the broader context of the subsurface and its research, exploring 3D GIS functionalities is not limited to the subsurface domain and its data. The subsurface could have corresponding characteristics with, for example, atmospheric research and data. Although the atmosphere may be more easily visible to the naked eye than the subsurface, there are similar challenges when it comes to 3D mapping. For example, pollutants move in the air, just like this happens with contamination in the subsurface. Certain harmful substances in the atmosphere are not visible to the naked eye, similar as to the subsurface. Research, techniques and outcomes of soil research can therefore be of use in atmospheric research and vice versa.

NASA is, for example, working on the development of the 3D modelling of certain substances in the atmosphere. The movement and emission of carbon dioxide is tracked by scientists by the use of weather satellites. NASA developed a highly detailed map of carbon dioxide movements (Borneman, 2017). In Figure 2.22 the 3D model created by a supercomputer is shown. Because of these mixed interests and concerns it is of great importance that the focus is not limited to the subsurface domain. Other areas of expertise are perhaps working on similar developments which could be useful.

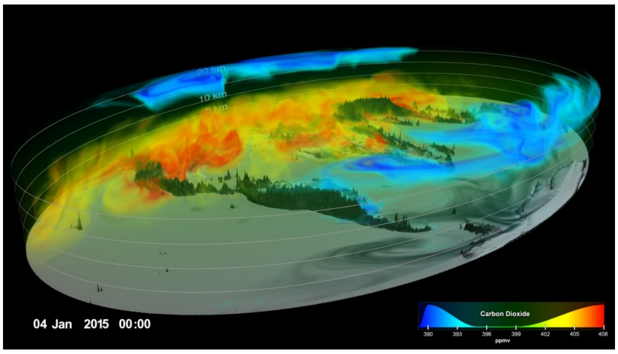



**Figure 2.22:** 3D model of carbon dioxide movement
*Source:* Borneman (2017)

## 2.4 Subsurface of The Netherlands

The Netherlands as lowland makes the country and its subsurface very unique. Large parts of the Dutch land has been reclaimed by means of strategic water management techniques which resulted in below sea level areas and a flat surface. These techniques date back from the Middle Ages whereby large areas of land have been drained and dikes have been built to repress the seawater (Lynn, 2018). Partly due to this history, the Netherlands consist of a variety of different geographic subsurface regions. The soil structure of the Netherlands is unique because the country can be characterised as large river delta.

Because a large part of the Netherlands is below sea level, groundwater is on average very high. More than 90 percent of the country has a groundwater level within 1,4 meters below surface resulting in hydroformed properties in most Dutch subsurface (Hartemink and Sonneveld, 2013). Artificial draining is therefore often required. Hardly any soil is derived from consolidated rock, making the soil relatively soft and sandy. Sandy soils (43%), marine clays (24%), organic soils (14%) and fluvial clays and loams (8%) dominate the non-urban areas (Hartemink and Sonneveld, 2013).

Loess (1,4%) soils mainly appear in Southern areas of the Netherlands. These unique geographic properties of the soft soil regions in combination with high population densities has led to characteristic and extensive soil research and mapping approaches in the Netherlands.

### 2.4.1 Dutch Soil Mapping

The first national geographic map was published in 1822 by d'Omalius d'Halloy containing two unit areas: Southern Limburg and the rest of the country (de Bakker, 2013). There was need for a more detailed map describing the geological conditions of the Netherlands. This map was produced in 1844 by Staring including alluvial soils, diluvial soils and tertiary soils (Hartemink and Sonneveld, 2013). Reprints of these map were created later on in which the topography has been improved. The maps were not used for agriculture because of the low level of detail. In 1918 a more detailed geographic map was produced as a result of government decision with the view on agricultural use.

Soil research, surveys and fieldwork increased strongly as more subsurface areas were mapped. The scale of the cards increased, which resulted in more details. In 1945 the Dutch Soil Survey Institute (StiBoKa) was founded with the main goal to perform soil research as commissioned by the Department of Agriculture and other agencies and to support the use of the maps for reviewing subsurface suitability for agriculture, horticulture and forestry (Hartemink and Sonneveld, 2013). There was a high demand for soil maps in areas with severe damages caused by World War II. StiBoKa was requested to collect national subsurface information to support hydrological research of Dutch agricultural subsurfaces. The fieldwork required to this led to the development of the NeBo map, where the geographic position of different soil types became visible. Along with the NeBo map a standardised terminology was developed to describe soil texture, soil organic matter and soil colour (Hartemink and Sonneveld, 2013).

From the sixties more and more international interactions and discussions arose about soil research and soil classifications (de Bakker, 2013). As a result, the soil surveys and maps became more detailed. More soil types were considered, making the maps applicable for multiple purposes, such as water extraction, regional redevelopment projects and forestry rating (Hartemink and Sonneveld, 2013). The digitising of these maps started soon after the creation of these maps. The published paper maps were scanned and the subsurface data were stored in databases. The Dutch subsurface information System (BIS), a relational database, was developed in 1984 to store point data and maps. The database grew tremendously in the years that followed storing soil samples of approximately 300.000 locations in the Netherlands.

Advanced computer technology and new developments allowed for new methods in the field of soil mapping and updates of existing subsurface data from the 1990s. GIS, spatial statistics and existing soil maps were combined for DSM. Resulting from this digital age the use and production of subsurface information remains and continuous in many parts of the world, including The Netherlands (Hartemink and Sonneveld, 2013).

### 2.4.2 Basic Registration of the Subsurface

StiBoKa started in 1960 with the manufacturing of the soil map of the Netherlands on a 1:50.000 scale. This map was finished in 1995 and has recently become part of the Basic Registration of the Subsurface (BRO) of the Netherlands (see Figure 2.23). The BRO contains data on geological and soil structures and insofar as it is important for the utilisation of natural resources in the subsurface, underground constructions and user rights.

With this registration the government aims to strongly improve the public information provision to offer data about the subsurface in a standardised manner (de Vries et al., 2017). Information about the subsurface is now being managed by various organisations. Partly as a result, the data has not been digitised, standardised and harmonised in the same way. The BRO collects all data in one place and publishes it through one counter. On the First of January 2018 the BRO law officially entered into force. Constant maintenance is required in order to be able to use the information from the BRO adequately for national and regional applications. This maintenance is focused on: improvement and updating of the content information, improvement of geographical accuracy and quality indicators. The information provided by the BRO is divided into six domains:

- Soil and subsurface research: information derived from companies active in civil engineering, civil engineering and hydraulic engineering
- Soil quality: the data collected by the monitoring networks of the RIVM, the provinces and Alterra
- Groundwater monitoring domain: information from the network of wells in our country that continuously measure the composition, quality and quantity of the groundwater
- Groundwater: data about the extraction of groundwater by, for example, companies that have to apply for a permit under the Water Act
- Mining Act domain: information that companies have gathered through drilling for the exploration, extraction and storage of minerals and geothermal energy
- Models: includes the Soil Map of the Netherlands (scale 1:50,000), the Geomorphological Map (scale 1:50,000), DGM, REGIS II and GeoTOP

### 2.4.3 DINOloket

The operational manager for the realisation of the BRO is TNO, the Dutch Organisation for Applied Scientific Research. TNO is an independent research organisation connecting people and knowledge to create innovations that strengthen the competitiveness of companies and the well-being of society in a sustainable way. The section of TNO which is actually responsible for the subsurface information is the Geological Survey of the Netherlands (GDN). The aim of the GDN is to make geological knowledge applicable by means of powerful databases, GIS and the management of the BRO.

The precursor of the BRO is DINO (de Vries et al., 2017). DINOloket is the portal's name that makes the BRO data accessible. An important difference with the BRO is the legal aspect. DINOloket offers, among other things, access to the largest database of the Dutch subsurface. This database is a central place where geo-information about the deep and shallow subsurface of the Netherlands are collected and managed.

The database is updated daily and expanded with new data made available through DINOloket. The starting point is the improvement of availability and an increase in the (re)use of data from the Dutch subsurface. Due to the wide variety of open available subsurface data that is offered, DINOloket contains many different Dutch users types. Users of DINOloket are governments at national, provincial and local level as well as companies and individuals. DINOloket provides access to groundwater data, probing, geoelectric measurements, seismic data and drilling information, including results from geological, geochemical and geomechanical sample analyses, borehole measurements and drilling sample descriptions. The data included in DINOloket is an important source for Dutch subsurface information and can therefore certainly be of interest for additional data for subsurface models.

### 2.4.4 Public Services on the Map

Public Services On the Map (PDOK) is a platform for the publication of geodata sets by Dutch authorities. PDOK provides reliable digital geo-information as data services and files for both the public and private sectors. The PDOK services are based on open data and therefore freely available to everyone. A collaboration between the Land Registry, the Ministries of Infrastructure and Water Management, Ministry of the Interior and Kingdom Relations, Ministry of Economic Affairs and Climate Policy, Rijkswaterstaat and Geonovum resulted in the establishment of the open initiative PDOK. Every government organisation desired to reveal their geodata for reuse can utilise PDOK.

PDOK provides data about many themes, including nature and environment, economy, agriculture and livestock, water, transport, society and planning. In terms of the subsurface, data are available related to heights, land use, physical geographical regions and the BRO. These open source data can be useful when executing soil research. For GIS software it is therefore an added value if data files from PDOK, such as the BRO and the AHN files, are supported.

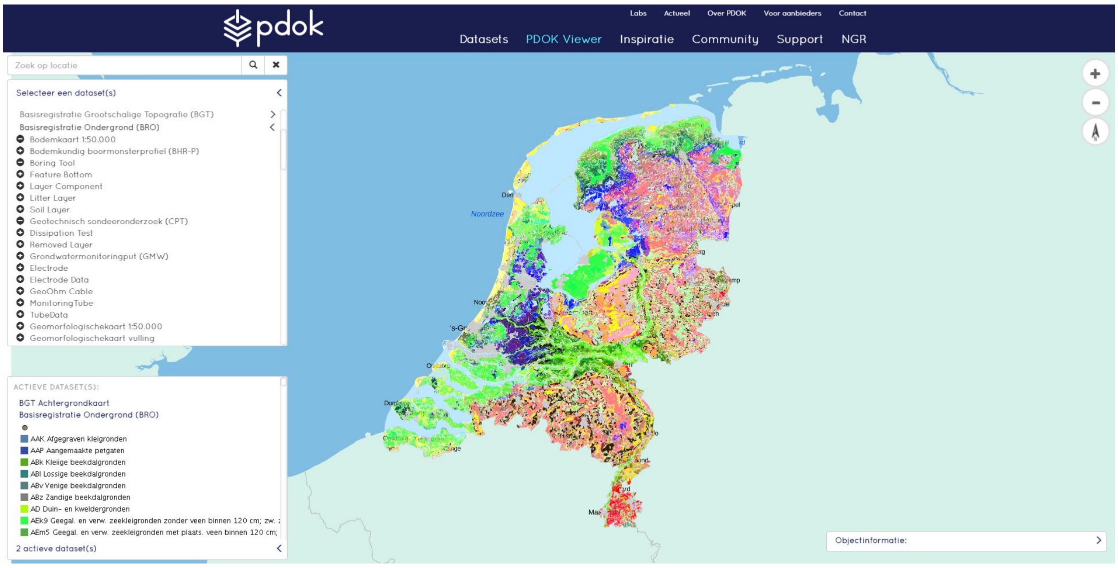



**Figure 2.23:** Soil map of the Netherlands provided by PDOK
*Source:* PDOK (2019)

### 2.4.5 SIKB Foundation

An important netwok organisation of soil management in the Netherlands is the Foundation Infrastructure, Quality assurance, Soil management (SIKB). SIKB is a network organisation in which the government and business communities together make practical quality guidelines for soil, water, archaeology, soil protection and data standards. The aim is quality assurance and improvement for market parties and governments. SIKB contributes to the Dutch soil management domain by drawing up guidelines and protocols for soil research and fieldwork, preserving soil samples, developing data standards for subsurface data, responding to new techniques and innovations and sharing knowledge through platform meetings, courses and conferences. The SIKB data standards and protocols are very useful in DSM.

The SIKB data standard SIKB0101 offers an unambiguous way and an error-free exchange of data by means of (GIS) software. SIKB regularly updates this standard on the basis of new demands, needs and developments in the soil market. SIKB0101 is consistent with all relevant national and international standards, and anticipates to new developments, such as the BRO since early 2018 (SIKB, 2018). The standard SIKB0101 outlines the technical rules for the implementation of an import or export function in software, describing:

- An exchange model (UML) describing which data can be exchanged via the standard according to which structure
- Domain tables where the contents of a number of fields are set in fixed lists
- The format for exchange (XML) for any data
- Rules for the implementation of the standard (protocol)

The XML format is used worldwide to digitally store data and share and upload it on the internet. Virtually all subsurface information systems on the Dutch market use the standard SIKB0101 (SIKB, 2018). Users create XML files of their subsurface data to exchange it with other parties and stakeholders.

### 2.4.6 Current Height of The Netherlands

The Current Height of The Netherlands (AHN) is the digital height map of the country. It contains detailed and precise height data with an average of 8 height measurements per square meter. The altitude is measured with laser altimetry: a technique in which an aircraft or helicopter uses a laser beam to scan the earth's surface. By both the measurement of the running time of the laser reflection and the position of the aircraft an accurate result is provided (AHN, 2018).

The acquisition of the AHN started in 1997. AHN1 was the first available height data set that contained a point density of 1 point per 16 square meters. After the completion of AHN1 the need arose for a more accurate data set, which matched the new available techniques in the field of laser altimetry, digitisation and mapping. The result was the higher resolution of AHN2 with an average point density of 6 to 10 points per square meter. The acquisition of the newest data set AHN3 runs until 2019.

In addition to these different resolutions, the AHN is available in different data formats and types. Objects located on the surface, such as buildings and vegetation, are measured by the laser. However, the laser techniques are advanced and can distinguish the ground level. In Figure 2.24 this is shown. Both the ground level and the total file, including buildings and vegetation, are available for download. Besides this classification, different data formats are available including raster, LAZ point cloud and Geo-TIFF. The AHN files are delivered by PDOK.

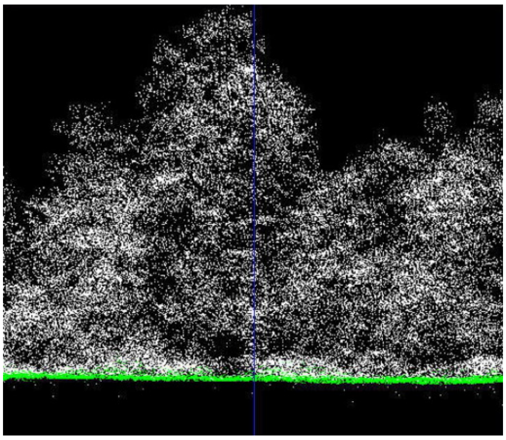


**Figure 2.24:** Ground level (green) and vegetation (white) recognition
*Source:* Fugro (2018)

### 2.4.7 Normal Amsterdam Level

In order to compare heights within the Netherlands a zero level is used: the Normal Amsterdam Level (NAP). All heights are measured relative to the same level. A NAP height of 0 meter is approximately equal to the average sea level of the North Sea. The highest point in The Netherlands is 322,38 meters above NAP located near Vaals in Limburg, and the lowest point is 6,78 meters below NAP located in Nieuwerkerk aan den IJsel in Zuid-Holland. In order to determine the height in relation to the NAP approximately 35.000 benchmarks are placed throughout the country. These NAP benchmarks have a height in relation to the NAP and are embedded in, among other things, houses, bridges, viaducts. Almost throughout the Netherlands a NAP benchmark is located within the distance of 1 kilometer.


**Figure 2.25:** NAP benchmark in Lobith
*Source:* RCE (2007)

## 2.5 Dutch 3D subsurface models

The GDN has developed a few 3D models of the Dutch subsurface based on drilling, probing, monitoring well and seismic measurement information. These models provide information about the sequence, the lithology and the properties of the soil layers.

### 2.5.1 DGM

The Digital Geological Model (DGM) includes the Dutch soil layers to 500 meters deep, with a few outliers to about 1200 meters. DGM is modelled based on a selection of around 20.000 available borehole measurements from the DINO-database. The model is suitable to use for regional levels. Additional information is necessary for more local use. In Figure 2.26 the model can be seen. DGM-deep is a version of the model focusing on the subsurface deeper than 500 meters. The model is used for the support of minerals studies, such as hydrocarbons and geothermal energy. The main application of DGM is the input for REGIS II and GeoTOP.

### 2.5.2 REGIS II

The hydrological model REGIS II, shown in Figure 2.27, contains information about the water permeability of the subsurface. The data is mainly obtained from boreholes and geophysical measurements. REGIS II provides images of the hydrogeological structure on a regional level, corresponding to a usage scale of approximately 1:100.000.

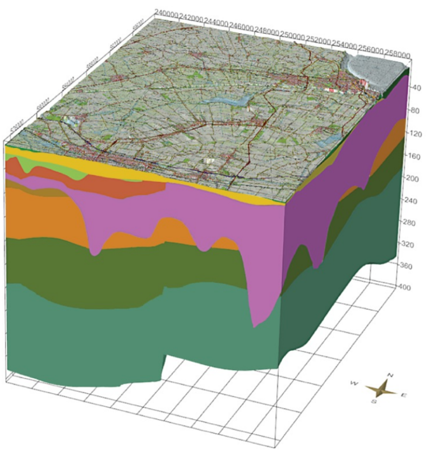


**Figure 2.26:** DGM
*Source:* GDN (2019)

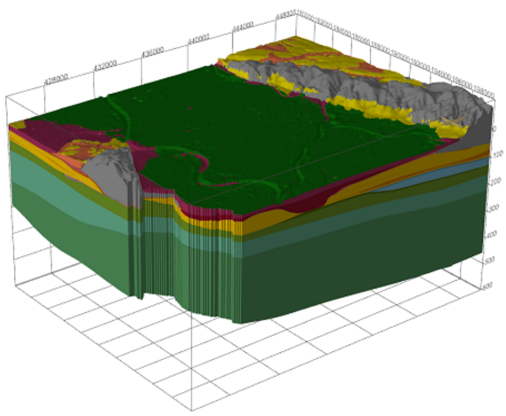


**Figure 2.27:** REGIS II
*Source:* GDN (2019)

### 2.5.3 GeoTOP

GeoTOP offers an estimation of the geometry of the geological units and of some properties of the subsurface for approximately 60 percent of The Netherlands. The information in the model reaches to about 50 meters below NAP. The GeoTOP model is made up of voxels from 100 by 100 meters in horizontal direction and 0,5 meter in vertical direction. Every voxel contains information about the subsurface lithology and properties. Unique is that almost all 500.000 available boring measurements are used to build the model, which provides much more details than DGM and REGIS II. In Figure 2.28 the GeoTOP is shown.

### 2.5.4 NL3D

The NL3D model is the low resolution version of GeoTOP. The voxels of the NL3D model are 250 by 250 meters in horizontal direction and 1 meter vertically, causing less visible details in NL3D. Furthermore, the degree of geological guidance, which is the usage of geological information from other sources such as maps and publications, is less in NL3D than in GeoTOP. In Figure 2.29 the NL3D model is shown.

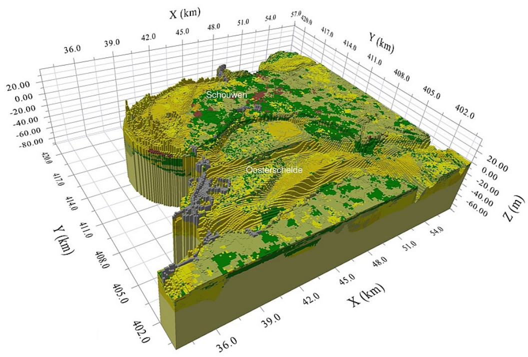



**Figure 2.28:** GeoTOP
*Source:* GDN (2019)

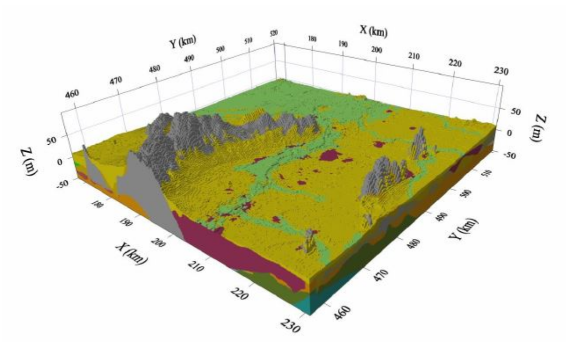



**Figure 2.29:** NL3D
*Source:* GDN (2019)

The Dutch 3D models are useful examples to refer and look at in this research. Moreover, the models can be used to add supplementary 3D information to the case data.

## 2.6 3D Visualisation Advancements

Besides 3D functionalities that are included and are being developed within GIS software, there are also 3D visualisation advancements in (non-)GIS technologies which can be of value for the presentation of subsurface data. These innovative visualisation developments can be useful to (re)present the subsurface data three-dimensionally which provides more spatial insights. Besides, entertaining and impressing the audience can be the goal of these development, whereby actual functionalities are not included.

### 2.6.1 3D Projector

A screen in which 3D objects can be viewed by means of 3D glasses has been on the market for some time now, for example in cinemas. 3D glasses can be divided into passive glasses, that do not need a source of electricity, and active glasses, that do need a source of electricity. With these glasses a stereoscopic film or image can be viewed three-dimensionally. For the 3D glasses technique different depths are used in the movie or image for the right and left eye which creates an optical 3D images (Fukiage et al., 2017). Esri's ArcScene anticipated to this technique with the stereo view option for anaglyph glasses. Two separate images on top of each other are created, a red image for the left eye and a cyan image for the right eye, as shown in Figure 2.30.

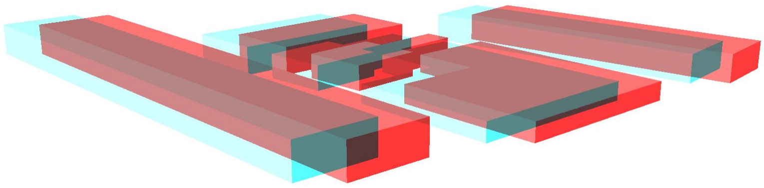


**Figure 2.30:** Stereo view of buildings in ArcScene

Nowadays, screens are being developed where the screen converts the image into 3D ensuring the glasses no longer needed. The screen contains a special lens structure or grid which performs the stereoscopic splitting, instead of the glasses. However, with this technique it is important to look at the screen from a specific viewing angle to see the 3D effect. This is not a big point in question with small screen devices, but when scaled up to large screen sizes it makes implementing glasses-free 3D viewing technology very difficult and expensive. There are a few 3D projectors in large screen beamer format where a 2D presentation can be viewed in 3D. This makes it possible to view a 2D subsurface data map in 3D for instance. This technique is used currently with entertainment purposes. No actual 3D analyses can be carried out.

### 2.6.2 3D Viewers

The market is reacting to the current 3D movement in the area of spatial and geographic information. Companies and institutes develop their own desktop and online applications to view spatial data three-dimensionally. The viewers are used to interactively view and manage different data layers.

The Dutch company StrateGis developed the 3D Geoviewer available for desktop and as online application. This viewer delivers quick access to spatial data and includes options to combine different layers and to clearly present data. 3D Geoviewer offers some standard layers and features regarding the natural and built environment, noise, energy, cultural objects and the subsurface. For the subsurface data the Digital Geological Model (DGM), the hydrological model (REGIS II) and water permeability values kh (horizontal permeability) and kv (vertical permeability) are provided. In Figure 2.31 an example the 3D Geoviewer is shown.

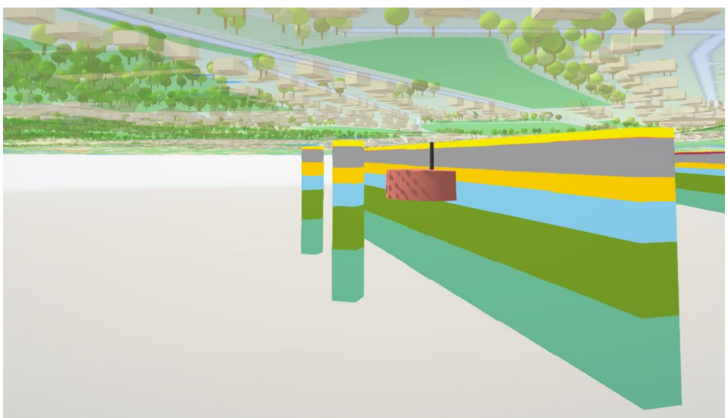


**Figure 2.31:** 3D Geoviewer
*Source:* StrateGis (2019)

Another application to view 3D subsurface data is the SubsurfaceViewer. This viewer includes map images, profiles and full 3D views providing insights into the predicted structure and properties of the subsurface, as shown in Figure 2.32. The SubsurfaceViewer supports and includes the Dutch 3D models GeoTOP, NL3D. REGIS II, DGM and DGM-deep.

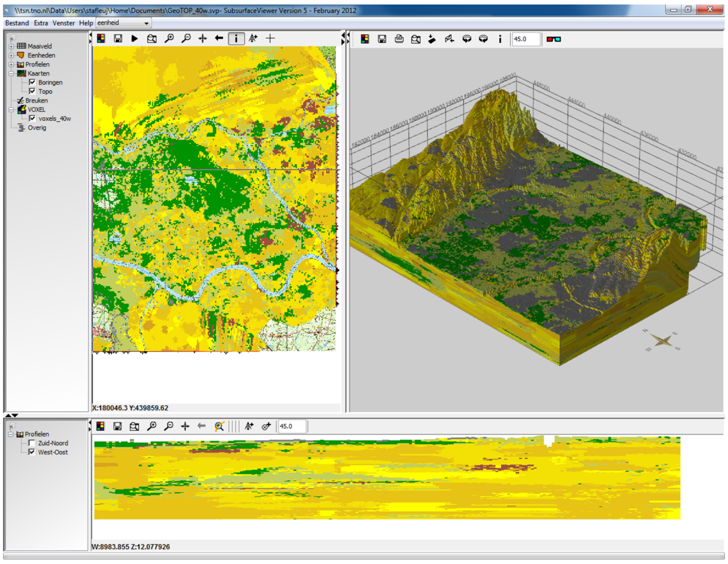


**Figure 2.32:** SubsurfaceViewer
*Source:* GDN (2019)

### 2.6.3 Virtual and Augmented Reality

A combination of GIS and Virtual and Augmented Reality is on the rise, called Virtual Reality Geographical Information System (VRGIS) and Augmented Reality Geographical Information System (AGGIS). In this development the virtual interactive interface of VR and AR and the spatial analyses and functionalities of GIS are integrated (Wang et al., 2015; Kamel Boulos et al., 2017). AR adds virtual components such as digital images, graphics or sensations as a new layer of interaction to reality to enhance experiences. On the other hand, VR build its own reality that is completely computer generated and driven. VRGIS and ARGIS can be useful within the soil sciences in different ways.

TNO implemented a VR viewer in which 3D voxel models, such as GeoTOP, can be freely navigated by the user. Navigating, slicing and selecting the model is done with a virtual controller. This VR view allows for detailed examining and reviewing of large volumes of geological data. An example of the usefulness of ARGIS within soil research is discussed by Huuskonen and Oksanen (2018). The research addresses opportunities to support the collection of soil samples with AR glasses. Still seeing the real world is indispensable to obtain soil samples in the field, making AR an appropriate method to assist during soil survey.

# CHAPTER 3

# METHODOLOGY

As stated in the theoretical framework, it is of great importance that research is carried out in advance into available software. Selecting a software package without preliminary research can result in incorrect application, non-usable functions and budget overrun. Therefore, this chapter will address the methodology of selecting applicable GIS software for this research. It will take into account certain criteria and requirements defined from literature, experts and stakeholder. In addition to an evaluation and inventory of the capacities of the GIS software packages, the methodology will result in a ranking of the software on applicability and suitability.

## 3.1 Multiple-Criteria Decision Making

The goal of this research methodology is to inventory and assess GIS alternatives in order to select a suitable software for this research. This selection depends on a number of criteria and requirements. The decision made to select the software is carried out using Multiple-Criteria Decision Making (MCDM). MCDM and corresponding Multiple-Criteria Analyses (MCA) fit well to tackle such complex decision problems. MCDM contains multiple criteria that the software must meet, the weights of these criteria, the software alternatives and the assessment of these alternatives. In Figure 3.1 an overview of the MCA methodology is provided containing all steps that will be discussed in this chapter.

MCDM and MCA are developed as a support during the decision making process. It provide useful tools and guidelines for decision-makers. MCDM methods do not result in the same decision or solution for every decision-maker, because it incorporates subjective information (Ishizaka and Nemery, 2013). Subjective information, in MCDM also referred to as preference information, is provided by the decision-maker and the stakeholder(s) and is indispensable for the decision to be made.

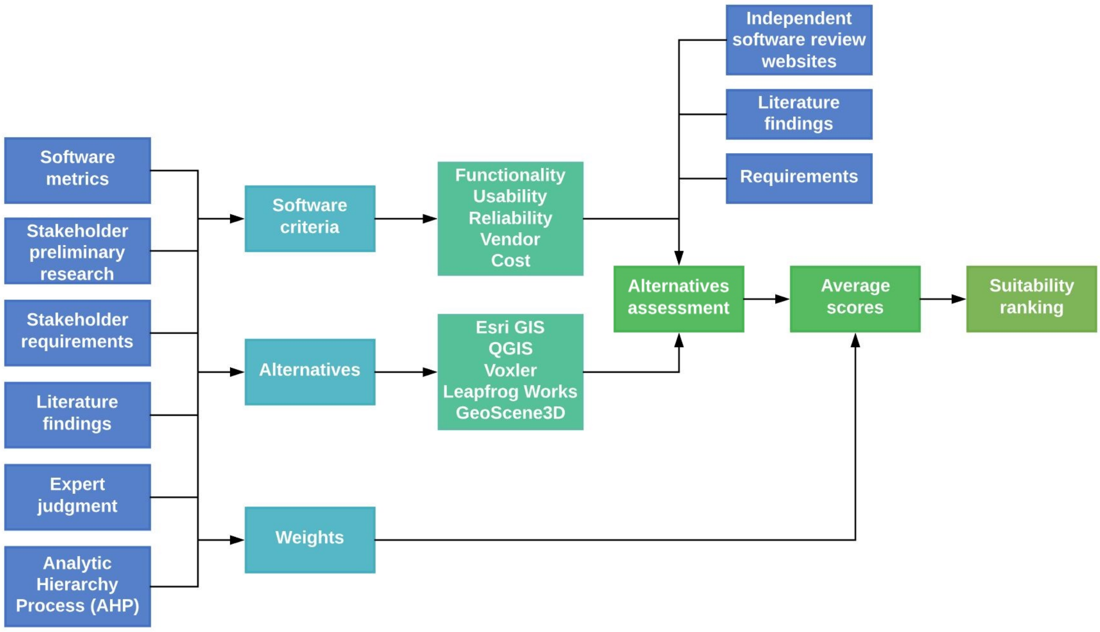



**Figure 3.1:** MCA overview

Because the information may contain a degree of subjectivity and abstractness, it can be challenging to score the alternatives and compare them. MCDM methods are developed to tackle such problems in a scientifically based manner in order to take well-considered decisions. These methods are conceived to make the criteria measurable and to score and weigh them correctly and equally. MCDM methodologies are investigated and applied for many different disciplines, among which informatics, mathematics, management, psychology, social science and economics (Ishizaka and Nemery, 2013).

Also for the purpose of software selection, several MCDM studies are elaborated and conducted. Herein, various sources are used for the definition of the criteria and sub-criteria, including literature findings, stakeholders opinions and requirements, expert judgements and software metrics. A combination of these inputs will be applied to define and establish the criteria of this research (Eldrandaly, 2007; Jadhav and Sonar, 2009; Eldrandaly and Naguib, 2013; Bataineh et al., 2017).

## 3.2 Criteria

### 3.2.1 Software Metrics

The criteria on which the software packages are evaluated are very important in the decision making process. The requirements and desires that the software should meet are set by the criteria. Studies are carried out describing methods and tools for software selection (Eldrandaly, 2007; Jadhav and Sonar, 2009; Jamwal, 2010; Bataineh et al., 2017; Pacheco-Cardenas, 2018). These studies, together with expert judgement, stakeholder requirements and screening, resulted in the determination and development of criteria, requirements and standards in order to evaluate and score software. These criteria and principles are scientifically embodied and formalised in so called in software metrics.

The software metrics contain several criteria and sub-criteria to evaluate the software. Drawing up appropriate criteria is a crucial step in evaluating a software package among a list of alternatives (Pacheco-Cardenas, 2018). Clearly defining the software criteria will increase the knowledge and insight of the software packages. The increased variety and complexity of software nowadays led to a large amount of criteria and sub-criteria delineated in the software metrics. In order to formulate the criteria for this research, different software metrics will be used. In addition to this, the judgement of stakeholder Antea Group is applied to supplement and tighten up the criteria. These judgements mainly consist of requirements and desires that the software should contain or should be able to perform.

### 3.2.2 Main-Criteria

After reviewing literature about software evaluation and selection, five main-criteria are defined for selecting suitable GIS software: functionality, usability, reliability, vendor and cost, as shown in Figure 3.1 (Eldrandaly, 2007; Jadhav and Sonar, 2009; Jamwal, 2010; Eldrandaly and Naguib, 2013; Yatsalo et al., 2015; Bataineh et al., 2017; Pacheco-Cardenas, 2018).

**Functionality**
Criteria related to functionality evaluate the availability of all required and desired functions of the software. The examination of the capability of the GIS software package is a crucial step in selecting suitable GIS software (Eldrandaly, 2007). Because, if the software is seriously deficient in the available functionalities the software is rather unprofitable, regardless of what the other criteria may score. Predetermined actions or operations must be executed at a certain level with the available tools and functionalities. The functionalities or actions that are required and desired for the GIS packages are determined and defined based on literature and by the requirements and desires of the stakeholder and are addressed in Section 3.5.

**Usability**
The effectiveness, efficiency and satisfaction with which the product users can operate and achieve their goals is appointed as usability (Jadhav and Sonar, 2009). The usability criteria reflect the quality of use characteristics (Pacheco-Cardenas, 2018). Ease of use, user types and interface are examples of sub-criteria of usability.

**Reliability**
Software reliability evaluates the quality of the software's performance. The software system must be able to perform the required functions under stated conditions, including at a certain speed or for a certain data size (Eldrandaly and Naguib, 2013). Maturity, fault tolerance and recoverability pertain reliability.

**Vendor**
Vendor contains criteria to measure the service and support which is supplied with the software package. This includes sub-criteria that relate to the tools and support that the seller offers. Tutorials, manuals, consultancy and help services are part of the vendor criteria (Jadhav and Sonar, 2009).

**Cost**

The main-criteria cost contains all expenditures associated with the GIS software packages (Eldrandaly and Naguib, 2013). This includes the software product, license, training, software subscription, maintenance and support services costs. These costs can be divided into two groups: capital expenditures and operating expenditures. Capital expenditures are non-recurring costs including the software product, training and license. Operating expenditures are recurring costs involved in the GIS project, such as maintenance and service costs.

### 3.2.3 Sub-Criteria

Intangible criteria, such as usability, are complex and can therefore be challenging to define and measure. The main-criteria are defined and divided by means of sub-criteria in order to make the criteria more distinguishable, measurable, and understandable in terms of empirical observations.

Many studies provide lists of criteria to evaluate software, in general or for specific software systems. Despite the definitions of these criteria, there is still room for personal interpretation and preference information that is often filled up by judgements from stakeholders and experts. In this study, the main- and sub-criteria are drawn up by a combination of relevant literature studies and requirements set by the stakeholder. The sub-criteria serve as tools to provide a score for each main-criteria of the software alternatives. The main-criteria and sub-criteria are shown in Table 3.1.

| Criteria | Sub-criteria | Meaning |
|---|---|---|
| 1. Functionality | Included functionality | Needed functionalities that the software covers |
| | Data formats | Essential data formats that the software supports |
| | Data visualisation | Desired visualisation tools that the software provides |
| | Adaptability | Ability of the software to customise personal settings |
| | Data sharing | Possibilities of data sharing and outputs offered by the software |
| 2. Usability | User interface | Ease with which user can use the software interface |
| | User types | Ability of the software to support different levels of users |
| | Ease of use | Ease with which user can operate and manage the software |
| | Domain variety | Capability of the software to be used in different projects and services |
| | Error reporting | Ability of messaging and error reporting of the software |
| 3. Reliability | Time behaviour | Ability to produce results in reasonable amount of time relative to data size |
| | Robustness | Software capability to run consistently without crashing |
| | Backup and recovery | Software capability to support backup and recovery features |
| 4. Vendor | User manual | Availability of a user manual |
| | Tutorial | Availability of user tutorial(s) |
| | Demo version | Availability of a free-trial version of the software |
| | Training | Availability of (online) user training courses or webinars |
| | Forum | Availability of interactive support forum |
| 5. Cost | Software license | Cost for obtaining the software license |
| | Installation | Cost for installing the software |
| | Training | Cost for training the users of the software |
| | Maintenance | Cost for maintenance of the software |
| | Support service | Cost for support services of the software |

**Table 3.1:** Criteria and sub-criteria

## 3.3 Alternatives

The alternatives are the GIS software packages that are evaluated. The alternatives are included as alternatives based on literature findings and stakeholder preliminary research and observations.

### 3.3.1 Esri GIS software

Environmental Systems Research Institute, Esri, is an international supplier of several GIS software products. They develop map software and spatial analysis software for both desktop applications, software as a service and enterprise applications. The products created by Esri are well-known and commonly used GIS and contain the largest global market share. Esri consist of a 43 percent share in the GIS market, while the second-largest supplier contains relatively 11 percent share (Cozzens, 2015). As a result, Esri is also called the dominant player in the global GIS market (Noel, 2015).

The products by Esri include ArcMap, ArcCatalog, ArcToolbox, ArcScene, ArcGlobe and ArcGIS Pro. The fundamentals are ArcMap, ArcCatalog and ArcToolbox allowing users to authorise, manage, analyse, map, share and publish spatial data. ArcScene and ArcGlobe provide a 3D environment for the spatial data. ArcGIS Pro is a version of ArcMap with advanced applications and extensions.

### 3.3.2 Leapfrog Works

Leapfrog is a geological modelling tool provided by Seequent. Leapfrog offers several modules, including Leapfrog Geo and Leapfrog Works. Leapfrog Works is specifically developed for the modelling of the subsurface and environmental projects and provides insights into subsurface data within a 3D environment. The geological modelling software allows fast operation of geological networks directly obtained from drill hole data. Leapfrog Works offers several paid licensing options for different purposes.

### 3.3.3 Voxler

Voxler is a 3D well and volumetric data visualisation software application provided by Golden Software. Golden software provides several software solutions including Strater, Surfer, Grapher and Didger. Some of these packages are more focused on maps and graphics while others are developed for modelling. Voxler is a modelling package with a specific focus on the creation and visualisation of geologic and geophysical models. The tools available in Voxler allow the visualisation of multi-component spatial data for geologic and geophysical models, contamination plumes, LiDAR point cloud or borehole models.

### 3.3.4 GeoScene3D

GeoScene3D is a GIS software system developed to model 3D geological data. The software focuses on geology, groundwater, soil contamination or other tasks involving geological structures and phenomenon. GeoScene3D is specifically designed for geologists using geoscience data, including drill hole and well data, geophysical data, soil and water chemistry, terrain surfaces and geological layers. The software contains different modules and extensions compiled in the same installation. The available functionalities are directly linked to the purchased licence type.

### 3.3.5 QGIS

QGIS is an open source GIS where geographic information can be viewed, edited and analysed. QGIS is a Free and Open Source Software (FOSS) and relies therefore on the support of volunteers and donors. QGIS offers a growing number of functionalities, in the application itself and as well as by the installation of plugins. Since a year, QGIS includes a 3D plugin offering tools for 3D visualisations.

## 3.4 Scores

Scores are assigned to each criteria for each software alternative. The evaluation of the sub-criteria results in an overall final score of each main-criteria for each software alternative. The alternatives are ranked by lining up the average scores from high to low. In order to assign scores to the alternatives a 5-points scale is used, according to the scoring methodology of De Beer (2006). The minimum score 1 signifies the worst possible and the maximum score of 5 the best possible. Consequently, a score of 5 is ideal.

Esri software products and QGIS are well-known GIS packages applicable for a wide range of domains and purposes. For these two alternatives, several scientific studies have already been carried out into the included functionalities, usability and suitability. For instance, Anlauf et al. (2018) combined a hydrological instrument to simulate water and pesticide transport in soils with ArcGIS by means of Python programming. Schokker et al. (2017) evaluated current techniques and identified good practices in 3D geological modelling and visualisation of the urban subsurface, among which toolboxes, interpolation method and techniques in ArcGIS. A research into the extending of ArcGIS functionalities to increase the usability and accessibility was conducted by Noel (2015). Petrangeli et al. (2016) developed a Python programming tool in ArcGIS to model the contamination of aquifers. Due to the great development and dissemination of FOSS they are investigating if the tool can be reproduced with the functionalities of QGIS. Friedrich (2014) executed an extended comparison research into ArcGIS and QGIS using functionality, reliability, usability, efficiency, maintainability and portability indicators. In this research guiding principles are provided concerning the possibility of replacing ArcGIS software by QGIS software depending on their included functionalities and properties as well as skills of different users. Lush and Lush (2014) conducted a research into the assessment of functionalities provided by QGIS compared to functionalities included in ArcGIS. A review of included tools and functionalities in QGIS and significant differences with ArcGIS are provided by the research. Since there are many relevant scientific studies that deal with the properties and ability of ArcGIS and QGIS, these will be used to assign the scores. In addition, expert judgements, stakeholder observations and independent software review sources including Capterra, G2 Crowd and TrustRadius are used to complement the literature findings.

Leapfrog Works, Voxler and GeoScene3D are subsurface domain specific GIS software and therefore less familiar. This results in limited available scientific research into the capabilities of the software. It is therefore not significant to substantiate the scores only by literature findings. Therefore, scores will be assigned based on the software's ability to perform required actions. As mentioned earlier, the ability to execute required functionalities and actions are crucial for the suitability of GIS software.

Required actions are drawn up to be performed in the software on which the criteria are evaluated and assessed:

- The import of the monitoring wells and drilling as tabular data. The data is visualised by means of 3D rods indicating the different intervals and filters of the measurements
- The import and georeferencing of a topographical or height map
- The visualisation and analysis of the different soil types included in the drilling data. The soil types are made visible along the drilling and eventually are interpolated for the case area in 3D
- The visualisation and analysis of groundwater levels included in the wells data. The groundwater levels are interpolated to height fields or surfaces referenced at the actual NAP height
- The visualisation and analysis of concentrations of substances included in the wells data. The concentrations are interpolated 3D voluminous spots, or a contamination plumes. The volume of the concentrations are calculated for different thresholds
- The import and visualisation of additional objects and civil engineering designs, such as buildings and infrastructure, preferably AutoCAD file formats (e.g. DXF, DWG)
- Executing queries on the data (e.g. selecting certain depths or years of the wells data)

The data types and content of the different subsurface data that is used and mentioned above are provided in Appendix B.

## 3.5 Requirements

Requirements are drawn up in order to assess the alternatives and to assign the scores. In order to determine requirements and desires the MoSCoW method is applied. MoSCoW is a prioritisation technique and abbreviation for: Must have, Should have, Could have and Will not have. All of the requirements determined with the MoSCoW method are relevant, but they are prioritised by importance. It is a useful prioritising method in software development and management since there is always more to do than there is time or funding (Ahmad et al., 2017).

The Must have category includes critical requirements that are indispensable for the research to succeed. Should have requirements are really desired, but are not necessary to deliver success or are not time- or budget-critical. Could have requirements can be nice improvements as budget and time permits but are not critical. Since the Could and Will not have requirements are the least-critical and are not considered in the short term, these requirements are out of scope for this research. The research mainly focuses on Must and Should have requirements.

During the MCA the Must have requirements are indicated and rated for each alternative, since the software must have a certain capability to be suitable for this research. If these Must have requirements are insufficiently met by the software, it will receive low scores and ultimately be excluded. The Should have requirements are also explored during the MCA for further distinction. However, a software package can not be excluded on this. In Appendix C the Must have and Should have requirements are provided for each criteria. The Should and Could have requirements can be useful improvements and desires to strive for after the most suitable software is optimised and implemented as a product solution.

## 3.6 Weights

The main-criteria are not equally imported in the decision making process. Therefore, weights are assigned to each main-criteria to decide the final ranking. The weights are assigned by means of the Analytic Hierarchy Process (AHP).

### 3.6.1 Analytic Hierarchy Process

AHP is a decision making technique used to organise and analyse complex decisions (Bataineh et al., 2017). Ishizaka and Nemery (2013) argue that this method runs on the motto 'Divide and conquer'. AHP operates by decomposing the decision into sub-decisions hierarchically. These sub-decisions can all be analysed independently.

After the criteria and sub-criteria are established, priorities will be set. The criteria are judged based on pairwise comparison, which means that they are weighed against each other by means of a 1-9 point scale, as summarised in Table 3.2 (Eldrandaly, 2007; Ishizaka and Nemery, 2013; Bataineh et al., 2017; Mu and Pereyra-Rojas, 2017).

| Relative importance | Definition | Explanation |
|---|---|---|
| 1 | Equal importance | Two activities contribute equally to objective |
| 3 | Moderate importance | Experience and judgement slightly favour one activity over another |
| 5 | Strong importance | Experience and judgement strongly favour one activity over another |
| 7 | Demonstrated importance | An activity is strongly favoured as can be demonstrated in practice |
| 9 | Extreme importance | Evidence favouring the activity is of the highest order of affirmation |
| 2, 4, 6, 8 | Intermediate values | When a compromise is needed |

**Table 3.2:** Pairwise comparison scale

The pairwise comparisons are stored in a matrix called $A$ :

$$A = \begin{vmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{vmatrix} \tag{3.1}$$

where

$$a_{ij} = \frac{1}{a_{ji}} \tag{3.2}$$

### 3.6.2 Weights

In Table 3.3 every main-criteria is weighted on each other criteria by means of the importance ratings from Table 3.2. The weights are determined based on stakeholder judgement, expert knowledge and findings from the literature (Eldrandaly, 2007; Bataineh et al., 2017; Pacheco-Cardenas, 2018).

| | 1 | 2 | 3 | 4 | 5 | $\sum$ | weight factor |
|---|---|---|---|---|---|---|---|
| 1. Functionality | | 5 | 6 | 7 | 4 | 22,00 | 0,54 |
| 2. Usability | 1/5 | | 3 | 4 | 1/2 | 7,70 | 0,19 |
| 3. Reliability | 1/6 | 1/3 | | 3 | 1 | 4,50 | 0,11 |
| 4. Vendor | 1/7 | 1/4 | 1/3 | | 2 | 2,73 | 0,07 |
| 5. Cost | 1/4 | 2 | 1 | 1/2 | | 3,75 | 0,09 |

**Table 3.3:** Weight factors

## 3.7 Sensitivity Analysis

In order to reduce uncertainty in the output of the MCA a sensitivity analysis is performed. The recognition and reduction of uncertain factors in the analysis is considered to be prerequisite in scientific research by Chen et al. (2011). Due to the increasing reliability of results when performing a sensitivity analysis, the recognition of the importance in these methods has increased significantly.

Saisana et al. (2005) argue that the most debated and uncertain issue of the MCA is the proper assessment of the relative importance of the weights according to the criteria. They recommend participatory approaches, including the AHP method, to prevent inconsistencies in the results. The AHP method therefore already reduced the uncertainty of the assigned weights. To increase the reliability of the results and to review inconsistencies in the assigned weights a sensitivity analysis technique will be performed. This technique includes the leave-one-out method, or also called bootstrapping analysis, through which the impact is shown by the exclusion of a criteria (Heywood et al., 2011).

The MCA is repeated five times in which one criteria from Table 3.3 is excluded alternately. The assigned values of the pairwise comparison scale of the four included criteria do not change. By the exclusion of one criteria the weight factors change at each iteration, but are added up to 1 each time. In Table 3.4 the weight factors are shown that will be multiplied by the scores of each alternative during the iterations.

| | Functionality | Usability | Reliability | Vendor | Cost | Total |
|---|---|---|---|---|---|---|
| (-) Functionality | | 0,42 | 0,24 | 0,14 | 0,20 | 1 |
| (-) Usability | 0,67 | | 0,16 | 0,10 | 0,07 | 1 |
| (-) Reliability | 0,62 | 0,18 | | 0,09 | 0,11 | 1 |
| (-) Vendor | 0,64 | 0,16 | 0,06 | | 0,14 | 1 |
| (-) Cost | 0,61 | 0,24 | 0,12 | 0,03 | | 1 |

**Table 3.4:** Weight factors minus alternately one criteria

## 3.8 Analysis Environment

For the purpose of comparing the GIS software equally, the evaluation and assessment of the alternatives is performed with the same hardware, software operating system, and data. The analyses and functionalities that are conducted in this thesis research will be implemented with the following parameters:

**Hardware and operating system**
Windows 10 Enterprise, 64bit on Dell Precision M6800 laptop, Intel(R) Core(TM) i7-4800MQ CPU, 2.70 GHz, 16 GB RAM

**Software**

- Esri: ArcMap 10.5.1 for Desktop Advanced [Windows] including 3D Analyst, Geostatistical Analyst, Network Analyst and Spatial Analyst extensions; ArcScene 10.5.1 for Desktop Advanced [Windows] including 3D Analyst, Network Analyst and Spatial Analyst extensions; ArcGIS Pro 2.0.1 for Desktop Advanced [Windows] including 3D Analyst, Geostatistical Analyst, Network Analyst and Spatial Analyst extensions; ArcGlobe 10.5.1 for Desktop Advanced [Windows] including 3D Analyst, Geostatistical Analyst, Network Analyst and Spatial Analyst extensions
- Leapfrog Works 2.2 for Desktop [Windows] 64-bit including Hydrology module
- Voxler 4.3.771 for Desktop [Windows] 64-bit
- GeoScene3D 10.0.13.574 for Desktop [Windows] 64-bit including Hydro extension
- QGIS 2.18.13 for Desktop [Windows] 64-bit

**Data**
In order to evaluate and assess the software equally and to generate outputs a case data set is used. The content of this data set is provided in Appendix B. Supplementary spatial data, such as topographic maps, height files and infrastructural objects, are obtained from open source portals including PDOK and DINOloket.

# CHAPTER 4

# RESULTS

In the first section of this chapter the evaluation of the alternatives on the criteria is discussed and substantiated. In the second section the results of the MCA are shown, including the average scores per criteria and the final ranking of the alternatives.

## 4.1 Alternatives Evaluation

### 4.1.1 Esri GIS Software

Esri products offer different support for 3D data, in the field of cities, scale models, scenery's and terrains. ArcScene, ArcGlobe and ArcGIS Pro offer **functionalities** for viewing and mapping 3D spatial data, available with the 3D Analyst extension. With the default tools in Esri GIS products it is not possible to manage 3D borehole or well data. However, third parties have developed custom tools to import and analyse 3D subsurface data. Demeritt (2012) and Carrell (2014) discuss the custom made tool Visual Basic for Applications (VBA) for Esri GIS. With the toolbar the user can create 3D borehole features from tabular log data, edit the geometry and attributes of those features, quickly create surfaces from queried borehole intervals in ArcScene or take cross-sections (Carrell, 2014). This tool solves the limitation of the lack of 3D editing tools within ArcScene. In figures 4.1 and 4.2 examples of 3D drilling and soil type data in ArcScene are shown.

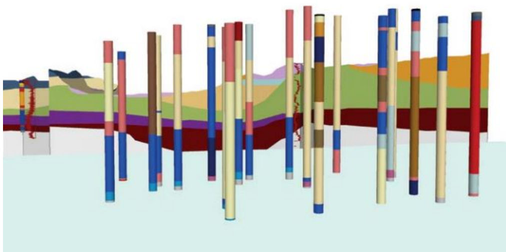


**Figure 4.1:** 3D borehole features
*Source:* Carrell (2014)

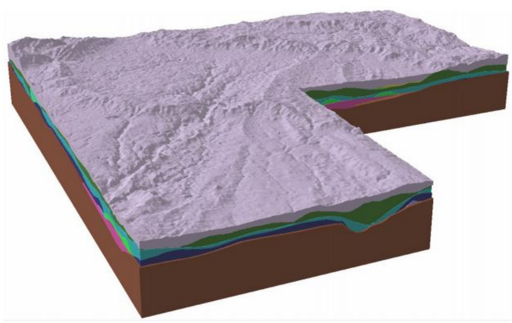


**Figure 4.2:** 3D soil type block diagram
*Source:* Carrell (2014)

The limit of the VBA toolbox is that the outputs remain static and in voxel or block format. The development of creating 3D triangulated volumes or isosurfaces resulted in the software crashing or producing errors citing lack of memory (Carrell, 2014). Reviews on Capterra (2018), TrustRadius (2018a) and G2 Crowd (2018a) confirm this crash sensitivity and common error reports which reduces its **reliability**. This does not make it possible to perform advanced analyses and calculations for the 3D soil types and contamination models. This complicates the desired spatial and geological interpretation of the subsurface.

D&T Geodata management (2018) developed a similar toolbox to present boreholes in 3D. With theses tools it is possible to view stratigraphic layers, the groundwater level and borehole traces. It is useful for the 3D modelling of geological features in combination with civil engineering, exploration of oil, gas and minerals, and for hydrogeological surveys. In Figure 4.3 a visual representation of drill data and the ground level created with the D&T 3D borehole toolbox is shown. The limits of this tool correspond to the VBA toolbox: the 3D options are fairly basic and advanced analyses are not feasible.

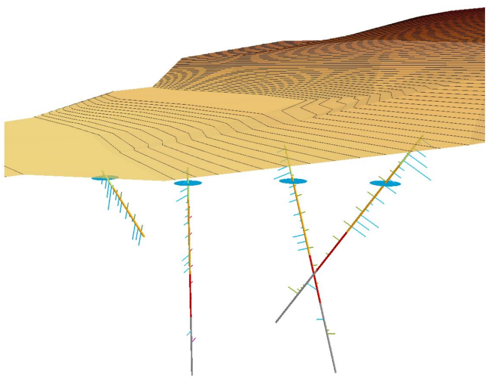


**Figure 4.3:** 3D borehole by D&T toolbox
*Source:* D&T Geodata management (2018)

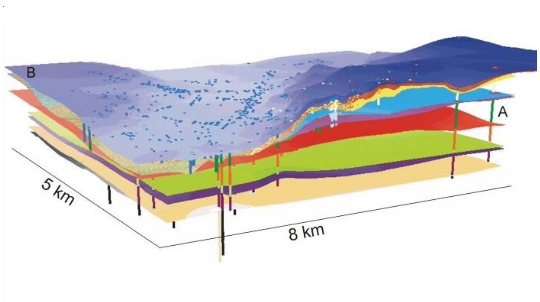



**Figure 4.4:** 3D surfaces of Brussels geology
*Source:* Devleeschouwer and Pouriel (2006)

Commissioned by the Geological Survey of Belgium, Devleeschouwer and Pouriel (2018) are developing GIS tools to create 3D models of the urban geology of Brussels. An application is developed in ArcGIS Desktop by means of the ArcGIS 3D Analyst extension. The application consists of a relational database storing the content of the subsurface data and a cartographic management system managing the raster and vector subsurface data (Devleeschouwer and Pouriel, 2006). For the interpolation methods use is made of external GIS software developed by Golden Software, including Voxler. Another shortcoming is that the model can rather be seen as 2.5D model since the output is created by piling up surfaces, as indicated by Figure 4.4, instead of full 3D blocks or volumes.

In addition to these developed toolboxes there is the possibility to program custom tools with Python scripting. However, this is very time-consuming, only feasible for expert programmers or GIS specialists and does not guarantees success for data of different projects, sizes and qualities. Besides the Python work space within Esri GIS the overall software environment is discussed to be expert or advanced level. The **usability** of the Esri GIS products is evaluated by differences sources as hard and not easily accessible for basic users (Friedrich, 2014; Capterra, 2018; G2 Crowd, 2018a; TrustRadius, 2018a).

Since the software environment, interface and tools are advanced it is desirable that the user already possesses some knowledge (Friedrich, 2014). This is also confirmed by user reviews at Capterra, G2 Crowd and TrustRadius where ArcGIS is described as a complex software program. Due to the complexity of the software and the advanced tools that are available Friedrich (2014) argues that spatial analyses could usually not be performed on the first attempt.

Because Esri GIS products are well-known and market leading there are many sources, publications, articles, tutorials and other (online) information sources available. In addition, Esri as **vendor** offers a large platform, for desktop and online, where information and data can be searched, shared and retrieved. Because of the wide range of services, market dominance, publicity, extensive functionalities for multiple purposes and work domains the average **costs** for purchase, license and maintenance are high. Besides, additional costs are charged when purchasing (often necessary) extensions. This is indicated as a big negative to the software by the users (Friedrich, 2014; Lush and Lush, 2014; Capterra, 2018; G2 Crowd, 2018a; TrustRadius, 2018a).

### 4.1.2 Leapfrog Works

Leapfrog Works provides tools and functions to model subsurface data in 3D. Numeric and domain modelling, visualisation tools and interpolation methods are included. Hodkiewicz (2013) argues that the functionalities and tools of Leapfrog Works are innovative and provide better and faster insights in the viewing, modelling and interpreting of subsurface data. Imagery, cross-sections and maps can be imported and geo-referenced on coordinates and thus be implemented into the 3D subsurface output.

Advantageous of Leapfrog Works is that it is developed with a subsurface specific focus and therefore provides suitable and desired **functionalities** to represent subsurface information in 3D. subsurface data is central which facilitates the input, analysis and visualisation of boreholes, wells and other soil survey data. In addition, Leapfrog Works includes a design module through which AutoCAD design of civil engineering projects can be imported and adjusted. This makes it possible to analyse and visualise the subsurface data in larger context with what is above ground.

An advantage of Leapfrog Works is the variety of 3D data outputs. In addition to 3D points, lines and surfaces, the software also provides voxel and mesh outputs. This makes it possible to create, analyse and present different data types in both Volume- and Surface-based outputs. Geological knowledge of the area, such as chronology, age and composition of the subsurface, can be entered or set as parameters resulting in a more verified output. In addition, the output can be manually edited to match the model more closely with reality. In Figure 4.5 a contamination plume, boreholes and soil layers are shown.

Imported tabular data can be edited and queried within the software. The adjustments are immediately implemented and updated for all performed tools and the output model. In a Leapfrog Works project one main data set is determined to which the coordinates and IDs are referenced. This can be a disadvantage if there are several data sets, for example both drilling and well data. It results in more time editing the table before importing or working with different projects.

Leapfrog Works responds well to large data files and produces results in a short time compared to the other alternatives. The **reliability** of the software is evaluated as high since no errors or crashes occurred when performing several analyses during the test period. In addition, projects, outputs and settings are automatically stored so nothing can accidentally get lost.

The automatic storing feature contributes to the **usability** of Leapfrog Works. In addition, the software provides a clear and simple overview of all data, functionalities and outputs. The interface contains three main parts: a project tree where all data and functionalities are stored, a scene view where different sides and aspects of the output can be viewed and a object property manager where visible layers can be edited. Besides, tasks can be prioritised, to view the effect of changes without reprocessing all objects in the project, resulting in the software being more pleasant to use.

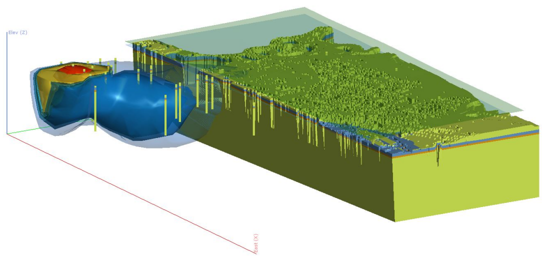


**Figure 4.5:** 3D output in Leapfrog Works

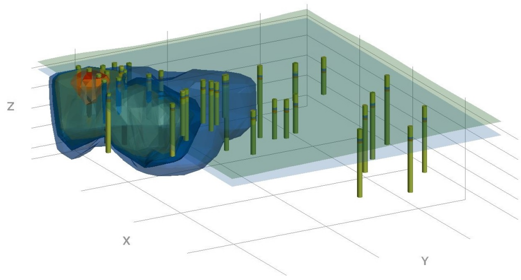



**Figure 4.6:** 3D output in Leapfrog Dashboard

Since the software is specifically developed for geologists analysing subsurface data it requires some knowledge or experience with geological modelling software to work efficiently with Leapfrog Works. It can be argued that for beginners or simple users it can be challenging to work with. However, Hodkiewicz (2013) and Birch (2014) state that there are training and tutorials for beginners that can be completed in a few days. Leapfrog, as **vendor**, offers an active online user platform with tutorials, webinars, forum interactions and sharing options. An online dashboard can be created by the user where projects can be uploaded and shared. Without downloading software or sharing the actual data, collaborators are able to view, move and visualise the created project. This is a very desirable and innovative way to easily and interactively share data with customers, stakeholders and third parties. The online dashboard is shown in Figure 4.6. As international developer of several GIS software, the **costs** of Leapfrog software products are not low. An annual license for leapfrog will easily cost $10.000, maintenance included.

### 4.1.3 Voxler

Voxler is focused on 3D subsurface models, including boreholes, wells, surfaces, point clouds and contours. It offers various **functionalities** for modelling 3D subsurface data, among which interpolation, filter, mathematical, transformation and extraction operations. Multiple tables, even with different IDs and locations, can be imported as either well or point data. Several 3D outputs can be created, including contours, voxels, height fields and surfaces. Voxler supports image formats, cross-sections and map files which support subsurface representation outputs. In Figure 4.7 a contamination plume, ground(water) levels and monitoring wells are visualised.

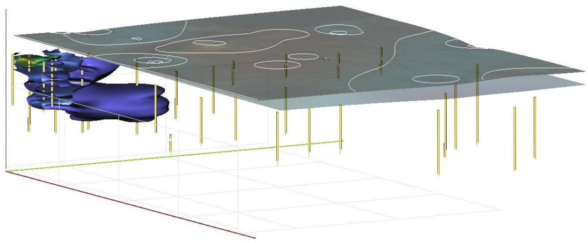


**Figure 4.7:** 3D output in Voxler

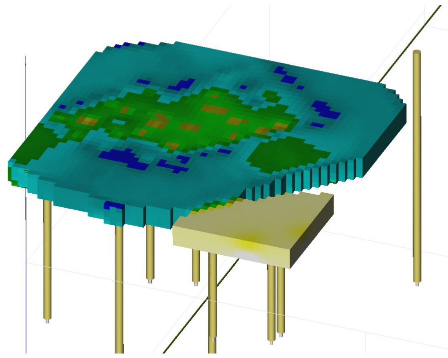


**Figure 4.8:** 3D soil types in Voxler

A limit to the functionalities and tools provided by Voxler is the determination on numerical values. Imported data is only recognised as numeric, which reduces the reliability and versatility in the output. For example, soil types are not numerical values and it is unlikely that in reality averages are set between different soil types. It must be able to import soil types as qualitative value (clay, sand etc.) and not as a quantitative number In Figure 4.8 this limitations is shown. Here averages are calculated between the measured points representing soil types.

Despite shortcomings in the functionalities, Voxler does provide a clear and straightforward interface. The software scores well on **usability** because it is easy to operate with. A model builder screen is built-in in which all inputs, functions and outputs can be managed and only data applicable tools are visible (G2 Crowd, 2018c). Users indicate that Voxler is open and suitable for less experienced users. Besides, options are included for the user to personalise the analysis and output by changing parameters and customising visualisation preferences.

Even though Voxler does not commonly crashes or indicates errors, the software slows down when multiple analyses or functions are performed or larger files are imported (e.g. $\leq$ 100 MB TIFF-files). Together with a relative long time to produce results this reduces the **reliability** of the software. However, users accept more easily these deficiencies since prices are low. A one-time license **costs** around \$500, exclusive \$150 updates.

### 4.1.4 GeoScene3D

GeoScene3D is a GIS software system developed to model 3D geological data. The software focuses on geology, groundwater, soil contamination and other themes involving geological structures and phenomenon. GeoScene3D focuses on three main integrated working environments: cross-sections that can be freely drawn and handled in the model, GIS Maps that provide a top view of the area and 3D Scenes of the model that can be viewed and adjusted. In addition, there are functionalities available that include tools to create and edit surfaces, points, voxels and layer attributes.

GeoScene3D offers extended **functionalities** to analyse and visualise subsurface data. Geological knowledge of the user about the subsurface of the area can be imported by changing soil parameters during the analysis. Characteristics about the geological material, age, direction, movement and attributes of the subsurface data can be added, entered and adjusted what contributes to the verification of the output. In addition, GeoScene3D provides both voxel and polygon 3D outputs. In Figure 4.9 a 3D voxel output of the soil types is shown together with 3D polygon contamination plumes.

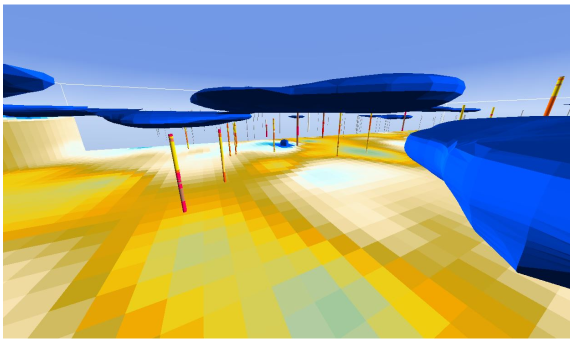


**Figure 4.9:** 3D voxel and polygon in GeoScene3D

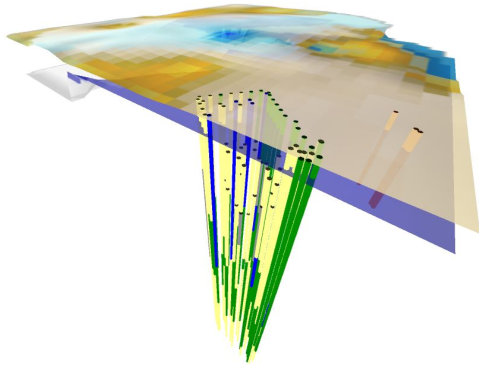


**Figure 4.10:** 3D output in GeoScene3D

A shortcoming to GeoScene3D functionalities are the tabular data options after importing. A black box is located between the import of x,y,z values of tabular data and the generated output making the internal working between these two steps unknown. In case of questionable or empty outputs and error messages it is hard to check where it went wrong. Error messages are commonly given and the software crashes and closes down without saving several times per session. When importing large (tiff-)files or when multiple 3D outputs are generated, the software slows down. The **reliability** of GeoScene3D is therefore rated low.

Because GeoScene3D is an advanced GIS software offering extensive functionalities to manage and operate subsurface data, it takes some time to get familiar with the software. The overview, working method and interface also differs from typical GIS software. For example, the generated output can only be viewed by placing cameras on fixed locations, no universal toolbox is available and attributes or properties of objects are not organised as with most typical and well-known GIS software. The software is not straight-forward to use, especially for beginners, and scores therefore low on **usability**.

Poor ease of use is reinforced by the lesser availability of resources by the **vendor**, especially in comparison with the other alternatives. A help menu is included in the desktop version, explaining functions and analyses. However, it focuses on data available from Danish portals and it is not clearly explained how the data inputs should be organised. In addition, an interactive online platform is missing making users less involved and less likely to ask for help. Prices to purchase GeoScene3D are relatively high. A one-time license **costs** \$15.000, excluding annual maintenance and update costs of \$2.500.

### 4.1.5 QGIS

QGIS recently includes a 3D plugin called Qgis2threejs. Here, 3D outputs and maps can be generated and viewed. Height fields can be created by interpolating points and soil survey data can be visualised as shown in Figures 4.11 and 4.12. The default **functionalities** for analysing and visualising subsurface data in 3D are limited to this plugin. As for Esri GIS, it is possible to build more advanced tools by means of Python modules and scripting. This is however very time-consuming and only feasible for users with advanced GIS and Python experience. QGIS default scarcely meet the required and desired tools and is therefore rated low on functionality.

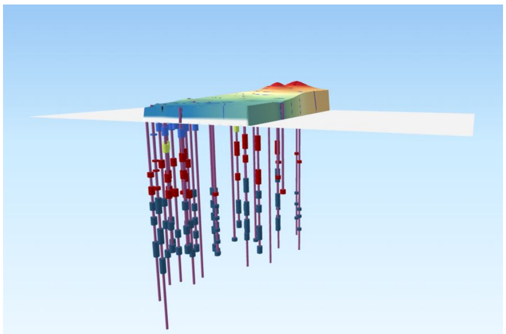


**Figure 4.11:** 3D monitoring wells in QGIS

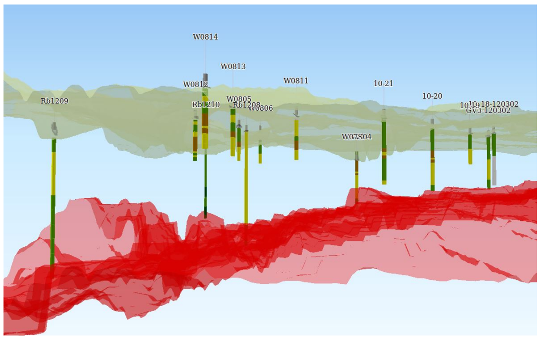



**Figure 4.12:** 3D output in QGIS

In addition to the narrow range of desired functionalities, the interface of QGIS also contains its limits. This is emphasised by Yilmaz and Çagiltay (2014) where it is discussed that the **usability** of QGIS, especially in the area of the interface is somewhat inefficient and ineffective. Users argued on G2 Crowd (2018b) and TrustRadius (2018b) that tools and functions cannot be found at logical places within the interface or toolbox. However, many articles, tutorials, researches and tools are shared on different platforms, because QGIS is supported by many different organisations, institutes, companies and individuals. QGIS as **vendor** offers a large online and interactive platform where users can request or seek help.

QGIS is crash sensitive, especially during extended operations such as interpolations. The crashes often result in the software being shut down immediately. Friedrich (2014) indicates that this reduces the **reliability** of the software. This can be defended somewhat by the new versions that QGIS releases every four months to solve these problems. In addition, an error code is often provided which can be searched on the internet when executing a wrong functionality, for example entering incorrect parameters. Users indicate that the poor reliability is worth sacrificing for because of QGIS being open source (G2 Crowd, 2018b; TrustRadius, 2018b). As a result of QGIS being easily accessible and does not includes any **costs** the range of user types is wide.

### 4.1.6 Discussion

The assessment framework of the map use cube is applied to determine the dimensions and user types of the GIS software. The software alternatives contain different dimensions of functionality, practice and ease of use, making the software suitable for different purposes and user types.

Esri GIS is versatile and applicable for different types of users due to the different products offered. The products range from desktop offering advanced exploration and analyses to online offering an interactive platform, resulting in different types of users identified by Esri. However, the default application aimed at supporting 3D subsurface data according to the requirements defined for this research is limited, which reduces the versatility of Esri GIS. The same applies to QGIS. it is a GIS software that can be used for different purposes by many types of users, but lacks the default functionalities to easily support 3D subsurface data. For this research, the information presented and audience are therefore confined, resulting in Esri GIS and QGIS being placed in the data viewer area of the map use cube.

Leapfrog Works, GeoScene3D and Voxler are specifically developed to support 3D subsurface data. Yet, the GIS software can be placed in different areas in the map use cube. Voxler really responds to the user with an easy to use software environment and support resources, but it lacks subsurface related functionalities and specifications on an advanced level. On the other hand, GeoScene3D does include these subsurface related tools, but lacks the straightforward interface, ease of use and user-friendliness. Leapfrog Works can be placed in between with both extended functionalities and a user-oriented interface and online platform. In Figure 4.13 the map use cube is divided into smaller areas. Here, an indication in which area of the cube the alternatives can be placed for this research is provided.

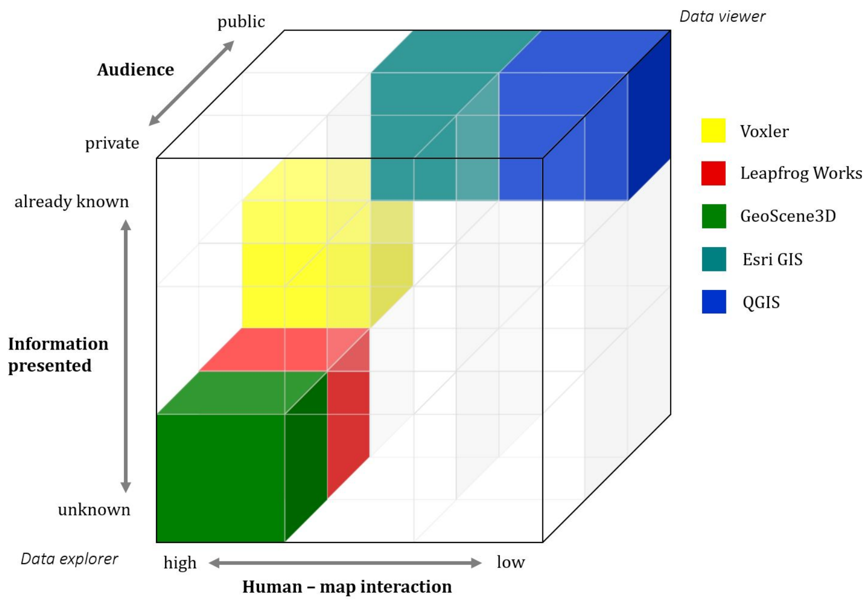



**Figure 4.13:** Placement of the alternatives in the map use cube

## 4.2 Multiple-Criteria Analysis

In this section the scores that are assigned to each alternative, based on the previous evaluations, are discussed. An overview of the assigned scores for each sub-criteria can be found in Appendix D. First, the main scores for each criteria are indicated and weighed. Hereafter, the alternatives are ranked to select the most suitable software package for this research.

### 4.2.1 Average Scores Main-Criteria

In Table 4.1 the average scores of the main-criteria are shown for each alternative. These average scores do no yet include the weights that are defined in Section 3.6.2. The average scores without the weights clearly show the qualities and pitfalls of the software alternatives. It can be seen that some software score high on functionality, while others are more focused on user-friendliness.The chart in Figure 4.14 shows the differences in scores between the alternatives. Esri GIS scores high on functionality and vendor, but is relatively expensive and less accessible to basic users. Leapfrog Works scores high on multiple criteria, especially functionality and vendor. Voxler gains points on the relatively low price and user-friendliness. The quality of GeoScene3D is the range of advanced 3D functionalities, which immediately prompts the pitfall: difficult to use. The biggest advantage of QGIS is that it is free and open source, but the range of 3D functionalities is limited.

| Criteria | Esri GIS | Leapfrog | Voxler | GeoScene3D | QGIS | Max. |
|---|---|---|---|---|---|---|
| Functionality | 18 | 23 | 15 | 19 | 15 | 25 |
| Usability | 15 | 17 | 17 | 12 | 14 | 25 |
| Reliability | 7 | 11 | 9 | 7 | 6 | 15 |
| Vendor | 22 | 23 | 24 | 11 | 21 | 25 |
| Cost | 15 | 20 | 22 | 17 | 25 | 25 |
| $\sum$ | 77 | 94 | 87 | 66 | 81 | 115 |
| $\sum_{rel}$ | 0,67 | 0,82 | 0,76 | 0,57 | 0,70 | 1 |

**Table 4.1:** Scores without weights

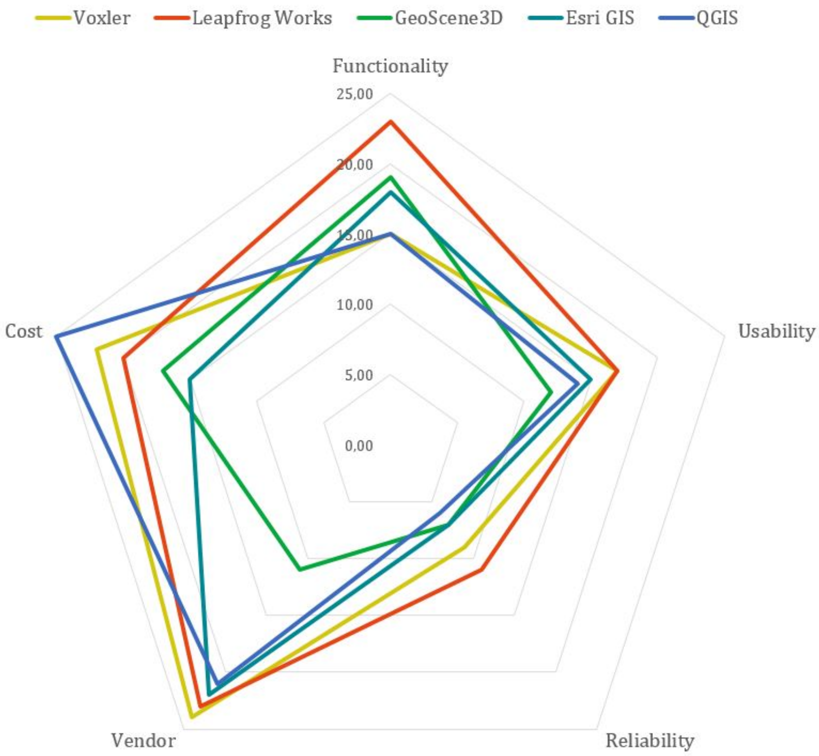



**Figure 4.14:** Radar chart of average scores without weights

The scores in Table 4.1 are multiplied with the weights from Table 3.3 which results in new average scores that are provided in Table 4.2. When comparing the relative sums of Table 4.1 and 4.2 the final score of Esri GIS, Leapfrog Works and GeoScene3D becomes higher, while the final score of Voxler and QGIS becomes lower. Since the functionality criteria has received the highest weight, the alternatives better scoring on functionality end up with a higher final score, as shown in Table 4.2.

| Criteria | Weight | Esri GIS | Leapfrog | Voxler | GeoScene3D | QGIS | Max. |
|---|---|---|---|---|---|---|---|
| Functionality | 0,54 | 9,72 | 12,42 | 8,10 | 10,26 | 8,10 | 13,5 |
| Usability | 0,19 | 2,85 | 3,23 | 3,23 | 2,28 | 2,66 | 4,75 |
| Reliability | 0,11 | 0,77 | 1,21 | 0,99 | 0,77 | 0,66 | 1,65 |
| Vendor | 0,07 | 1,54 | 1,61 | 1,68 | 0,77 | 1,47 | 1,75 |
| Cost | 0,09 | 1,35 | 1,80 | 1,98 | 1,53 | 2,25 | 2,25 |
| $\sum$ | | 16,23 | 20,27 | 15,98 | 15,61 | 15,14 | 23,9 |
| $\sum_{rel}$ | | 0,68 | 0,85 | 0,67 | 0,65 | 0,63 | 1 |

**Table 4.2:** Scores with weights

### 4.2.2 Alternative Ranking

The goal of the MCA is to select the most suitable GIS software, based on the evaluation of several relevant criteria and requirements. In Table 4.3 the final result of the MCA and the ranking on suitability of the alternatives can be seen. Leapfrog Works ends up with the highest score and is therefore selected for the In-Depth. Leapfrog Works has largely won through the wide range of functionalities to analyse and visualise 3D subsurface data within a user-friendly environment. In addition, Leapfrog Works satisfies all Must have requirements. In Appendix E the technical specifications and system requirements of Leapfrog Works are provided.

| Rank | Alternative | Score |
|---|---|---|
| 1 | Leapfrog Works | 0,85 |
| 2 | Esri GIS | 0,68 |
| 3 | Voxler | 0,67 |
| 4 | GeoScene3D | 0,65 |
| 5 | QGIS | 0,63 |

**Table 4.3:** Alternative ranking

## 4.3 Sensitivity Analysis

The MCA has been repeated five times with changed weights according to the leave-one-out technique. In Table 4.4 the recalculated final scores of each alternative for the five iterations are shown. In Figure 4.15 these scores are visualised in a bar graph. The changed weights result in varying final scores. The graph proves that Leapfrog Works ends with the highest score, regardless of which criteria is excluded. The leave-one-out technique herewith shows that the outcome of Leapfrog Works being the most suitable GIS software for supporting 3D subsurface data in this research has been tested for uncertainty and can be assumed reliable.

| | Esri GIS | Leapfrog | Voxler | GeoScene3D | QGIS |
|---|---|---|---|---|---|
| (-) Functionality | 0,61 | 0,75 | 0,74 | 0,61 | 0,65 |
| (-) Usability | 0,69 | 0,88 | 0,66 | 0,68 | 0,62 |
| (-) Reliability | 0,70 | 0,86 | 0,68 | 0,67 | 0,66 |
| (-) Vendor | 0,67 | 0,85 | 0,65 | 0,69 | 0,64 |
| (-) Cost | 0,66 | 0,83 | 0,62 | 0,64 | 0,57 |

**Table 4.4:** Final scores with one criteria excluded

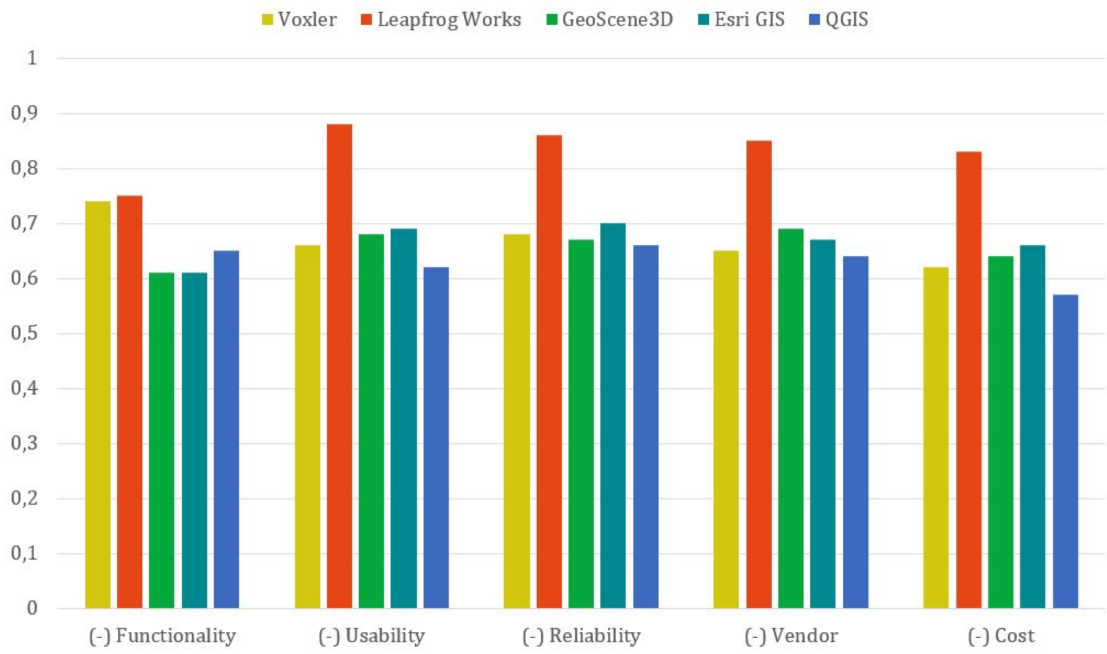



**Figure 4.15:** Final scores with one criteria excluded

## 4.4 Discussion

Prior to Chapter 5, the In-Depth, criteria related strengths and opportunities of Leapfrog Works are summarised below on which will be built on in the next chapter.

**Strengths**
Functionality

- Tabular data can be easily adjusted and queried within the software
- Both Volume- and Surface-based outputs are supported
- Includes multiple interpolation methods, e.g. RBF, IDW and LPI
- Includes input of soil parameters and properties
- Innovative online dashboard to easily and interactively share outputs and results
- Creation of different models: numeric, geologic, hydrologic etc.

Usability

- Multiple viewing screens and scenes
- Automatic saving
- Software environment customisation options
- Three straightforward scenes: object tree, property manager and 3D scene
- Prioritising of executive tasks

Reliability

- Produces fast results
- Responds well to large files
- No crashes or errors during test period

Vendor

- Extensive online dashboard to easily share outputs with customers
- Online forum with quick respond
- Extensive user manual
- Free trial version
- Live training sessions and webinars

Cost

- License linked to account (not to computer)
- Maintenance and updates included in purchase price
- Option to purchase cloud service

**Opportunities**
Exploration and discovery into:

- Fourth dimension (time)
- Real time data
- Database management
- Hydrologic flow models
- ERT point data
- Virtual and Augmented Reality
- Standardised input data
- Webservices (WMS)
- Black box

# CHAPTER 5

# IN-DEPTH

From the previous chapters it has resulted in Leapfrog Works being the best scoring, and thereby most suitable GIS software package to support 3D subsurface data. During the in-depth phase a closer look towards the software's capability is taken. This chapter is divided into three sections: the in-depth look, applications and presentation. The first part provides a more detailed evaluation of requirements as a follow up on the discussion in section 4.4. Hereafter, different cases are discussed where 3D subsurface outputs can be useful. Lastly, a detailed visualisation of the subsurface data is presented with the aim to comprehensibly represent the subsurface that includes real-world complexity.

## 5.1 In-Depth Look

In section 3.5 the requirements are prioritised according to the MoSCoW method. In the in-depth some Should have requirements and opportunities are addressed. Evaluating these desires will result in a better match between the demand and the software's output and eventually optimise the final package. The topics and requirements that are looked into in-depth are selected as a result of the MCA and considered with the stakeholder.

### 5.1.1 Fourth Dimension

The extra dimension that 3D contains as an extension to 2D is depth, which shifts an image from plane to spatial. Hereafter, a fourth dimension can be added to the 3D image which relates to time. A 4D image therefore includes three dimensions of space: height, width and depth, and one dimension of time. Although historically geographical models and representations consisted of a 2D view neglecting the concepts of depth and time, these dimensions are nowadays recognised as key dimensions (An et al., 2015).

4D allows for space-time analysis. An et al. (2015) define this as: *"the representation of changing location in space and time of a certain phenomenon, object, process, or event of interest."* The deeper meaning behind this is that not everything happens everywhere. Only when the connection between space an time is understood the complexity of human and spatial conditions and actions can be comprehended (An et al., 2015). Therefore, being able to add the time dimension within a GIS software package is very valuable.

GIS has developed into a very suitable medium for displaying space, but does a poor job in representing the time dimension. The fourth-dimension is usually displayed as a sequence of limited snapshots or frames in time, because it is a challenge to visualise dynamic time changes on a static map. In this case, GIS users have to contend with visualising spatial change over time (4D) on a 2D map. Animations or web maps with time sliders are innovative examples of better alternatives to reflect differences in space and time.

Measurements of different time periods are added to the case data set in order to add a fourth-dimension. With these data it is examined to what extent 4D presentations can be performed within Leapfrog Works. It resulted from this that limited functionalities or options are included in Leapfrog Works desktop to extend the 3D output to 4D. Visualising differences in time-space is therefore only practicable in the software by creating different outputs, as shown in Figure 5.1. However, the 4D output is herewith restricted to a sequence of limited snapshots in time. It is desired that Leapfrog develops a time lapse function in the Works software with which the time course can be presented in one output model. Currently, this is only available for hydrologic models as shown in Figure 5.6, but not yet for numerical models. This will also set steps towards the direction of real time data processing in a desktop version.

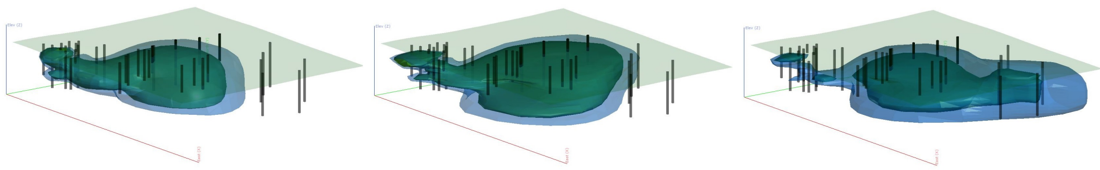


**Figure 5.1:** 3 snapshots in time of a contamination plume

### 5.1.2 Real Time Data

Real-time data (RTD) processing is very desired by companies, organisations and business nowadays. With RTD information is delivered immediately after the collection of data. RTD offers non-stop insights into results which makes it very popular. Patterns and regularities can be recognised more easily, because data is available at all times. This allows for better anticipation of future developments, and faster adjustments where necessary. These are the building blocks when designing new business models. In this way, predictions based on big data can lead to radical directional changes and improvements within organisations.

Gong et al. (2015) discuss the value of RTD processing within environmental data management using GIS. More and more environmental management systems are dealing with large streams of geographical information by the development of sensor technology. However, Gong et al. (2015) argue that many GIS and environmental data management systems do not yet meet the requirements to handle RTD. GIS processing RTD includes strict time controls and restraints causing all actions to be performed in a short and acceptable time. The research by Gong et al. (2015) proposes a Geospatial Service Web (GSW) application that integrates sensor, data, processing, information, knowledge, computing, network and storage resources to process and regulate real-time data. Real-time data is often combined with GIS web services, in order to monitor and observe trends and developments.

Leapfrog is reacting to the development of RTD processing with their online platform called Central. Leapfrog Central enables continuous modelling and provides access to geological models over time. Herewith, Leapfrog makes the connection with the fourth-dimension, but in an online or cloud-based environment. With the use of leapfrog Central all data is stored in a cloud and visualised in a browser application. Central provides access to the latest geological model, wherefore decisions can be made according to the most up-to-date information.

### 5.1.3 Standardised Input Data

The supported input data of Leapfrog Works is presented in Appendix E. The Dutch standard for subsurface data is SIKB0101 established by SIKB, mentioned in Subsection 2.4.5. The standard format of exchange is .XML. .XML is not supported by Leapfrog Works as input for borehole data. The SIKB0101 files therefore need to be standardised according to Leapfrog Works input metadata for fast and easy import of borehole data. The .XML file needs to be converted to a supported text file, such as .CSV, .ASC or .TXT, managed according to the metadata described in Appendix B. When implementing Leapfrog Works 3D subsurface outputs as a product within an organisation or company standardisation of the input data must be included in the product strategy and revenue model.

### 5.1.4 Database Management

GIS software are complex systems making the geoprocessing of large-scale data computationally intensive (Nourjou and Thomas, 2016). Certainly with real time data, enormous amounts of data are available to be processed. A cloud service is nowadays presented as a solution for large-scale spatial data processing and services. Nourjou and Thomas (2016) even argue that traditional GIS software systems are unlikely able to provide effective spatial information services and capacity to process large-scale spatial data.

Cloud-based GIS is the combination between traditional running desktop GIS and cloud infrastructure services. Leapfrog Central allows the user to store all data in the cloud and view it in a central browser. Advantages of Leapfrog Central's cloud-based solution are that the latest output can be easily accessed, the output can be reviewed through time, the modelling process and outputs are stored and backed up and outputs can be shared easily and quickly. However, many companies are withdrawn and conservative for cloud solutions and external cloud administrators. The control, security and authority is more or less placed in the hands of the cloud provider. Besides, the integrating of data with Leapfrog Central, or any other cloud providers, includes additional costs.

### 5.1.5 Black Box

In Subsection 2.2.6 the importance is raised of knowing the internal working behind the black box of a GIS software. Therefore, insights in the black box is included as Should have requirement. Birch (2014) conducted a research into the differences between more traditional geological modelling software and newer automatic geological modelling software. Traditional geological modelling relies on (manual) geological logging of boreholes. This method is very time-consuming and strongly relies on the understanding of the modeller. Newer methods perform spatial interpolation to establish and update geological models from borehole data, which is both faster and more efficient.

Birch (2014) argues that automated software are often seen as black boxes, because the computer is allowed to do the geological interpretation rather than the geologist. However, the geological software products developed by Leapfrog involve a lot of geology specific input parameters to be set by the user during analyses. Because of this it can be discussed whether Leapfrog Works, as newer geological modelling software, can be labelled as 'automatic'. Despite the new software environment and the fast processing of subsurface data, there is still much room for interpretation by the geologist. Leapfrog software products therefore improve the time-consuming nature of traditional methods, but maintain the reliability by inputs of the geologist.

The soil related parameters that can be entered manually in Leapfrog Works by the user provide insight into the internal workings behind the performed functionalities and analyses. This allows the user to discover and better understand the process behind the performed tasks and to critically consider the output.

### 5.1.6 ERT Point Data

In Appendix B the three ERT profiles that are obtained from the case area are shown. It can be profitable to add the ERT profiles to the 3D subsurface output, for example in combination with the contamination plume. Adding the profiles can be done as pseudo-section image according to the right coordinates. A more accurate way is to directly import the measured resistivity values as point data. In this way the measured resistivity points can be used for calculations, analyses and queries.

It results that ERT data can be imported in leapfrog Works as both images and points. In Figure 5.2 the profiles are visualised in the software by means of geo-referenced images. Since the supplied case data set only consists of the ERT pseudosection images, the three measured profiles of the case area cannot not be imported as points. However, if ERT point data are available it can be imported in Leapfrog Works as shown in Figure 5.3.

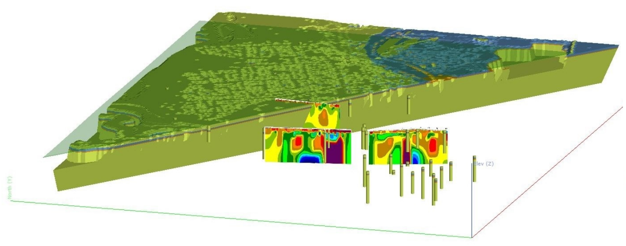


**Figure 5.2:** ERT profiles as images

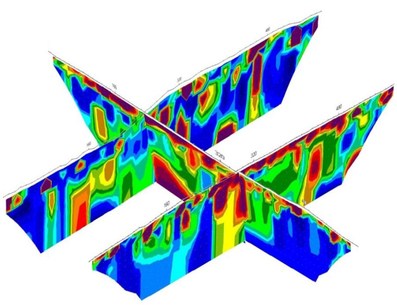


**Figure 5.3:** ERT profiles as point data

### 5.1.7 Virtual and Augmented Reality

In Subsection 2.6.3 the usefulness is addressed of GIS in combination with VR and AR. Leapfrog Works has responded to this development with Leapfrog Aspect. Leapfrog Aspect is an AR tool to view 3D outputs within a real world view. The tool is designed as application that can be downloaded on Android devices. The possibility to download the app on wireless devices allows to view the model in the field.

In addition, Leapfrog developed the Unearthing 3D modelling application where geological models can be experienced in AR. The application is in development making it only possible to view a demo project at the moment. This can be done by scanning a printed PDF marker by hoovering the device over it. The 3D model shows up on the camera screen, as can be seen in Figure 5.4. Hereafter, the model can be interactively operated and moved and layers can be turned on and off in the real space. Because the applications can be downloaded on wireless devices, a self-created 3D model can be viewed interactively on the location itself.

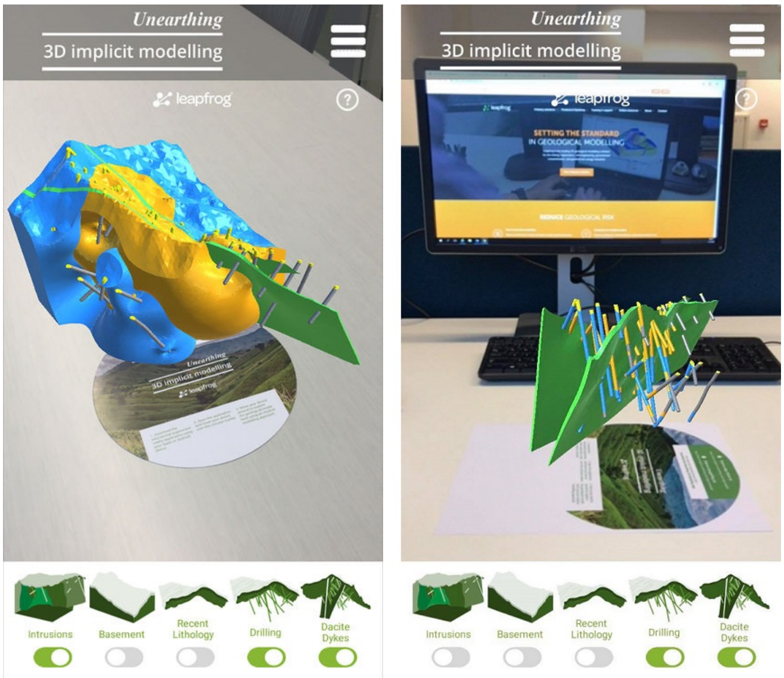



**Figure 5.4:** Leapfrog unearthing 3D modelling application

### 5.1.8 Hydrologic Flow Models

A hydrologic model is a representation of a real-world system that aims to illustrate, predict and manage water resources, including the flow and quality of the water. Because many geological phenomenon are related to subsurface water flows, such as soil contamination, it is an enrichment to integrate hydrologic models and geological models.

With the hydrogeology module in Leapfrog Works ModFlow and FEFLOW models can be imported or created. A geological model must be defined in order to create a hydrologic model. The hydrologic model is based on the soils and subsurface parameters of the geological model. Hydrological parameters, including hydraulic conductivity, specific storage and drainable porosity values, can be entered or edited manually. Due to limits in data availability and time no hydrological model is created for the case area. In Figures 5.5 and 5.6 examples of two hydrologic flow models are shown relating the geological model with head values, which indicates the amount of mechanical energy available in the water. A strength of the hydrological models in Leapfrog Works is the time steps, outlined in Figure 5.6. Hydrology moves much faster than geology making it an important application, as already discussed in Subsection 5.1.1.

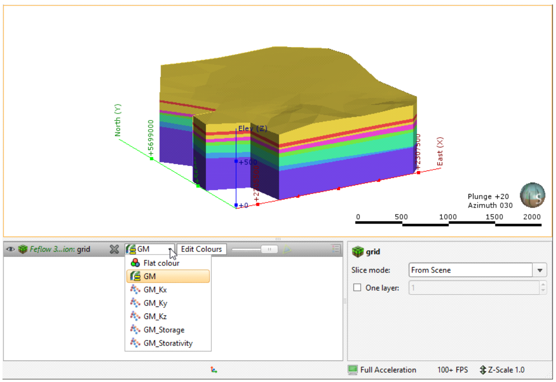


**Figure 5.5:** Hydrologic flow model
*Source:* Leapfrog (2019)

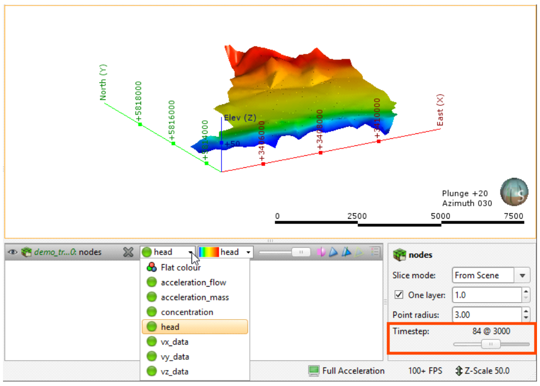


**Figure 5.6:** Hydrologic flow model
*Source:* Leapfrog (2019)

## 5.2 Application

This section will discuss and demonstrate a number of applications of 3D subsurface outputs created in Leapfrog Works. A number of cases are devised to be applied for the case area. The case area being anonymous is still valid. The cases include:

- Visualising boreholes and predicting planned drilling measurements
- Illustrating the geological structure of the case area
- Detecting differences in groundwater level
- Localising and monitoring contaminated groundwater
- Smart planning of civil engineering designs

The explanation and steps of how the outputs of these cases are generated can be found in Appendix F.

### 5.2.1 Drilling Data

In Figure 5.7 3D boreholes are visualised showing soil types along the traces. Three (random chosen) planned boreholes are shown in the right figure, where the soil types that are encountered during the drilling is predicted. The 3D output provides spatial insight in the distribution of the measurements and offers prognoses of planned boreholes.

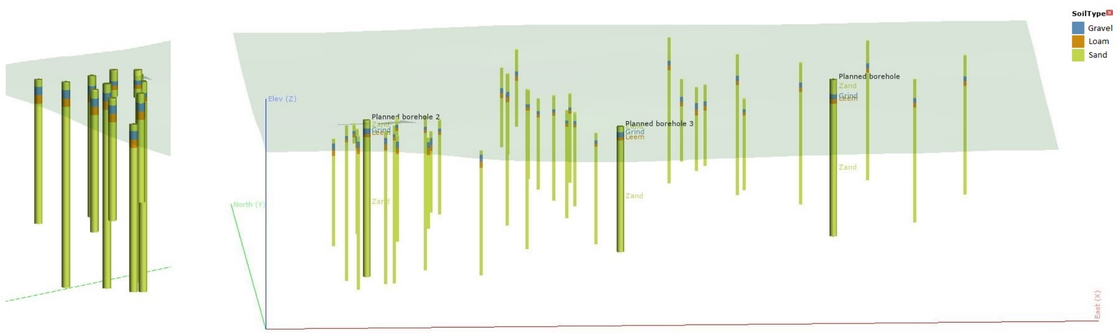



**Figure 5.7:** (Planned) boreholes

In Figure 5.8 graphs are visualised along the borehole traces showing the values related to concentrations of bromide. The figure demonstrates in which places high concentrations are measured in the groundwater. In this way, the core and direction of concentrations of a contamination plume are documented and localised in a quick overview without performing interpolation on the contamination values.

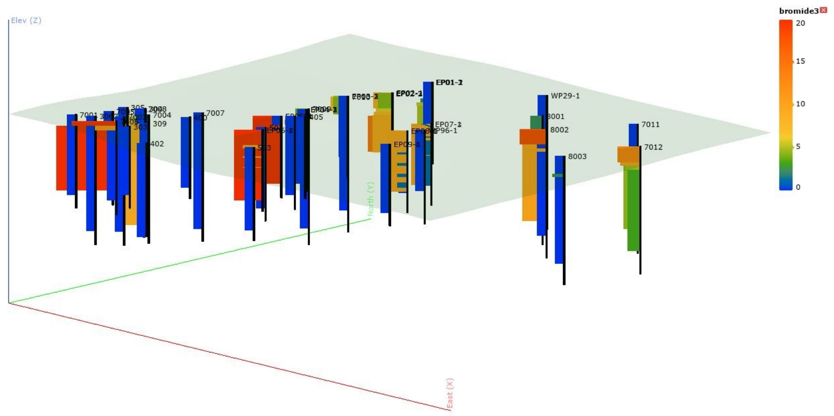


**Figure 5.8:** Borehole graphs

### 5.2.2 Geological Structure

In Figure 5.9 the geological model, representing the geological structure of the case area, is shown. The model includes soil layers of sand, loam and gravel. A geological model provides spatial insights in the chronology and structure of the subsurface and also offers an image of the values in between the measurement locations. This model is structured based on a relatively simple case area. In reality multiple layers and break lines are present in the subsurface. Such a 3D image of the geological structure provides a clear observation and understanding of the situation, compared to cross-sections and tables.

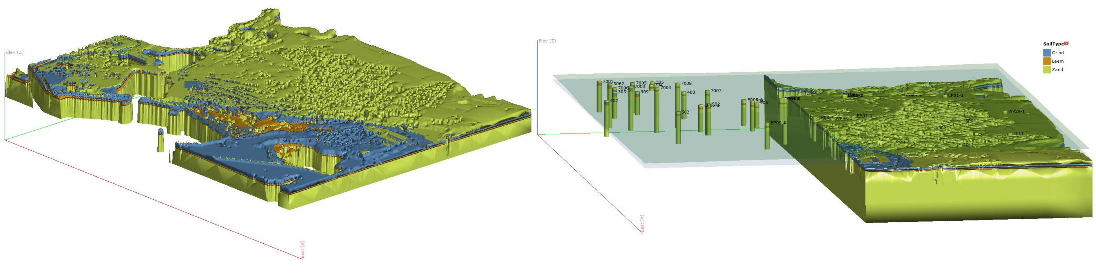


**Figure 5.9:** Geological structure of case area

### 5.2.3 Differences in Groundwater Level

In Figure 5.10 groundwater levels of two different time periods (red and blue) are shown. The figure is vertically exaggerated in order to visualise the differences. The ground level and drilling measurements are added as reference. Figure 5.11 includes the geological model of the area in order to investigate a relationship between (changes in) groundwater level relative to geologic structures. The groundwater surfaces give a clear visual image of the (elevation of the) levels and flowing direction in comparison to displaying numerical values in a table.

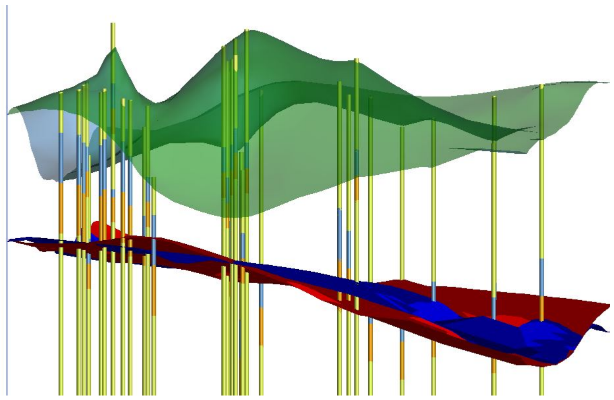


**Figure 5.10:** Groundwater levels of two time periods

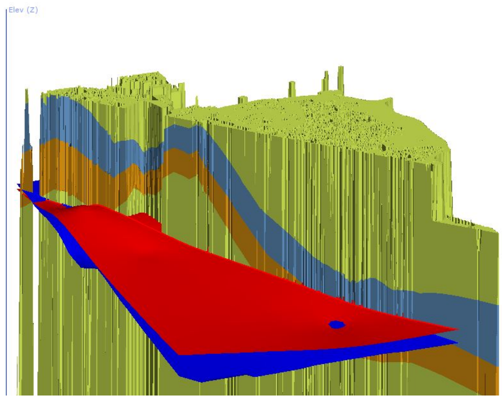


**Figure 5.11:** Groundwater relative to lithology

### 5.2.4 Contamination Plume

In Figure 5.12 a contamination plume of bromide is shown. The colours indicate different concentration thresholds of bromide. This makes it possible to conclude where harmful concentrations of a specific substance are located below the surface. The right figure is sliced in half to visualise the core of the plume. The 3D outputs help localising and monitoring the contaminated soil and groundwater. Besides, calculations can be performed in order to quantify the contamination and to set thresholds. Additionally, proximity or distance functions can be executed including buffer and trend analyses.

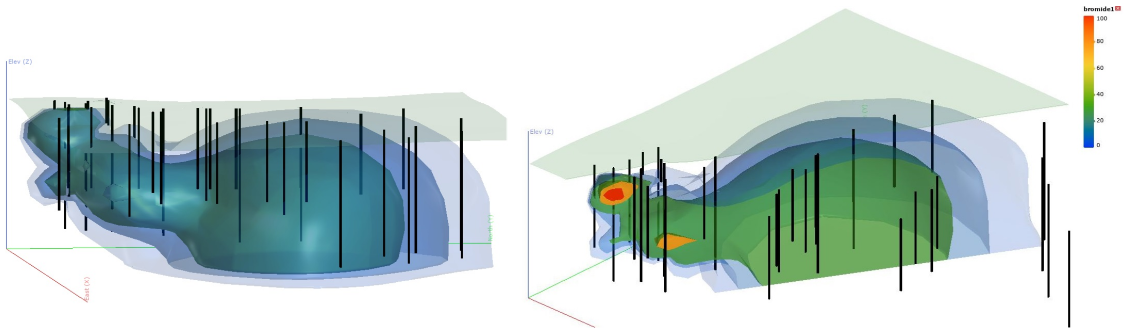


**Figure 5.12:** Contamination plume of concentrations bromide

### 5.2.5 Civil Engineering Designs

Integrating civil engineering designs in combination with subsurface information can be very serviceable and profitable. A planned parking lot is imported in Leapfrog Works, which is shown in Figure 5.13. Here, the subsurface data relates to a contamination plume. The parking lot is specifically planned that no contaminated soil or groundwater is encountered during excavation. But, when it is unavoidable to situate a planned design within the contamination, the software and 3D output can be used to predict what kind of polluted substances will be encountered and to what depth. Another application could be to investigate what type of soil is located under the planned design and what the volume is when excavating, for example in case of a tunnel.

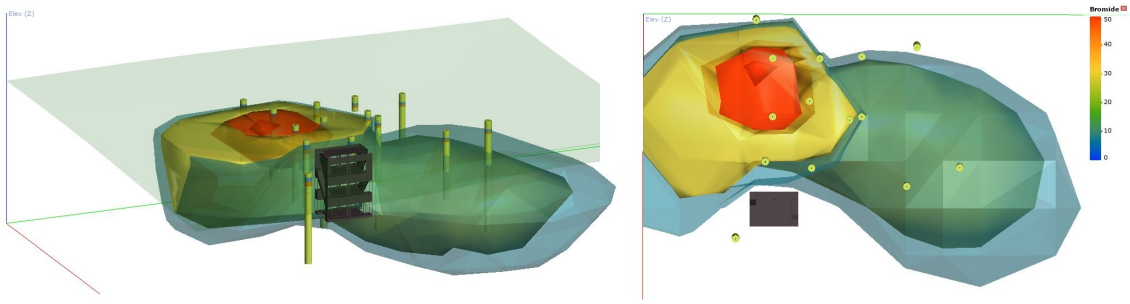



**Figure 5.13:** Smart planning of a parking lot

## 5.3 Presentation

An important focus of this research is the presentation of 3D subsurface data that includes real-world complexity. 3D presentations can complement the lack of spatial complexity and context of 2D presentations. In this respect, it is essential that the 3D output is spatially clear and in line with reality. With a realistic 3D presentation of a subsurface situation basic GIS users, such as data viewers defined in the map use cube, are able to interpret and understand the 3D output. In this section, the aim is to create a 3D representation of the subsurface of the case area in Leapfrog Works that matches the desires of the stakeholder, includes real-world complexity, fits in with the actual project area and is therefore also understandable for non-experts.

### 5.3.1 3D representation

The created output consists of:

- Drilling data including boreholes and monitoring wells
- A geological model containing data about the soil layers and geological structure
- A numerical model incorporating contamination values of bromide in $\mu$g/L
- Surfaces concerning groundwater levels and the ground level
- Surrounding objects such as buildings and infrastructure
- Civil engineering design

In Figure 5.14 the 3D subsurface representation of the case area is shown. Additions that are missing in this figure due to the anonymity of the area are topographic maps or images, coordinates, signs and labels. These objects or landmarks will make the final output more recognisable and closer towards reality. Besides, the added value of 3D is the interactively movement of the output, what is not perceptible in this 2D image of the output. Interactively moving through the 3D output in the software, desktop or online, is the best way to view the representation.

However, the 3D representation clearly shows the location of the contamination plume and boreholes, together with the soil structure of the area. Surrounding objects are added, including buildings, roads and a planned civil engineering design. The power of the software and output is not to visualise all data at the same time, but to dynamically turn on layers and objects and zooming in on a specific case, as demonstrated in Section 5.2.

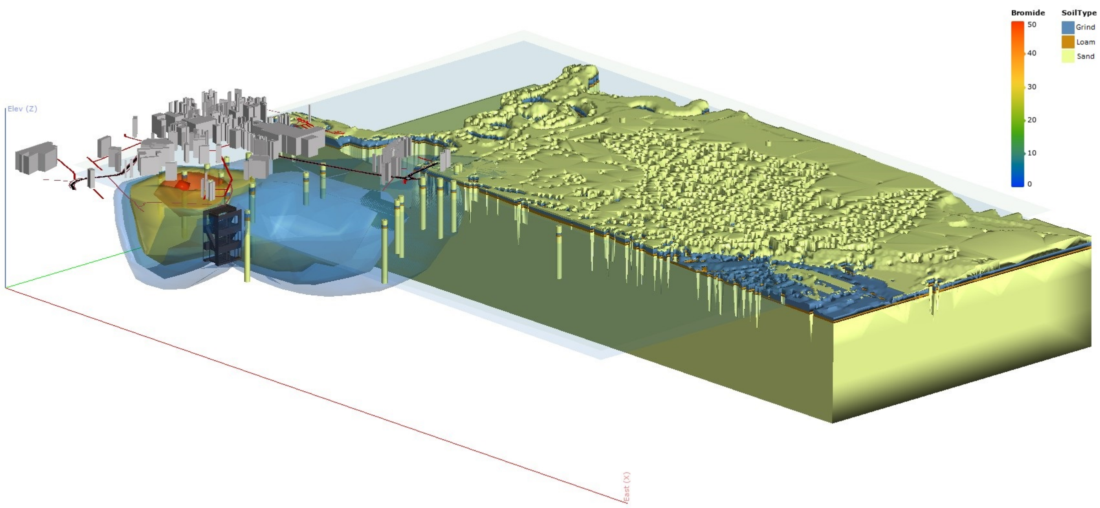



**Figure 5.14:** 3D representation of the subsurface of the case area

When comparing the 3D output to a 2D output, the added spatial context is immediately clear. In Figure 5.15 a 2D cross-section of the case area is shown, in which the soil types and contamination plume is visible. The location of the cross-section is indicated in Figure 5.16. A big difference is that this cross-section can only show the data of one line of coordinates, making it impossible to view and prospect the direction, flow and volume of the contamination plume for example. Certainly for non-experts these 2D images are difficult to interpret. The three-dimensional spatial subsurface outputs are more in line with reality, indicate its spatial context and are therefore easier to understand and exchange among different stakeholders and communities. The 3D output is able to visualise a much larger area in space in one figure, resulting in better spatial insights, increased spatial context and accessible observation.

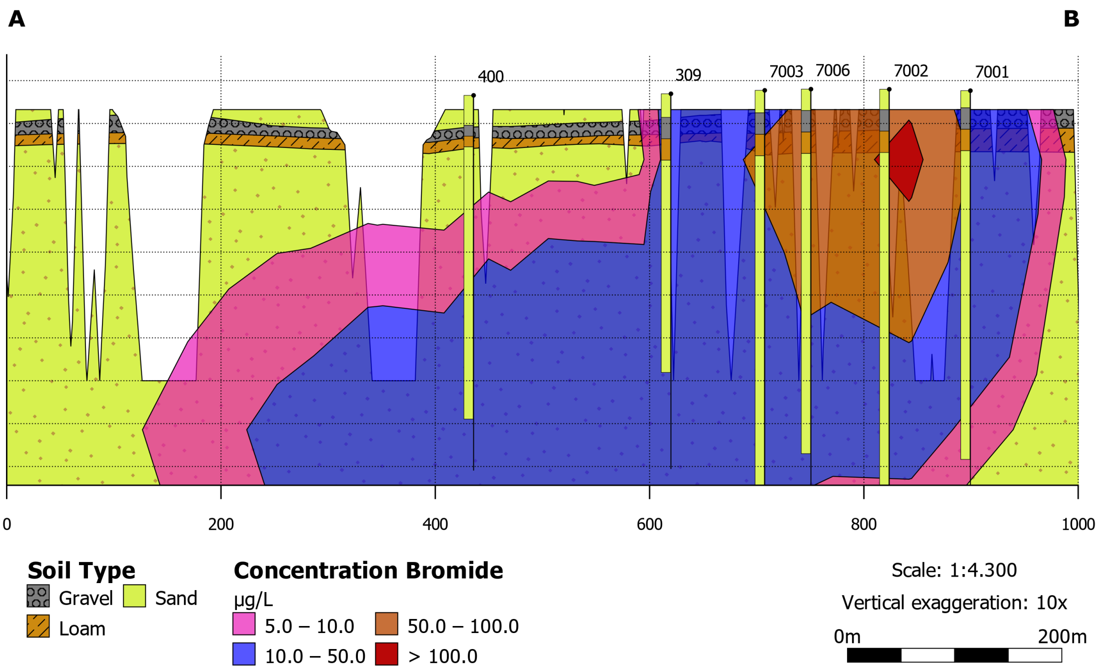



**Figure 5.15:** Subsurface cross-section of the case area

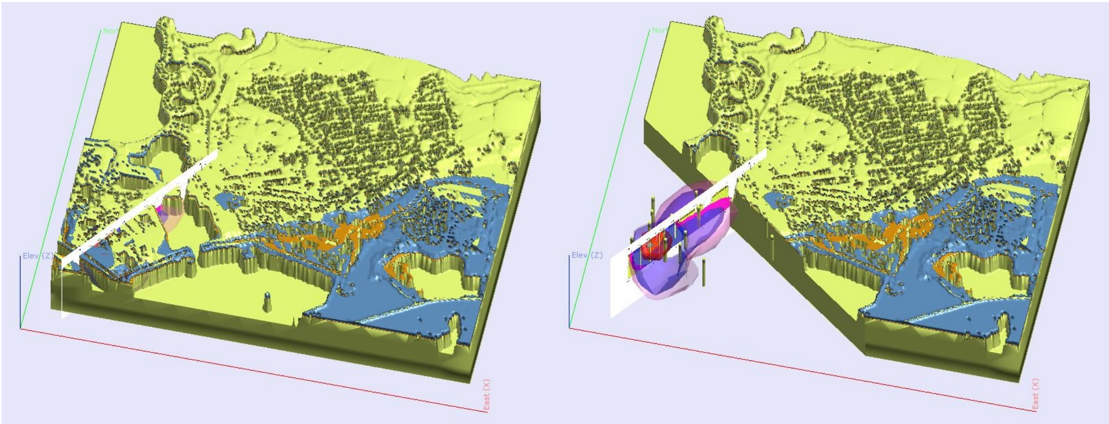


**Figure 5.16:** Subsurface cross-section of the case area

Lastly, the 3D output is able to indicate the real-world complexity of the subsurface. Multiple geologic phenomenon can be represented in one output. These phenomenon can be linked to each other during the analyses, which is also applicable to the real subsurface situation. For instance, soil characteristics and geological structures can be connected to the flow and direction of the groundwater, which are also dependent in reality. Coupled with the human objects and designs above and below surface it results in a representation that meets real world fundamentals and phenomenon.

### 5.3.2 3D sharing

As indicated in the previous subsection, the free movement through a 3D output is a great added value and contributes to the spatial understanding of the area. Especially for basic users or viewers, this free movement can be the solution for more spatial insight. Leapfrog offers an innovative and practical solution for sharing a generated 3D output with an easy to use interface. An online dashboard is included with the license account on which 3D outputs and scenes can be loaded. As a result, only the generated and selected layers are uploaded, excluding actual data files. Clients, stakeholders and third parties can be easily added to the project by e-mail. Authorisations to edit the output can be assigned to the contact persons if necessary. The online dashboard offers several functionalities, including layer property options, colour bar and data settings, slice and measure tools and a slide panel. In Figure 5.17 and 5.18 the generated 3D output of the case area is visualised in Leapfrog dashboard, showing some functionalities and properties to be set by the user. This is an innovative way to interactively share outputs without having to download software or exchange data sets.

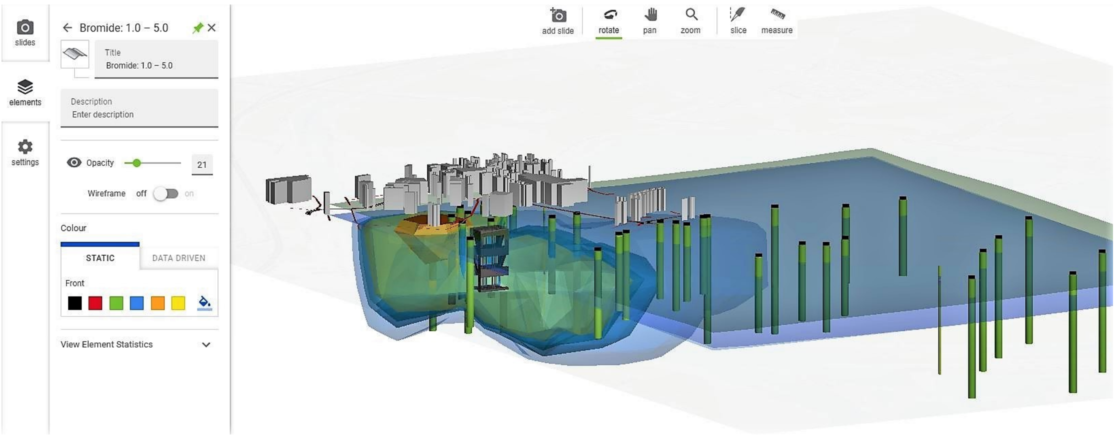



**Figure 5.17:** Layer properties in Leapfrog online dashboard

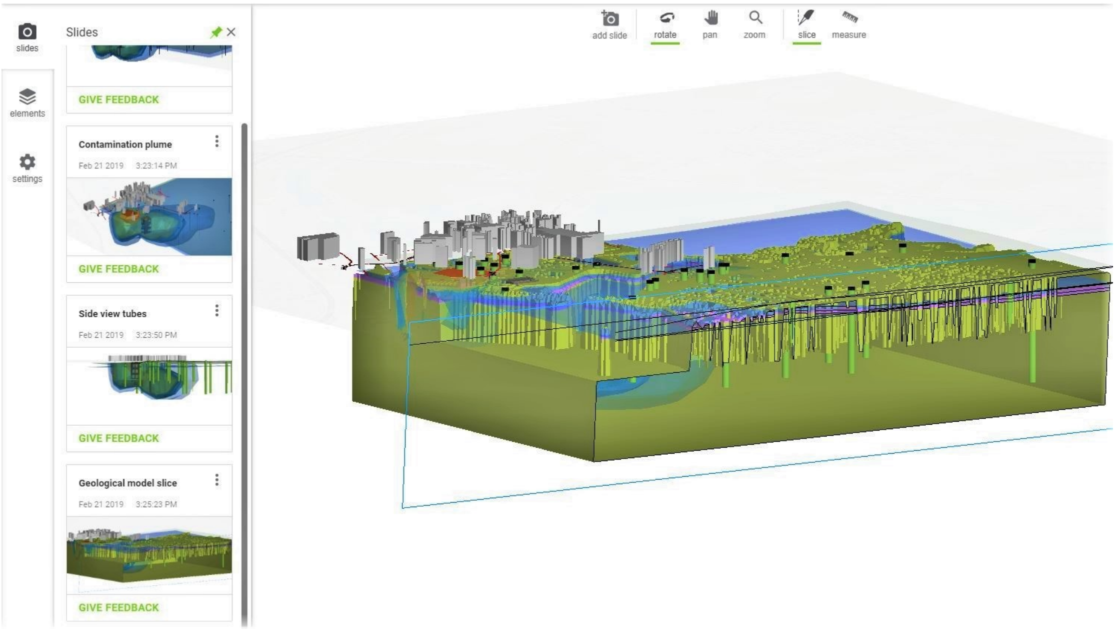



**Figure 5.18:** Slides function in Leapfrog online dashboard

# CHAPTER 6

# CONCLUSION

This final chapter aims to provide a short overview of the results, answers to the research questions defined in Chapter 1, a critical discussion of these findings and the research strategy and recommendations for future work.

## 6.1 Research Questions

The need for 3D information of the earth is rapidly increasing, because it provides more spatial insights, better interpretation of geological relations and improves the communication between experts and non-experts. Subsurface data is still frequently visualised by means of 2D representations, due to a shortage of spatial subsurface data, time-consuming and complex 3D techniques and limitations in current 3D GIS software. In order to tackle this problem and to broaden the knowledge regarding 3D GIS and subsurface data several research questions are formulated, that are answered in this section.

*What is subsurface data and how is it visualised?*
The first sub-question defines subsurface data and methods to visualise this information. Subsurface data cover large parts of the earth, including information of great depths below surface and other earth spheres. A distinctions is made between Conventional Soil Mapping (CSM) and Digital Soil Mapping (DSM), where CSM strongly relies on extensive soil surveys and DSM more focuses on computational advances and digital analyses. The subsurface data referred to in this study is defined as the data from the ground level to about 50 meters deep below surface. Common methods for visualising subsurface data are: cross-sections, pseudosections and top-view and side-view 2D maps. The visualised information often relates to lithology, geological structures and characteristics of soil types and groundwater, obtained by probing, drilling and geo-electrical measurements.

*How is the subsurface data of the Netherlands stored and mapped?*
Much soil research is carried out in the Netherlands. To standardise and exchange this data various organisations, institutes and initiatives are set up. An important Dutch body for soil management is SIKB, who have drawn up guidelines, protocols and standards. SIKB0101 is a commonly used .XML standard for the processing and exchange of Dutch subsurface data.

The Current Height of The Netherlands (AHN) and Normal Amsterdam Level (NAP) are examples of Dutch soil measurement interoperability references. Public Services on the Map (PDOK) and DINOloket are online platforms for the storage, managing and visualisation of Dutch subsurface data and maps. Various soil maps can be found here, such as the Key Registration of the Subsurface (BRO).

*What is 3D spatial data and how does it differ from 2D spatial data?*
3D data includes the third dimension: depth. 3D spatial data represents both layers, features and objects and their spatial relationships in 3D. An advantage and big difference with 2D is that 3D contains much more spatial context, complexity and reality in its output. As in 2D GIS, the distinction between vector and raster data remains in 3D GIS. However deviating from 2D, z-values representing height are adopted causing the third dimension. Surface- and Volume-based objects are distinguished in 3D, respectively representing vector and raster objects. Surface-based representations cover the boundary of 3D objects, while Volume-based representations include the interior. Discussions arise about the importance and presence of vector and raster based 3D object in GIS. The results show that not every software package contains both representations, as for some programmed tools in QGIS and ArcGIS stacking up surfaces, which limits the 3D outputs options. The generated outputs show that it is an advantage if both representations are supported to create a realistic and multifaceted subsurface representation.

*Which criteria should be taken into account when selecting a suitable GIS software package to support 3D subsurface data?*
In Chapter 2 the map use cube and its different user dimensions is discussed. This framework shows that GIS software are made for and focus on different user types and purposes. In order to select suitable GIS software for appointed users and goals, the software should meet certain criteria. For this research the five main-criteria functionality, usability, reliability, vendor and cost are established based on relevant literature studies, expert judgements and stakeholder requirements. Functionality is respected as most important criteria, because if the software can not perform certain actions it is actually useless for the research. Poor usability and reliability complicate performing tasks and produce results making this also important criteria to take into account. Vendor criteria contribute to a pleasant working atmosphere, user engagement and increased product-knowledge. Cost criteria relate to user satisfaction and possibilities to purchase a product and its license.

*Which software packages are suitable to support 3D subsurface data?*
The MCA shows that the five GIS software packages all contain separate characteristics, making them suitable for different users and purposes. The biggest difference can be observed between Esri GIS and QGIS, being developed for more general purposes resulting in almost no default subsurface related functionalities, and Leapfrog Works, Voxler and GeoScene3D, being developed with a subsurface specific focus including a wide range of subsurface related functionalities. Due to this difference in purpose and the limits in the field of default 3D analysis and visualisation tools, Esri GIS and QGIS are ascertained as not suitable to support 3D subsurface data for this research. Leapfrog Works, Voxler and GeoScene3D are able to support 3D subsurface data since they are specifically developed to support subsurface data within a 3D environment. Nevertheless, clear differences can be observed. Voxler provides a user-friendly environment, but falls short on advanced subsurface specific 3D functionalities.

GeoScene3D does include these advanced functionalities, but accommodates a very advanced user environment making it suitable for experts only. Leapfrog Works includes good usability as well as advanced functionalities. In addition, the software offers certain desires, such as online upload and share options, management of large files, prioritisation of executive tasks and a large online platform. This results in Leapfrog Works being the most suitable GIS software to support 3D subsurface data.

*For which applications can the 3D subsurface representation be useful?*
3D representations of subsurface data are useful for various purposes and applications. A number of applicable cases are mentioned in Chapter 5, including the visualisation of drilling data. The 3D outputs contribute to increased spatial insights in the measurements distribution and prognoses of planned boreholes. In addition, 3D outputs of the geological structure can be created which provide clear observation and understanding of subsurface areas. 3D outputs of groundwater can be useful in different ways. Differences in levels can be detected and calculated, the direction and flow of the groundwater can be monitored or relations with geological structures can be investigated. Besides, pollutants and contamination plumes can be made visible in 3D. The outputs could be used to localise and monitor contaminated area, determining threshold values and identifying hazardous regions. Finally, an interesting application available in Leapfrog Works is the connection with civil engineering designs. These can be added to the 3D outputs making it possible to smart plan designs and to forecast and calculate planned excavations.

*Which real-world components can be included and represented by the 3D subsurface output?*
The created representations show that various real-world components and objects can be three-dimensionally visualised and presented in Leapfrog Works. The geological structure can be realistic represented by entering and setting up soil specific parameters, such as chronology, age and parent material. In addition, different interpolation methods, trend settings and data classification methods allow numerical values and models to be visualised with actual knowledge about the area incorporated. In addition, surrounding elements, such as buildings, infrastructure and natural objects, enrich the 3D output with more context, complexity and reality. By adding topographic maps, photos, images and labels the area can be recognisably represented.

The answers and results of these sub-questions together form the set-up to answer the main-question of this research:

*Which software package is suitable to support 3D subsurface data when exploring its 3D functionalities, purposes and dimensions;*
*and to what extent is the generated output able to provide a comprehensible 3D subsurface representation that includes real-world complexity?*

The first part of the question is mainly answered by sub-question five. Leapfrog Works, Voxler and GeoScene3D are suitable to support the analysis and visualisation of 3D subsurface data. Here, Voxler has a strong focus on visualisation options, while GeoScene3D offers more expertise on 3D functionalities and tools. Leapfrog Works supports both analysis as visualisation aspects and is therefore regarded as most suitable GIS software package considering the criteria of this research. The generated 3D outputs show ability to create a comprehensible subsurface representation and the possibilities to include real-world objects and phenomenon.

Through the inclusion of area-specific and soil related parameters and settings, the output can be tuned and adapted to the particular case whereby the complexity and attributes of that area can be included.

> The 3D outputs always remain representations of reality, but because of the variety in types of input data; geological, numerical and hydrologic models; spatial analyses and output objects, a comprehensible 3D subsurface representation can be created that is committed to and takes into account case area characteristics and real-world complexity.

Because of the extended desktop software product, focused on advanced GIS users working with extended 3D functionalities, and the innovative online sharing dashboard, focused on basic views and movements of the output, Leapfrog Works is suitable for creating reliable subsurface models by experienced users, as well as viewing and exploring the output by beginners or non-experts.

## 6.2 Discussion

This research aimed to, as the title suggests, explore 3D functionalities within software suitable to support 3D subsurface data. Five GIS software packages are evaluated based on predefined criteria, in order to assess the suitability to support 3D subsurface data. With the most suitable software it is explored to what extent real-world complexity could be included in the 3D output representation. A Multiple-Criteria Analysis (MCA) is applied to deliberately assess and compare the software alternatives. The MCA approach resulted in reduction of uncertainty and more reliability of the results. The criteria, scores and weights are drawn up by means of various input sources, leading to solidity and reliability. Yet, since a MCA always has to deal with preference information the methodology can be discussed.

This research is carried out in collaboration with stakeholder Antea Group, through which the alternatives, criteria, weights and scores are set up in consultation. Despite the fact that independent parties and literature studies are included, other stakeholders can provide variant additions to these parameters. Therefore, it is not embedded that this research will produce the same results with inputs from other stakeholders. In addition, this research is performed with regard to the hardware, software and database environment of Antea Group. The hardware, software and database capabilities must be taken into account when re-examination is carried out.

Since this research specifically focuses on the subsurface domain the reproducibility for other domains can be questioned. The assessed alternatives are specifically developed to support subsurface data and the evaluated functionalities relate to the subsurface. When examining other expertises, such as air or surface data, the alternatives, weights and requirements will have to be adjusted. Nevertheless, the methodology offers a general approach and guidance for evaluating GIS software. The five main-criteria are applicable to each GIS software, regardless the domain of evaluation. In addition, the map use cube framework provides a directory and classification of GIS software in general. The user types, purposes and dimensions that are established in the cube serve as a guidance in examining, selecting and use of the GIS software.

The strength of this research method should therefore be seen in the approach to evaluate and assess GIS software packages, using embedded criteria and theories such as the map use cube, where domain dependent parameters can be put in as alternatives, criteria, weights and requirements.

The conclusions of Esri GIS and QGIS being ascertained as not suitable to support 3D subsurface data for this research may seem implicit or questionable when looking at the alternative ranking in Table 4.3. Esri GIS ends up in the ranking as number two, but is stated in the Conclusion as not suitable by default. When looking at the final scores Esri GIS, Voxler, GeoScene3D and QGIS are really close. As a result of this, and because Esri GIS scores average or good on non-subsurface and 3D related requirements such as vendor, it ended up in the second place. The result of Leapfrog Works as significant winner is reliable since it is the only software alternative that meets all predefined requirements. The other four alternatives do not meet all requirements making it difficult to distinguish. To refine and rank the other alternatives correctly, the requirements will have to be tightened.

From the results it is concluded that the five software alternatives have an own identity in the area of users, purposes, goals and dimensions. This finding relates to the existing body of the map use cube as is outlined in Chapter 2. The software can be placed in different sides of the cube. This directly substantiated the importance of selecting suitable GIS software. Identifying and recognising different user types and purposes form the base in determining requirements and ultimately selecting a suitable software. From the software evaluation and the In-Depth it can be stated that the challenge of 3D representation of the subsurface is tackled. The results and created 3D figures certainly meet the scientific relevance that are mentioned in Chapter 1 to provide insights into 3D GIS functionalities applicable for 3D subsurface data. The research proves that useful 3D subsurface outputs can be created in GIS software that are of added value for various cases. The outputs of this research also match the practical relevance, since it is confirmed that the 3D subsurface representations can be combined with data from other domains, such as civil engineering designs, and can be easily and online shared which advances the communication between contractor and client.

## 6.3 Recommendations

This research offers proof of concept, showing the importance and added value of 3D representations of subsurface data created in GIS software. However, there is still more research to be done to gain knowledge about 3D GIS functionalities and to improve and standardise the use of 3D subsurface representations. This section therefore provides recommendations for future work.

In Chapter 5 the included functionalities and applications of Leapfrog Works are reviewed in-depth. Desires are discussed and recommended. In order to increase the knowledge of the software, it is necessary to look further into this. The options and costs of Leapfrog Central must be better identified, to see if this is profitable and desirable for Antea Group. In addition, the possibilities to incorporate hydrologic models must be further investigated, by personally importing and creating a model. Also the options to manually edit the 3D output must be viewed more closely.

In addition to further investigation of the included functionalities and possibilities of Leapfrog Works, the software should be used to process multiple case area data sets. In this research, one case area is used, of which some data is manipulated in order to better show and interpret the output. The reliability of the software will be verified if multiple case area data sets are used. Likewise, the applicability will become more visible.
In order to validate the research methodology it can be suggested to carry out similar research into other working domains, such as infrastructure, environmental sciences, safety and water management. In this way it can be tested to what extent the criteria and the map use cube framework are applicable for similar studies. Additionally, it is useful to include these working domains in this research direction. As mentioned in Chapter 2, the subsurface is in direct contact with the other earth spheres, making it very relevant to test whether these data can be combined in Leapfrog Works. In this way, underlying processes and connections between different working domains can be analysed and visualised. Additionally, in this way the genericity of the research methodology and assessment framework of the map use cube can be considered.

A strength of the research methodology is the assessment of Voxler, Leapfrog Works and GeoScene3D according to identical data and performed actions. As a result, the software packages are evaluated and compared equally. Esri GIS and QGIS however are evaluated differently, as a result of the presence of many similar previous studies and restrictions in time. In case of follow-up research, the performed actions and data could also be applied to Esri GIS and QGIS for more equality. However, it can be discussed whether Esri GIS and QGIS should be included in repetitive research, since they contain little or no 3D soil functionalities by default.

Implementing the 3D subsurface representations created in Leapfrog Works as a package to visualise the subsurface, gain geological insights and share knowledge with clients and stakeholders is defined in Chapter 1 as the research objective of Antea Group. To realise this, different cases should be worked out in which the 3D representation are applicable. To do this it is necessary to standardise the subsurface data based on Leapfrog Works's input data to import the subsurface information quickly and easily. Besides, it is important to conduct additional research into the optimisation of the data processing, so that 3D representations can be created as efficient as possible. It would be desirable to optimise the data processing in such a way that a 3D representation can be created that includes diverse subsurface data inputs, different types of models and surroundings objects within a day.

This research performs a base to build on when continuing the investigation towards the exploration of 3D GIS functionalities and representing the subsurface in 3D. In addition, it provides insights and a generic assessment framework to evaluate GIS packages on different dimensions, purposes and user types.

# BIBLIOGRAPHY


Adams, N. E. (2015). Bloom's taxonomy of cognitive learning objectives. *Journal of the Medical Library Association : JMLA*, 103(3):152–153.

Ahmad, K. S., Ahmad, N., Tahir, H., and Khan, S. (2017). Fuzzy-MoSCoW: A fuzzy based MoSCoW method for the prioritization of software requirements. In *Intelligent Computing, Instrumentation and Control Technologies (ICICICT), 2017 International Conference*, pages 433–437. IEEE.

AHN (2018). Over Actueel Hoogtebestand Nederland.

Aitken, S. C. and Michel, S. M. (1995). Who Contrives the 'Real' in GIS? Geographic Information, Planning and Critical Theory. *Cartography and Geographic Information Systems*, 22(1):17–29.

Ali-Sisto, D. and Packalen, P. (2017). Forest change detection by using point clouds from dense image matching together with a LiDAR-derived terrain model. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 10(3):1197–1206.

An, L., Tsou, M. H., Crook, S. E., Chun, Y., Spitzberg, B., Gawron, J. M., and Gupta, D. K. (2015). SpaceTime Analysis: Concepts, Quantitative Methods, and Future Directions. *Annals of the Association of American Geographers*, 105(5):891–914.

Anlauf, R., Schaefer, J., and Kajitvichyanukul, P. (2018). Coupling HYDRUS-1D with ArcGIS to estimate pesticide accumulation and leaching risk on a regional basis. *Journal of Environmental Management*, 217:980–990.

Bataineh, O., Hjeelah, D. A., and Arabiat, S. (2017). Multi-Criteria Decision Making Using AHP to Select the Best CAD Software. *International Conference on Intelligent Information Technologies for Industry*, pages 106–115.

Becker, S., Walter, V., and Fritsch, D. (2012). Integrated management of heterogeneous geodata with a hybrid 3D geoinformation system. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, I(2):87–92.

Berry, J. (2007). Map analysis: understanding spatial patterns and relationships. Technical report, GeoTech Media.

Birch, C. (2014). New systems for geological modelling-black box or best practice? *Journal of the Southern African Institute of Mining and Metallurgy*, 114(12):993–1000.

Boone County GIS (2008). User Classifications and GIS Application Toolsets. Technical report, Boone County Planning Commission.

Borneman, E. (2017). 3D Model of the Movement of Carbon Dioxide Through EarthâĂŹs Atmosphere.

Bouma, J. (2009). Soils are back on the global agenda: Now what? 150:224–225.

Bouwbedrijf Lichtenberg (2016). Wat is een sondering?

Brevik, E. C., Calzolari, C., Miller, B. A., Pereira, P., Kabala, C., Baumgarten, A., and Jordán, A. (2016). Soil mapping, classification, and pedologic modeling: History and future directions. *Geoderma*, 264:256–274.

Capterra (2018). ArcGIS reviews.

Carrell, J. (2014). Tools and Techniques for 3D Geologic Mapping in ArcScene: Boreholes, Cross Sections, and Block Diagrams. Technical report, U.S. Geological Survey Open-File Report.

Chen, H., Wood, M. D., Linstead, C., and Maltby, E. (2011). Uncertainty analysis in a GIS-based multi-criteria analysis tool for river catchment management. *Environmental Modelling and Software*, 26(4):395–405.

Child, C. (2004). Interpolating surfaces.

Cozzens, T. (2015). Esri Has 43 Percent Share of GIS Market.

Culshaw, M. (2005). From concept towards reality: developing the attributed 3D geological model of the shallow subsurface. *Quarterly Journal of Engineering Geology and Hydrogeology*, 38(3):231–284.

de Bakker, H. (2013). *Major soils and soil regions in the Netherlands*. Springer Science & Business Media.

De Beer, J. (2006). *Methodisch ontwerpen*. Boom Uitgevers Amsterdam, Amsterdam, second edition.

de Vries, F., Walvoort, D., and Brouwer, F. (2017). Basisregistratie Ondergrond (BRO) Actualisatie bodemkaart. Technical report, Wageningen University.

Demeritt, M. (2012). Creating dynamic subsurface perspectives in ArcScene. Technical report, Esri.

Devleeschouwer, X. and Pouriel, F. (2006). Brussels Urban Geology (BUG): a 2D and 3D model of the underground by means of GIS. In *Proceedings of the 10th IAEG Congress*, Nottingham, United Kingdom.

Devleeschouwer, X. and Pouriel, F. (2018). The Subsurface Geology of Brussels, Belgium, Is Modeled with 3D GIS.

D&T Geodata management (2018). Borehole 3D.

Ecopedia (2018). Peilbuis.

Eldrandaly, K. A. (2007). GIS software selection: A multi criteria decision making approach. *Applied GIS*, 3(5):1–17.

Eldrandaly, K. A. and Naguib, S. M. (2013). A Knowledge-Based System for GIS Software Selection Spatio-Temporal Inreoplation Using Intelligent Techniques View project A Knowledge-Based System for GIS Software Selection. Technical Report 2.

Elzakker, C. (2004). The use of maps in the exploration of geographic data. Technical report, International Institute for Geo-Information Science and Earth Observation, Enschede.

ESDAC (2019). Soil Resources map of Nigeria. Map of present productivity of soils.

Esri (2018a). How global polynomial interpolation works.

Esri (2018b). How IDW works.

Esri (2018c). How local polynomial interpolation works.

Esri (2018d). How radial basis functions work.

Esri (2018e). The five key types of ArcGIS users.

Esri (2018f). User types, roles, and privileges.

Friedrich, C. (2014). *Comparison of ArcGIS and QGIS for Applications in Sustainable Spatial Planning*. PhD thesis, University of Vienna.

Fugro (2018). Aerial Mapping.

Fukiage, T., Kawabe, T., and Nishida, S. (2017). Hiding of phase-based stereo disparity for ghost-free viewing without glasses. *ACM Transactions on Graphics*.

G-tec (2018). Resistiviteits beeldvorming (ERT) resultaten Edelchemie. Technical report.

G2 Crowd (2018a). Esri ArcGIS reviews.

G2 Crowd (2018b). QGIS reviews.

G2 Crowd (2018c). Voxler reviews.

GDN (2019). 3D-modellen.

Geoterra (2018). Geoterra carry out urgent subsurface laser scan survey following major road collapse in Scotland.

Gerrow-Wilcox, K. (2018). What's Coming in ArcGIS Online: Introducing User Types.

GITTA (2018). Trend surface analysis.

Gong, J., Geng, J., and Chen, Z. (2015). Real-time GIS data model and sensor web service platform for environmental data management. *International Journal of Health Geographics*, 14(1):2–14.

Hartemink, A. E. and Sonneveld, M. P. (2013). Soil maps of The Netherlands. *Geoderma*, 204:1–9.

Herrador, M., Graciano, A., Feito, F. R., and Ortega, L. (2016). Proceedings of the Arquelogica 2.0 8th International Congress on Archaeology, Computer Graphics, Cultural Heritage and Innovation. Technical report, Valencia.

Heywood, I., Cornelius, S., and Carver, S. (2011). *An introduction to Geographical Information Systems*. Pearson Education Limited, Harlow, fourth edition.

Hodkiewicz, P. (2013). Leapfrog: new software for faster and better 3D geological modelling. Technical report, SRK Consulting.

Hong, J. E. (2016). Identifying Skill Requirements for GIS Positions: A Content Analysis of Job Advertisements. *Journal of Geography*, 115(4):147–158.

Hoovering Solutions (2017). London Crossrail tunnels are scanned using Drones.

Humboldt State University (2018). Raster to vector.

Huuskonen, J. and Oksanen, T. (2018). Soil sampling with drones and augmented reality in precision agriculture. *Computers and Electronics in Agriculture*, 154:25–35.

Ishizaka, A. and Nemery, P. (2013). *Multi-Criteria Decision Analysis*. John Wiley & Sons.

Jadhav, A. S. and Sonar, R. M. (2009). Evaluating and selecting software packages: A review. *Information and Software Technology*, 51(3):555–563.

Jamwal, D. (2010). Analysis of Software Quality Models for Organizations. Technical Report 2.

Kachelriess, R. (2018). There is a New Way to Go Pro.

Kamel Boulos, M. N., Lu, Z., Guerrero, P., Jennett, C., and Steed, A. (2017). From urban planning and emergency training to Pokémon Go: Applications of virtual reality GIS (VRGIS) and augmented reality GIS (ARGIS) in personal, public and environmental health. *International Journal of Health Geographics*, 16(7):1–11.

Kempen, B., Brus, D. J., Stoorvogel, J. J., Heuvelink, G. B., and de Vries, F. (2012). Efficiency Comparison of Conventional and Digital Soil Mapping for Updating Soil Maps. *Soil Science Society of America Journal*, 76(6):2097–2115.

Kvamme, K. (2018). Getting Around the Black Box: Teaching (Geophysical) Data Processing through GIS. *Journal of Computer Applications in Archaeology*, 1(1):74–87.

Leapfrog (2019). Flow models.

Lin, H. (2010). Earth's Critical Zone and hydropedology: Concepts, characteristics, and advances. *Hydrology and Earth System Sciences*, 14(1).

Liu, H., Oosterom, P., Meijers, M., and Verbree, E. (2018). Towards 1015 -level point clouds management - a nD PointCloud structure. *Geospatial Technologies for All: Short papers, posters and poster abstracts of the 21th AGILE Conference on Geographic Information Science (A. Mansourian, P. Pilesjö, L. Harrie, R. van Lammeren, eds.), Lund University*, page 7.

Lopez, J. (2017). Beyond drilling: using geophysic's to understand what is beneath the surface.

Lush, C. and Lush, M. (2014). QGIS Suitability Assessment. Technical report.

Lynn, J. (2018). Countries With The Lowest Average Elevations.

MacEachren, A. M. and Kraak, M. J. (1997). Exploratory cartographic visualization: advancing the agenda. *Computers and Geosciences*, 23(4):335–343.

McBratney, A. B., Mendonça Santos, M. L., and Minasny, B. (2003). On digital soil mapping. *Geoderma*, 117(1-2):3–52.

McCarthy, J. D. and Graniero, P. A. (2006). A GIS-based borehole data management and 3D visualization system. *Computers and Geosciences*, 32(10):1699–1708.

MDH (2018). Flowing Well and Boring Special Construction Area.

Mu, E. and Pereyra-Rojas, M. (2017). Understanding the Analytic Hierarchy Process. In *Practical Decision Making*, pages 7–22.

Neset, T. S., Opach, T., Lion, P., Lilja, A., and Johansson, J. (2016). Map-Based Web Tools Supporting Climate Change Adaptation. *Professional Geographer*, 68(1):103–114.

Noel, E. J. (2015). *Increasing Usability and Accessibility of GIS Technology Through Extension of Existing Software Tools*. PhD thesis, North Dakota State University of Agriculture and Applied Science.

Nourjou, R. and Thomas, J. (2016). System architecture of cloud-based web GIS for real-time macroeconomic loss estimation. In *Proceedings of the 5th ACM SIGSPATIAL International Workshop on Mobile Geographic Information Systems - MobiGIS '16*, pages 55–63, Burlingame.

Pacheco-Cardenas, Y. (2018). Application of Multi-Criteria Decision Analysis to the Selection of Software Measures. *Computing and systems*, 22(1):203–213.

Paterson, G., Turner, D., Wiese, L., Van Zijl, G., Clarke, C., and Van Tol, J. (2015). Spatial soil information in South Africa: Situational analysis, limitations and challenges.

PDOK (2019). PDOK Viewer.

Petrangeli, A. B., Preziosi, E., Campopiano, F., Corazza, A., and Duro, A. (2016). CREGIS-Q: a GIS tool to support decision making in case of aquifer contamination emergency. *PeerJ Preprints*, 4.

Poggio, L. and Gimona, A. (2017). 3D mapping of soil texture in Scotland. *Geoderma Regional*, 9:5–16.

Poore, B. S. (2003). The open black box: The role of the end-user in GIS integration. *Canadian Geographer*, 47(1):62–74.

Raska, N. (2017). 3D subsurface models canada. Technical report, Lund University.

RCE (2007). Beeldbank van de Rijksdienst voor het Cultureel Erfgoed.

Richards-Rissetto, H. (2017). What can GIS and 3D mean for landscape archaeology? *Journal of Archaeological Science*, (84):10–21.

Rinaldi, V., Guichon, M., Ferrero, . V., Serrano, C., and Ponti, N. (2006). Resistivity Survey of the Subsurface Conditions in the Estuary of the Rio de la Plata. *Journal of geotechnical and geoenvironmental engineering*, 132(1):72–79.

Rowell, D. L. (2014). *Soil Science: Methods and Applications*. Routledge: Taylor &. Francis Group.

Saisana, M., Saltelli, A., and Tarantola, S. (2005). Uncertainty and sensitivity analysis techniques as tools for the quality assessment of composite indicators. *J. R. Statist. Soc. A*, 168(2):307–323.

Samouëlian, A., Cousin, I., Tabbagh, A., Bruand, A., and Richard, G. (2005). Electrical resistivity survey in soil science: A review. *Soil and Tillage Research*, 83(2):173–193.

Schokker, J., Sandersen, P., De Beer, H., Eriksson, I., Kallio, H., Kearsey, T., Pfleiderer, S., and Seither, A. (2017). 3D urban subsurface modelling and visualisation-a review of good practices and techniques to ensure optimal use of geological information in urban planning. Technical report, COST: European Cooperation in Science and Technology.

Seequent (2017). User Manual for Leapfrog Works version 2.0. Technical report, ARANZ Geo Limited, Christchurch, New Zealand.

SIKB (2018). SIKB0101 Bodembeheer.

Softtree support (2017). Digital Terrain Modelling.

StrateGis (2019). 3D Geoviewer.

TrustRadius (2018a). ArcGIS reviews and ratings.

TrustRadius (2018b). QGIS reviews.

USDA (2017). Soil Survey Manual Soil Science Division Staff Agriculture Handbook No. 18. Technical report.

Van Leusen, M. and Van Gessel, S. (2016). Towards 3D GIS: Notes from the 2012 CAA-NL/DE chapter session from 2.5 to 3 spatial dimensions. *The Three Dimensions of Archaeology, Proceedings of the XVII Union Internationale des Sciences Préhistoriques et Protohistoriques World Congress*, 7:33–37.

Vaughan, A. (2014). Black Boxes and GIS for Anthropological Research.

Verruijt, A. (2017). *An Introduction to Soil Mechanics*. Springer.

Wang, W., Lv, Z., Li, X., Xu, W., Zhang, B., and Zhang, X. (2015). Virtual reality based GIS analysis platform. In *International Conference on Neural Information Processing*, pages 638–645, Cham. Springer.

Wikle, T. A. and Fagin, T. D. (2015). Hard and Soft Skills in Preparing GIS Professionals: Comparing Perceptions of Employers and Educators. *Transactions in GIS*, 19(5):641–652.

Wilding, L. P. and Lin, H. (2006). Advancing the frontiers of soil science towards a geoscience. *Geoderma*, 131(3-4):257–274.

Wong, K. and Ellul, C. (2017). User requirements gathering for 3D geographic information in the United Kingdom. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, pages 89–96.

Yang, L., Jiao, Y., Fahmy, S., Zhu, A.-X., Hann, S., Burt, J. E., and Qi, F. (2011). Updating Conventional Soil Maps through Digital Soil Mapping. *Soil Science Society of America Journal*, 75(3):1044–1053.

Yatsalo, B., Didenko, V., Gritsyuk, S., Sullivan, T., Boris, Y., Sci, D., Vladimir, D., and Terrence, S. (2015). Decerns: A Framework for Multi-Criteria Decision Analysis. *International Journal of Computational Intelligence Systems*, 8(3):467–489.

Yilmaz, A. and Çagiltay, K. (2014). Usability analysis of GIS software: Quantum GIS. Technical report.

Yu, C., Zhang, B., Yao, Y., Meng, F., and Zheng, C. (2012). A field demonstration of the entropy-weighted fuzzy DRASTIC method for groundwater vulnerability assessment. *Hydrological Sciences Journal*, 57(7):1–13.

Zarroca, M., Bach, J., Linares, R., and Pellicer, X. M. (2011). Electrical methods (VES and ERT) for identifying, mapping and monitoring different saline domains in a coastal plain region (Alt Empordà, Northern Spain). *Journal of Hydrology*, 409(1-2):407–422.

Zlatanova, S., Nourian, P., Gonçalves, R., and Vo, A. V. (2016). Towards 3d raster gis: on developing a raster engine for spatial dbms. Technical report, Russian Federation.

Zlatanova, S., Stoter, J., and Isikdag, U. (2012). Standards for Exchange and Storage of 3D Information: Challenges and Opportunities for Emergency Response. Technical report, International Cartographic Association.

# APPENDIX A

# INTERPOLATION METHODS

Spatial interpolation consists of the estimation of property values of unsampled sites within an area covered by existing values (Heywood et al., 2011). The estimation of the values creates a degree of uncertainty. This limitation must be considered by researchers and data analysts when drawing conclusions. Because subsurface data consists of fixed point values obtained by soil surveys, spatial interpolation is a suitable method to estimate the unknown areas between these point values. A distinction is made between deterministic and geostatistical interpolation methods, see Figure A.1.

Deterministic interpolation is based on mathematical functions to create surfaces from the measured points. Geostatistical interpolation uses the statistical properties of the measured points to create a surface. Commonly used spatial interpolation methods in GIS will be discussed in this paragraph.

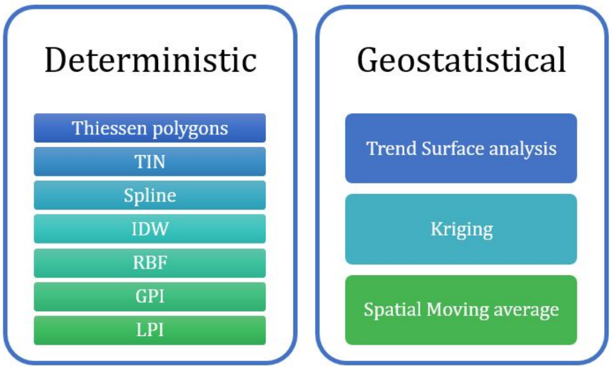



**Figure A.1:** Interpolation methods

## A.1 Thiessen Polygons

Considering the unknown values as equal to the nearest known value is a deterministic method of spatial interpolation called Thiessen polygons. This method creates polygons by drawing perpendicular lines between the known points. As a result area territories are established for a set of sampled points.

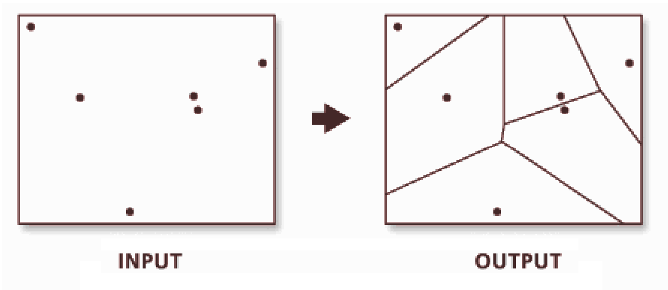



**Figure A.2:** Thiessen polygons
*Source:* Heywood et al. (2011)

## A.2 Triangulated Irregular Network

Another deterministic spatial interpolation method that creates polygons by drawing lines between known values is Triangular Irregular Network (TIN). TIN is a network of irregular triangles created by the connection of lines of the sampled values. Equations and trigonometry can be used to calculate any other value within the TIN, because each data point value is known (Heywood et al., 2011). This makes it possible to calculate the distance between the known points. A limitation of the method is that it is not possible to interpolate outside the sampled sites, because TIN relies on interpolating values between neighbouring data points.

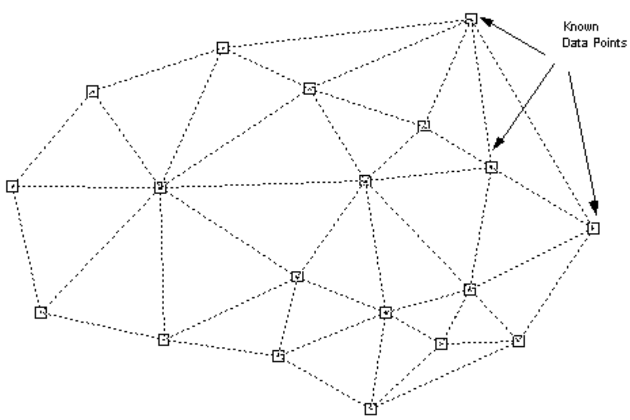



**Figure A.3:** TIN
*Source:* Softtree support (2017)

## A.3 Spatial Moving Average

The spatial moving average method calculates values based on the average values attached to neighbouring points within a user-defined area. Compared to Thiessen polygons and TIN the spatial moving average method is a geostatistical point interpolation method since it recalculates values and therewith excludes the known values. The method can still be useful in situations where the values of sampled sites are not exact.

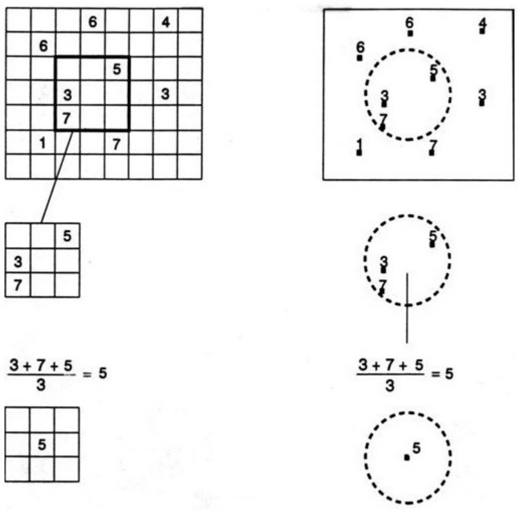



**Figure A.4:** Spatial moving average in raster and vector GIS
*Source:* Heywood et al. (2011)

## A.4 Global and Local Polynomial Interpolation

Global Polynomial Interpolation (GPI) fits a smooth surface to all measured points by means of mathematical functions (Esri, 2018a). The method of GPI can be used when the measured points vary slowly from region to region. Since the result is a flat descending surface, as shown in Figure A.5, and this often not responds with a real surface, mathematical polynomials are added. This technique is often referred to as trend surface, which will be explained in Section A.5.

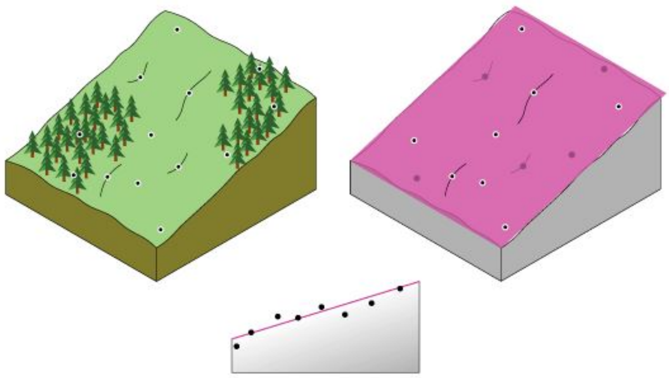


**Figure A.5:** Global Polynomial Interpolation
*Source:* Esri (2018a)

Local Polynomial Interpolation (LPI) also makes use of mathematical functions to fit a smooth surface to the measured points. However, the measured points are divided into neighbourhoods, as shown in Figure A.6. LPI captures short ranges variation in the landscape. Also for LPI, mathematical polynomials can be added to visualise the landscape more detailed. These polynomials are added for each neighbourhood and create the surface line, which can be seen in Figure A.7. The more polynomials are added, the more locations can be predicted (Esri, 2018c).

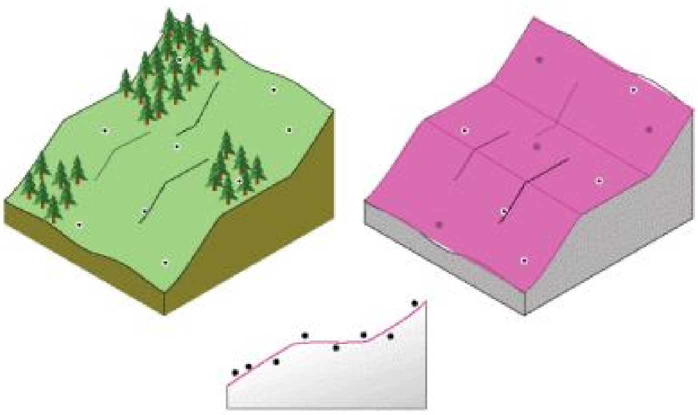


**Figure A.6:** Local Polynomial Interpolation
*Source:* Esri (2018c)

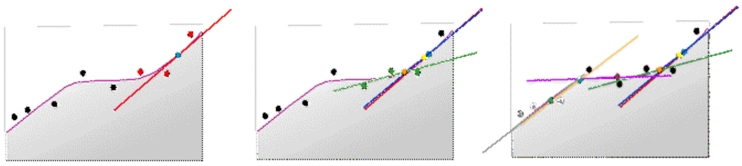


**Figure A.7:** LPI polynomials
*Source:* Esri (2018c)

## A.5 Trend Surface and Spline

Trend surface interpolation minimises the difference between the original value and the interpolated value of the data point by fitting a mathematically defined surface through all of the sampled data points, as shown in Figure A.8. This method fits a surface through 3D data points (x, y, z) instead of drawing a line through a 2D set of points (x, y). Trend surface interpolation is a global interpolator and a geostatistical method (Heywood et al., 2011). The trend surface can be made more complex by increasing the number of polynomials, as shown in Figure A.9. A first-order polynomial trend surface is a flat surface representing an inclined plane. A second-order polynomial trend surface is curved in one dimension in order to display the greatest height differences in the area. Third-order and fourth order polynomial trend surface respectively are curved into two and three dimensions making them more complex, see Figure A.9. Increasing the polynomials is limited by the number of data points. Excessive increase may cause an unrealistic representation.

A similar interpolation method is spline. The difference is that spline operates on local data points and that it is a deterministic spatial interpolation method. The formula for splines is:

$$S(x, y) = T(x, y) + \sum_{j=i}^{N} \lambda_j R(r_j) \tag{A.1}$$

Here j is 1,2 ... N, whereas N is the number of points. The coefficients that can be found by solving a system of linear equations is $\lambda_j$. The distance from point (x,y) to the j point is indicated by $r_j$.

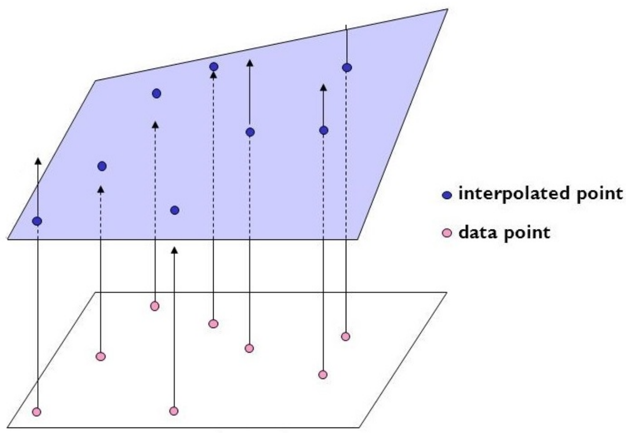



**Figure A.8:** Fitting a trend surface
*Source:* Heywood et al. (2011)

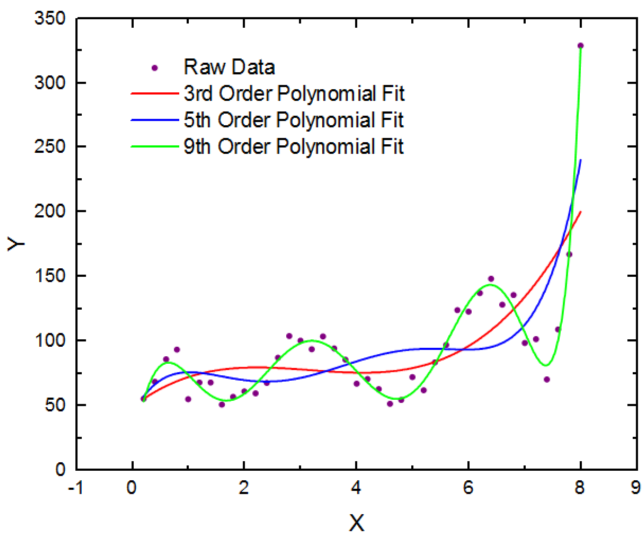



**Figure A.9:** Polynomial orders
*Source:* GITTA (2018)

## A.6 Radial Basis Functions

Radial Basis Functions (RBF) are a series of five exact interpolation methods. Because it is an exact technique the surface passes through the measured points. This corresponds to spline interpolation which also passes through the measured points, as shown in Figure A.12. Each RBF interpolation method indicates a special case of splines. The five methods that belong to RBF are: thin-plate spline, spline with tension, completely regularised spline, multiquadric function and inverse multiquadric function (Esri, 2018d).

When comparing RBF to an inexact interpolation methods, for example IDW, the differences can be seen. IDW will not provide predictions higher or lower than the measured value. As shown in Figure A.10, RBF can predict values higher or lower than the measured value. RBF methods are useful when creating a surface from a large number of data points. When large changes in the surface occur in short distances RBF is less useful (Esri, 2018d).

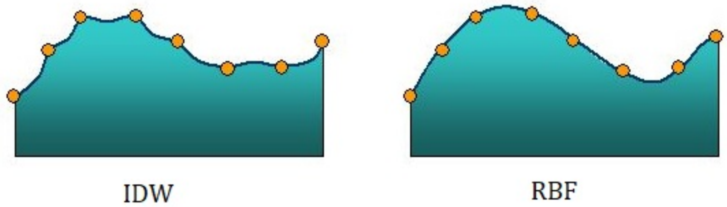



**Figure A.10:** IDW and RBF cross-section
*Source:* Esri (2018d)

## A.7 Inverse Distance Weighting and Kriging

The Inverse Distance Weighting (IDW) interpolation method uses a linearly weighted combination of known value points to determine unknown cell values. The unsampled value that is estimated is connected to the location of the sampled values in such a way that the greater the distance to the sampled value, the less influence this value has on the estimated value (Child, 2004). Compared to IDW kriging is a geostatistical interpolation method, but also uses the surrounding sampled values to make a prediction for an unsampled value. The general formula for both IDW and kriging is:

$$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z(S_i) \tag{A.2}$$

Here $Z(S_i)$ is the measured value at the $i^(th)$ location. $\lambda_i$ is the unknown weight for the measured value at the $i^(th)$ location. $S_0$ is the estimated location and N is the number of measured values. In IDW, the weight, $\lambda_i$, is only depended on the distance to the location of the estimated value. With the kriging interpolation method the weights are in addition to this also based on the overall spatial arrangement of the sampled data points.In Figure A.11 IDW and kriging are shown. Figure A.12 shows the difference between IDW, kriging and spline. The spline method passes exactly through the sampled points. IDW and kriging pass through none of the points. IDW moves between the points and kriging around the points.

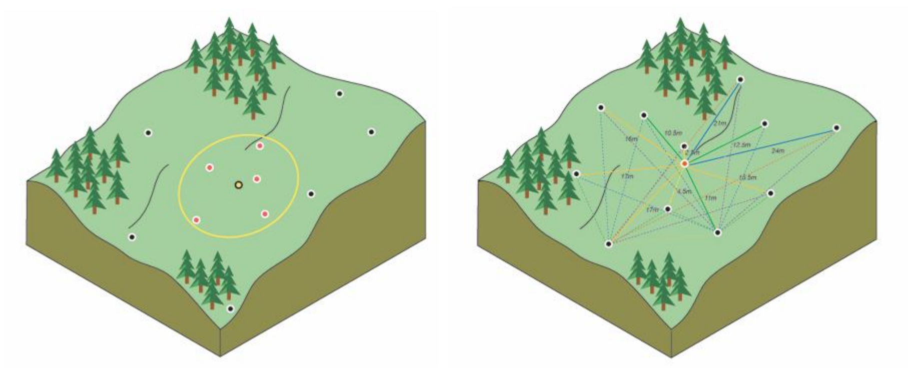


**Figure A.11:** a) IDW, b) Kriging
*Source:* a) Esri (2018a), b)(Esri, 2018b)

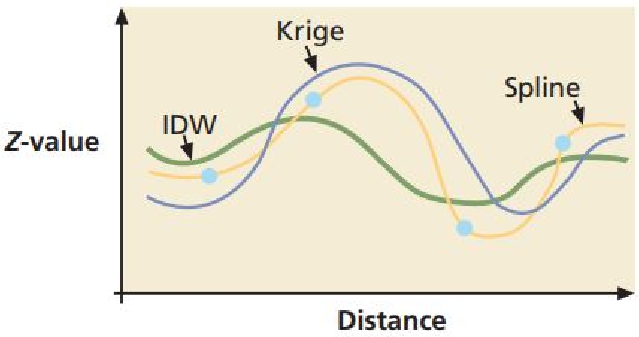



**Figure A.12:** IDW, kriging and spline
*Source:* Child (2004)

# APPENDIX B

# CASE STUDY

A case data set is used in order to explore the 3D functionalities and the support of the GIS software. This data set relates to a case study area where soil research is performed by Antea Group. Despite that the subsurface data of this case is used in this research as a sample to apply in the GIS software, it is an actual project based on real measurements. Due to the actuality of this project data, the data has been made anonymous.

## B.1 Case Area

The case area covers a location in the Netherlands. The location contains a contamination that originated from a chemical plant, referred to as company A. During the proceedings chemical substances or waste were spilled and polluted the soil and groundwater on the plant site. The main harmful substances in the contamination are nickel, chromium and (silver)bromide. The contamination is spreading through the groundwater in north-east direction. A large drinking water intake point is located nearby the chemical plant which might be threatened by the contamination. To judge the risk of the (future) situation a reliable model overview of the subsurface and groundwater is needed.

## B.2 Subsurface Data

In order to research the contamination in the case area different measurements have been performed, including monitoring wells, drilling and ERT measurements. In Figure B.1 the location of the monitoring wells, the ERT profiles, the water purification plant and company A are shown. This maps indicates the distribution between the measurements and the distance of the case area. Figure B.2 shows a smaller area close to the source of the contamination where drilling have been taken place.

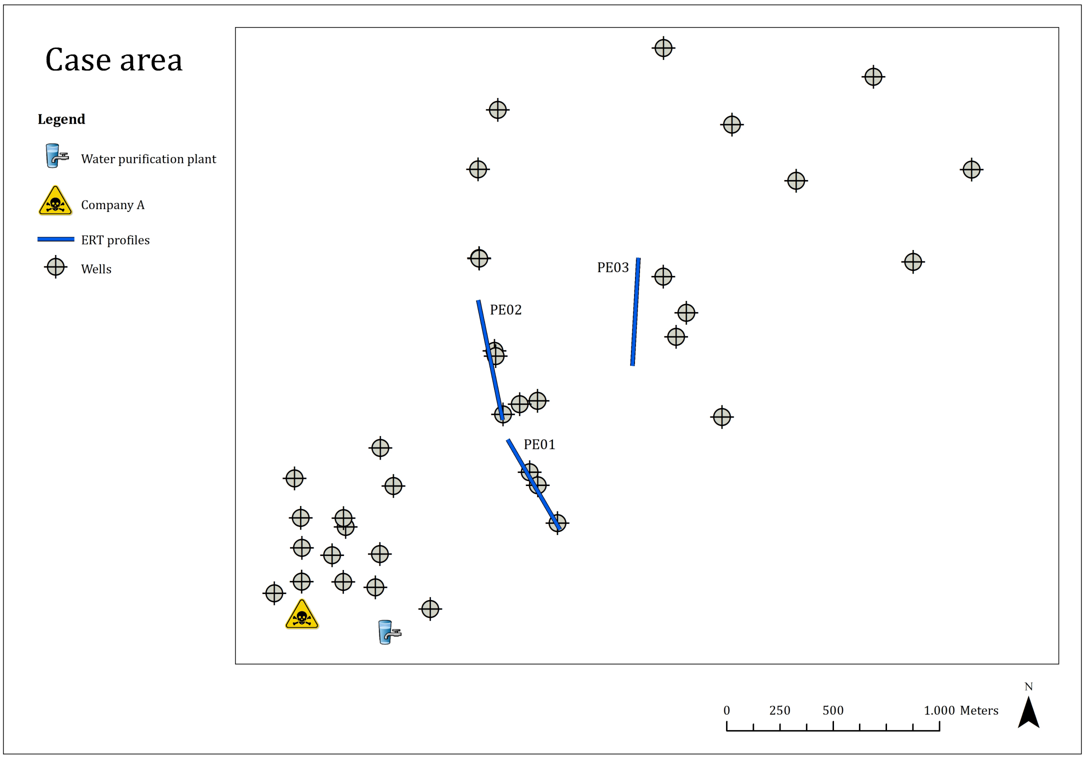



**Figure B.1:** Wells locations

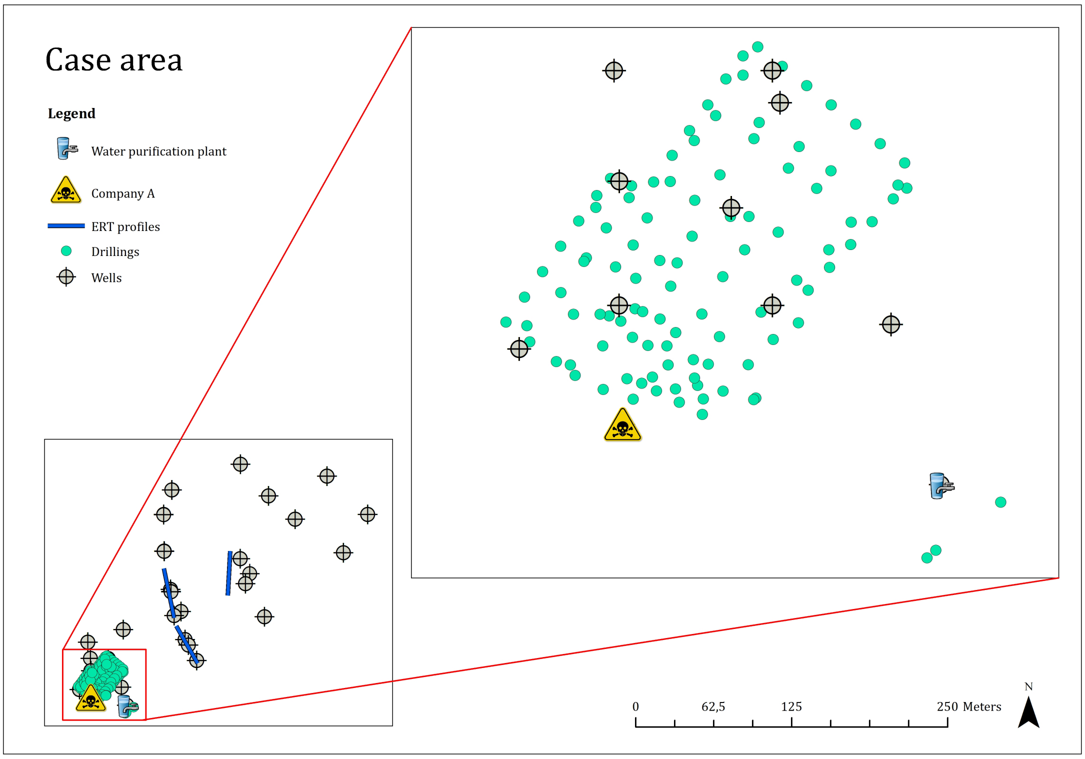



**Figure B.2:** Drilling locations

### B.2.1 Monitoring Wells

The monitoring wells have been placed in order to measure the level of the groundwater. The wells contain filters from which the information can be obtained. The wells and filters reach different depths to examine differences in depth levels. As mentioned in the theoretical framework, a difference in pressure and therefore groundwater level could arise from a confined soil layer. The data set is an Excel .CSV file consisting of various subsurface data parameters. In Table B.1 the parameters and metadata are provided. In Figure B.3 a visual representation of the soil parameters is shown.

| Parameter | Metadata |
|---|---|
| ID | The identification number of each monitoring well |
| Filter ID | The ID of each monitoring well followed by the identification number of the filter |
| From | Starting depth of the filter |
| To | End depth of the filter |
| X-coordinate | X-coordinate of the well |
| Y-coordinate | Y-coordinate of the well |
| MD | Total measured depth |
| NAP height | The NAP height of the ground level of the location of that well |
| From NAP height | NAP height minus From: the start depth of the filter |
| To NAP height | NAP height minus To: the end depth of the filter on NAP level |
| M-bkpb, year | Meters between the top of the well to the groundwater of a certain year |
| Groundwater level, year | NAP height minus M-bkpb: actual groundwater level on NAP level of a certain year |

**Table B.1:** Well data parameters

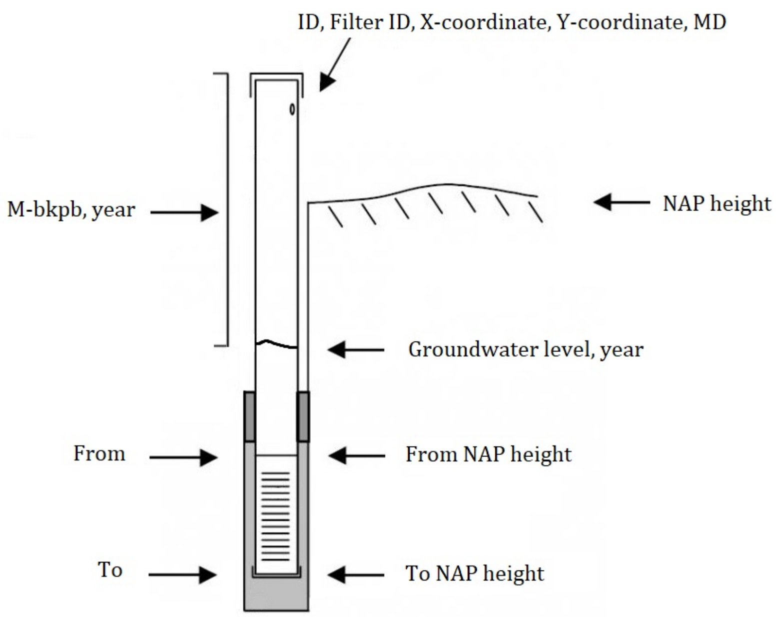



**Figure B.3:** Well data parameters

### B.2.2 Soil Drilling

Soil drilling has been taken place around company A and the water purification plant to examine the soil composition. The data obtained from the drilling shows from which soil types the subsurface is built up. The data is an Excel .CSV file consisting of various parameters. In Table B.2 the parameters and meta data are provided. In Figure B.4 a visual representation of the soil parameters is shown.

| Parameter | Metadata |
|---|---|
| ID | The identification number of each soil drilling |
| From | Starting depth drill survey |
| To | End depth drill survey |
| X-coordinate | Z-coordinate of the drilling |
| Y-coordinate | Y-coordinate of the drilling |
| MD | Total measured depth |
| Soil type | Description of the soil type |
| Soil type code | Corresponding code for the type of soil |

**Table B.2:** Drilling data parameters

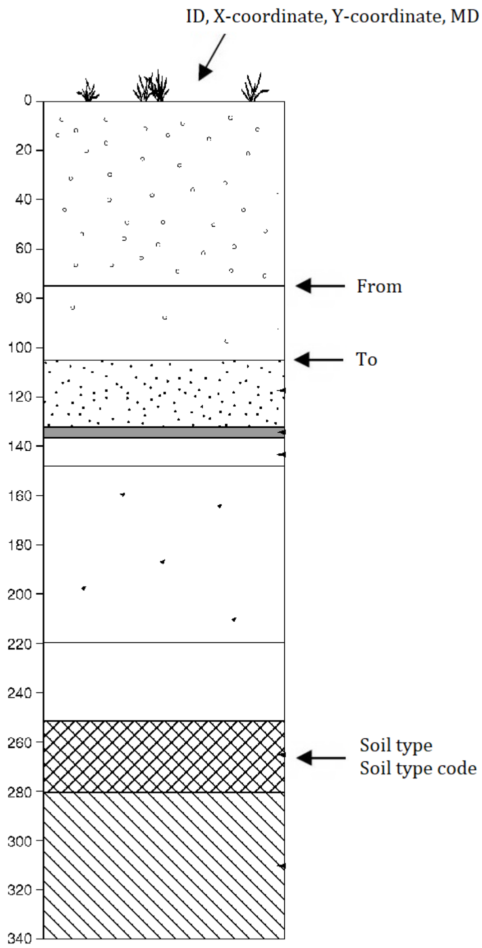



**Figure B.4:** Drilling data parameters

### B.2.3 ERT Profiles

Geo-electrical surveys are carried out in the case area. Three ERT profiles have been acquired in which imaged the soil composition and the contamination. The profiles were set up to gain insight about the situation and to suggest a further approach to follow the head of the contamination. In Figure B.5 the three profiles are shown corresponding to the profiles in Figure B.1. Profile PE03 is deliberately placed in a clean part of the case area to measure and image a natural situation of the subsurface. Brown coloured stains are clay lenses and contain a higher electrical resistivity, meaning that this soil material has a high resistance.

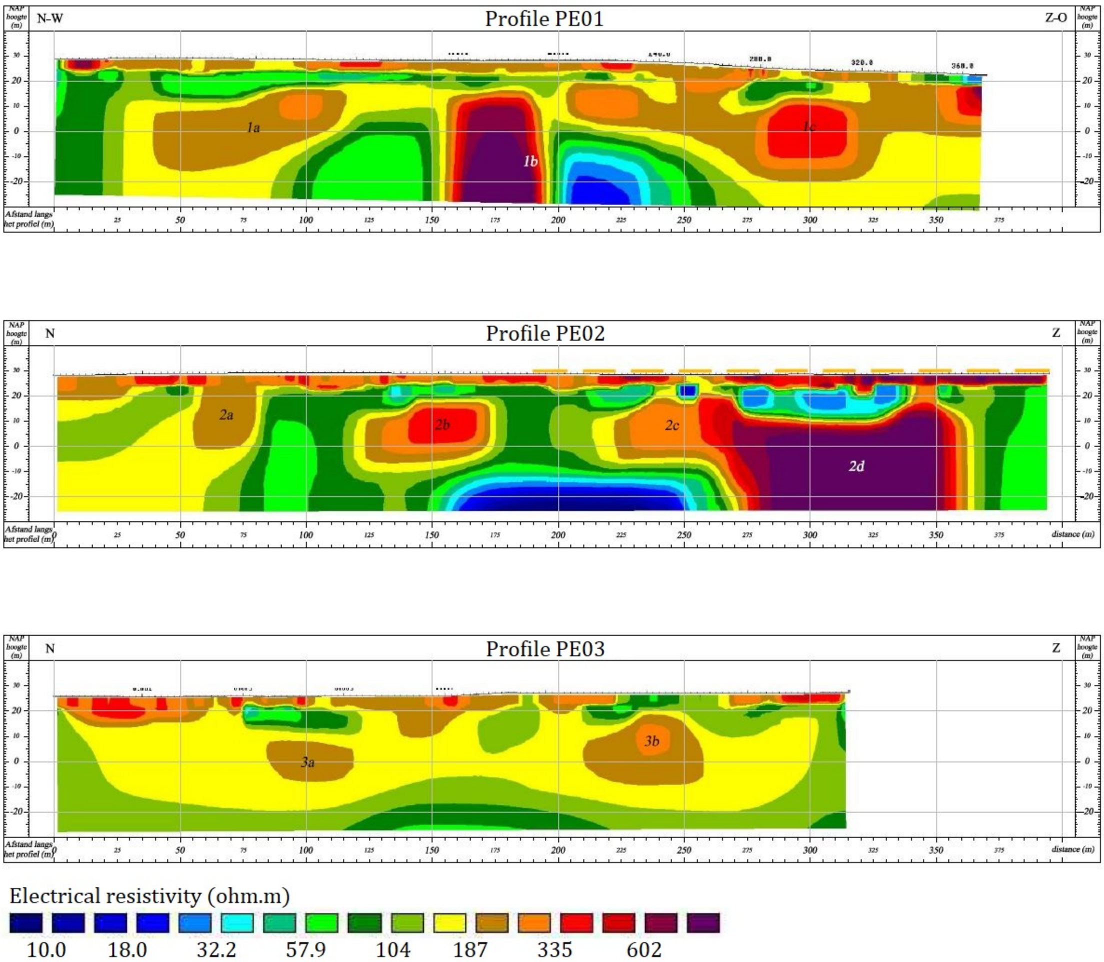



**Figure B.5:** ERT profiles

When looking at profile PE01 and PE02 there are clear differences. The spots in blue indicate a good electrical conductivity or, conversely, low specific electrical resistance. There can be two causes for the blue spots with a low electrical resistivity. First, excavations could have taken place where after stones and boulders have been deposited making the subsurface very permeable for groundwater. Second, high concentrations of bromide could be present in the subsurface which greatly reduces the electrical resistivity. The deep filters in the monitoring wells placed at the locations of the ERT profiles showed that there are actually extremely high concentrations of bromide present, which indicates the contamination.

# APPENDIX C

# REQUIREMENTS

| Must haves | Should haves |
|---|---|
| • Support of standard GIS data file formats (e.g. SHP, LAS, TIN, XML, GML, (GEO)TIFF, ASCII, BMP, XLSX, TXT, CSV, JPG/JPEG, PNG, GIF) | • Creation and layout of 2D cross-sections and maps of 3D output |
| • Support of different interpolations methods | • Connection to external database |
| • Manual editing and processing of outputs | • Ability to work without internet connection |
| • Calculation of volumes | • Import of SIKB0101 and GEF-files (Dutch standard for probing data) |
| • Support of both Surface- and Volume-based 3D outputs | • Option to share output without sharing data set |
| • Automatic updating of outputs and models when adjusting data | • Option to interactively view output without downloading software or purchasing license |
| • Input of soil characteristics/parameters during analyses | • Recognition of ERT profiles (not just points) |
| • Performance of queries on data | • Some insights into black box |
| • Input and execution of prognoses and plannings | • Extension to time-dimension (4D) |

**Table C.1:** Functionality requirements

| Must haves | Should haves |
|---|---|
| • Option to interactively zoom, pan, slice, tilt, rotate and see through the output<br>• Clear interface and toolbox that can be explored within few days<br>• Software and tools accessible for intermediate, advanced and expert users<br>• Integration with other tools/applications (e.g. Python, ArcGIS, MODFLOW, FEFLOW)<br>• Ability to expand to other domain fields<br>• Fancy, intuitive, structured interface | • Option to undo performed action<br>• Multiple viewing screens<br>• Customisation of settings, interface and visualisation options |

**Table C.2:** Usability requirements

| Must haves | Should haves |
|---|---|
| • Hardly to no crashes during session<br>• Provision of error code or explanation in case of failure<br>• Production of results in reasonable amount of time relative to data size<br>• No slow down when importing large or many data files (e.g. $\leq$ 100 MB TIFF-files) | • Automatic saving and/or recalling data backup<br>• Possibility of prioritising actions during execution of tools, tasks and analyses |

**Table C.3:** Reliability requirements

| Must haves | Should haves |
|---|---|
| • Online help and support platform<br>• User guide/manual<br>• Training material<br>• Demo version | • Webservices/WMS<br>• Interactive forum<br>• Webinars/YouTube tutorials<br>• Customer respond within work week |

**Table C.4:** Vendor requirements

| Must haves | Should haves |
|---|---|
| • Tutorial and support included in purchase price | • License linked to account, not to a computer<br>• Option to purchase multiple-license type<br>• Option to purchase software cloud service to store data |

**Table C.5:** Cost requirements

# APPENDIX D

## ASSIGNED SCORES

In table D.1 the scores for each sub-criteria are provided per alternative. Here, a score of 1 is the least desirable and a score of 5 is the most desirable.

| Criteria | Sub-criteria | Esri GIS | Leapfrog Works | Voxler | GeoScene 3D | QGIS | Max. |
|---|---|---|---|---|---|---|---|
| 1. Functionality | Included functionality | 2 | 4 | 2 | 3 | 1 | 5 |
| | Data formats | 4 | 4 | 4 | 4 | 3 | 5 |
| | Data visualisation | 3 | 5 | 3 | 5 | 3 | 5 |
| | Adaptability | 5 | 5 | 3 | 4 | 4 | 5 |
| | Data sharing | 4 | 5 | 3 | 3 | 4 | 5 |
| 2. Usability | User interface | 3 | 4 | 4 | 2 | 3 | 5 |
| | User types | 2 | 4 | 4 | 3 | 2 | 5 |
| | Ease of use | 3 | 3 | 4 | 2 | 2 | 5 |
| | Domain variety | 5 | 4 | 3 | 3 | 5 | 5 |
| | Error reporting | 2 | 2 | 2 | 2 | 2 | 5 |
| 3. Reliability | Time behaviour | 2 | 3 | 3 | 2 | 2 | 5 |
| | Robustness | 2 | 4 | 3 | 2 | 1 | 5 |
| | Backup and recovery | 3 | 4 | 3 | 3 | 3 | 5 |
| 4. Vendor | User manual | 4 | 5 | 5 | 1 | 5 | 5 |
| | Tutorial | 5 | 5 | 5 | 3 | 5 | 5 |
| | Demo version | 5 | 4 | 5 | 4 | 5 | 5 |
| | Training | 3 | 4 | 4 | 2 | 4 | 5 |
| | Forum | 5 | 5 | 5 | 1 | 2 | 5 |
| 5. Cost | Software license | 2 | 3 | 4 | 3 | 5 | 5 |
| | Installation | 4 | 4 | 5 | 4 | 5 | 5 |
| | Training | 2 | 4 | 4 | 4 | 5 | 5 |
| | Maintenance | 2 | 4 | 4 | 2 | 5 | 5 |
| | Support service | 5 | 5 | 5 | 4 | 5 | 5 |
| | $\sum$ | 87 | 94 | 66 | 77 | 81 | 115 |

**Table D.1:** Scores per sub-criteria

# APPENDIX E

# TECHNICAL SPECIFICATIONS

The technical specifications and system requirements of Leapfrog Works are provided in this appendix. The information is based on Leapfrog Works 2.2.1, November 2018.

## TECHNICAL SPECIFICATIONS

### 3D Modelling

- Full 3D modelling
- Fast Radial Basis Function(RBF) implicit interpolation engine
- Dynamic update with linked or reloaded data

### Geological modelling

- Model geology from borehole, structural, GIS, 2D grid, map, point, polyline, mesh/surface and historical cross section data
- Deposition, intrusion, erosion, stratigraphic sequence, vein, vein system, and fault modelling methods
- Structural modelling with form interpolants, stereonets and structural trends

### Numeric modelling

- Interpolate numeric values from boreholes, geotechnical investigations, well screens or points
- Spheroidal and linear variance controls
- Apply anisotrophic trends
- Create distance buffers

### Attributes

- Create user defined attributes to volumes
- Audit object history and properties
- Reference codes for job tracking

### Surfaces

- Create meshes from points, polylines and other mesh parts
- Repair and move meshes
- Extract top and bottom surfaces from 3D volumes
- Create contours and import photogrammetry surfaces

### Site investigations

- Borehole planning
- Borehole correlation of lithology with numeric downhole traces

### Cross-sections

- Create cross sections from model volumes, surfaces and boreholes
- Layout cross sections for presentation
- Generate cross and long sections relative to an alignment

### Model management

- Central model management interoperability:
  - Version controlled models in central repository
  - Review, collaborate and maintain audit trail of models

### Visualisation

- 3D manipulation, layer control, slice, sections in scene, draped GIS data
- Publish 3D scene to web browser with View upload
- Versatile colourmaps
- Saved scenes for interactive viewing in Leapfrog Viewer
- Multiple 3D views
- Create movies from scenes

DATA INPUTS

**Elevation grids**

- Arc/Info ASCII Grid Files (.asc, .txt)
- Arc/Info Binary Grid Files (.adf)
- Digital Elevation Model Files (.dem)
- Surfer ASCII or Binary Grid Files (.grd)
- SRTM Files (.hgt)
- ESRI .hdr Labelled Image Files (.img, .bil)
- GeoTIFF Image Files (.tiff, .tif)

**GIS Vector data**

- Shape Files (.shp)
- MapInfo Files (.tab, .mif)
- ESRI Personal GeoDatabase Files (.mdb, .accdb)
- MapInfo Batch File (.xml)
- ESRI Geodatabase (.gdb)

**2D grids**

- Arc/Info ASCII Grid (.asc, .txt)
- Arco/Info Binary Grid (.adf)
- Digital Elevation Model (.dem)
- Intergraph ERDAS ER Mapper 2D Grid (.ers)
- ESRI .hdr Labelled Image (.img, .bil)
- SRTM Files (.hgt)
- Surfer ASCII or Binary Grid (.grd)

**Borehole data**

- AGS Files (.ags) v3.1 & 4.0
- gINT projects (.gpj) via ODBC
- CSV Text File (.csv)
- ASCII Text File (.asc)
- Plain Text Files (.txt)
- Data Files (.dat)
- Via ODBC (.mdb, .accdb)
- TSV Text Files (.TSV)

**Points**

- CSV Files (.csv)
- ASCII Text Files (.asc)
- DXF Files (.dxf) • DWG Files (.dwg)
- Leapfrog Works 3D Point Data Files (.pl3, .ara)
- Via ODBC (.mdb, .accdb)

**Maps/Photos/Cross sections**

- PNG Files (.png)
- JPEG Files (.jpg, .jpeg)
- TIFF and GeoTIFF Files (.tiff, .tif)
- Bitmap Files (.bmp)
- Graphics Interchange Format Files (.gif)

**Designs**

- DXF Files (.dxf) versions R13 - R27
- DWG Files (.dwg) versions R13 - R27

**Meshes**

- Leapfrog Files (.msh, .ara)
- Leapfrog Model Files (.lfm)
- DXF Files (.dxf)
- DXF Polyface Files (.dxf)
- DWG Files (.dwg)
- Textured Alias Wavefront Object (.obj)

**Polylines**

- Drawing Interchange Polylines (.dxf)
- DWG Files (.dwg)
- Leapfrog Polylines (.lfpl, .csv, .txt)

**Flow models**

- ModFlow Models (.nam, .mf, .mfn)
- FEFLOW Models (.fem, .dac)

**Colour gradients**

- Geosoft Colour Files (.tbl)
- ERMapper Lookup Tables (.lut)
- MapInfo Colour Files (.clr)
- Leapfrog Colour Files (.lfc

DATA OUTPUTS

**Elevation/Thickness grids**

- Arc/Info ASCII Grid Files (.asc)
- ESRI .hdr Labelled Files (.bil)
- ENVI Raster Image Files (.img)
- Surfer ASCII Grid Files (.grd)

**GIS Vector data**

- Shape Files (.shp)

**Maps and Photos**

- Geo Tiff Files (.tif, .tiff)

**Borehole data**

- CSV Files (.csv)
- IFC v4 Files (.ifc)

**Points**

- CSV Files (.csv)
- DXF Files (.dxf)
- DWG Files (.dwg)

**Polylines**

- Leapfrog Polylines (.lfpl, .csv)
- Drawing Interchange Polylines (.dxf)
- DWG Files (.dwg)

**Scenes**

- Upload to View web application (web browser)
- Leapfrog Scene (Viewer/Aspect)

**Movies**

- Movie Files (.wmv)

**Rendered images**

- Image Files (.png, .jpg, .jpeg)

**Meshes (Model surfaces/Output volumes/Interpolant surfaces)**

- Leapfrog Files (.msh)
- DXF Files (.dxf)
- DWG Files (.dwg)
- DGN Files (.dgn)
- IFC v4 Files (.ifc) with user defined atributes
- Alias Wavefront Object Files (.obj)

**Cross section layouts**

- PDF Files (.pdf)
- Scalable Vector Graphics Files (.svg)
- PNG Image Files (.png)
- GeoTIFF Files (.tiff, .tif)

**Cross section evaluations**

- DXF Files (.dxf)
- DWG Files (.dwg)

**Flow models**

- ModFlow Models (.nam)
- FEFLOW Models (.fem)

## SYSTEM REQUIREMENTS

| | Supported | Recommended |
|---|---|---|
| **Operating System** | Windows 7 (64bit) | Windows 7 (64bit) |
| | Windows 8 (64bit) | |
| | Windows 8.1 (64bit) | Windows 8.1 (64bit) |
| | Windows 10 (64bit) | Windows 10 (64bit) |
| **Processor** | IntelCore™ i3, i5 or i7 CPU<br>Intel (2nd Generation or later) | Core™ i7-6800k |
| | | Intel Core™i7-6900k |
| | | Intel Core™ i7-7700 |
| | Intel Xeon™ | Intel Xeon™ E5-2630 v3 |
| **System memory** | 4 GB (Minimum) | 32GB RAM |
| **Free hard disk space** | Legacy spinning hard disk | Solid state disk drive |
| | 250 GB capacity | 1 TB capacity |
| | 25 GB free space | 100 GB free space |
| **Display resolution** | 1280 x 720 (Minimum) | 1920 x 1080 (HD) or better |
| | Single display unit | Multiple display setup |
| **Graphics** | **Nvidia™ (Desktop hardware)** | |
| | GeForce 700 series | |
| | GeForce 900 series | GeForce GTX 950i |
| | GeForce 1000 series | GeForce GTX 1050 Ti |
| | Quadro 600 series and above | GeForce GTX 1050 |
| | Quadro K series | |
| | Quadro P series | |
| | **Nvidia™ (Mobile hardware)** | |
| | GeForce 700M series | |
| | GeForce 800M series | |
| | GeForce 900M series | GeForce GTX 950M |
| | GeForce 1000 series | GeForce GTX 1050M[6] |
| | Quadro M series | |
| | Quadro P Mobile series | |

## SYSTEM REQUIREMENTS

| | Supported | Recommended |
|---|---|---|
| **Graphics** | **AMD™/ATI™ (Desktop hardware)** | |
| | Radeon HD 8000 series | Radeon RX 460 |
| | Radeon R5 series | Radeon RX 570 |
| | Radeon R7 series | |
| | Radeon R9 series | |
| | Radeon RX series | |
| | Firepro V series | |
| | Firepro W series | |
| | **AMD™ / ATI™ (Mobile hardware)** | |
| | Radeon HD 8000 series | Radeon R9 M375 |
| | Radeon R5 series | Radeon RX 460 |
| | Radeon R7 series | |
| | Radeon R9 series | |
| | Radeon RX series | |
| | FirePro M series | |
| | **Intel™ Integrated Graphics** | |
| | HD Graphics 2000 (Generation 2 or later) | |
| | HD Graphics 510 (Generation 6 or later) | |

# APPENDIX F

# WORKING METHOD

This appendix explains the abbreviated procedure and the selected parameters behind the creation of the 3D outputs of the cases mentioned in Section 5.2 in Leapfrog Works.

## F.1 Drilling Data

This working method explains the steps taken to import, visualise and predict the drilling measurements.

### F.1.1 Input

The drilling data is imported in Leapfrog Works as borehole data as follows:

- The drilling data is imported in Leapfrog Works as boreholes
- The table columns ID, X, Y, Z, and Max. depth are imported indicating the collars
- The table columns ID, From, To, Soil Types and Bromide values indicating the intervals
- Omit is assigned to missing intervals
- Duplicate intervals are ignored

### F.1.2 Processing

As boreholes are successfully imported these are evaluated *(only possible when a geological model is present)* as follows:

- New evaluation is selected for boreholes of case area
- The geological model of the case area is selected as input
- Warnings, errors and invalid values are fixed or deliberately ignored

### F.1.3 Output

When the boreholes are imported and evaluated the layout is set as follows:

- The soil types are displayed along the boreholes traces
- The borehole traces are set as solid traces with a radius of 11
- The colours for the soil types are set light yellow for sand, grey for gravel and orange for loam
- Graphs are added along the borehole traces for bromide concentrations
- The bromide colour ramp is set for the graphs ranging from 0 to 20
- When visualising the planned boreholes the surrounding traces are set to planar and
- The ground level is added as reference

## F.2 Geological Structure

This working method explains the steps taken to create the geological model of the case area.

### F.2.1 Input

The input data for the geological model is imported as follows:

- The borehole data is imported as mentioned in Subsection F.1.1
- Soil types data is indicated as Base Lithology Column while assigning columns
- Warnings, errors and invalid values are fixed or deliberately ignored

### F.2.2 Processing

As the data is successfully imported the geological model is built as follows:

- A new geological model is created from the soil type data of the case area
- The surface resolution is set to 200 (adaptive)
- The boundary extent is set to the drilling data
- Five deposit layers are built
- Chronology is set to: gravel, loam, sand
- Output volumes are generated from the built deposit layers
- Fault system can be created if desired

### F.2.3 Output

After the geological model is built the layout is set as follows:

- The colours for the soil types within the geological model are set light yellow for sand, grey for gravel and orange for loam
- Smooth faces for the geological layers are selected
- Locations of water areas are made transparent
- Boreholes, groundwater level and ground level are added as reference
- The geological model is sliced in half to display the inside of the model

## F.3 Differences in Groundwater Level

This working method explains the steps taken to import groundwater level data, create surfaces and visualise these.

### F.3.1 Input

The measurement data containing groundwater levels is imported in Leapfrog Works as point data as follows:

- The groundwater levels are imported in Leapfrog Works as point data
- The table columns ID, X, Y and Z are assigned to each point
- Warnings, errors and invalid values are fixed or deliberately ignored

### F.3.2 Processing

As the data is successfully imported as points these are interpolated to surfaces as follows:

- A new mesh is created from the points containing groundwater levels
- The extent is set to the boreholes boundary
- The resolution is set to 30 (adaptive)

### F.3.3 Output

When surfaces for two or more groundwater levels are created these are visualised as follows:

- The groundwater levels are visualised by flat colour, in red and blue
- The surfaces are vertical exaggerated with a scale of 120
- The ground level, borehole traces and lithology are added as reference

## F.4 Contamination Plume

This working method explains the steps taken to create the numeric model indicating the contamination plume of bromide.

### F.4.1 Input

The numeric values of the bromide concentration are imported as point data as follows:

- The bromide values are imported in Leapfrog Works as point data
- The table columns ID, X, Y, Z and bromide concentrations values are assigned to each point
- Warnings, errors and invalid values are fixed or deliberately ignored

### F.4.2 Processing

The numeric model is created by interpolating the concentration point data as follows:

- A numerical model is created by RBF interpolation
- The boundary is set to the borehole data extent
- The default resolution of 200 is managed
- Orientation is set to (dip, dip-azimuth, pitch) = (0, 0, 90)
- Lengths is set to (max, int, min) = (15, 20, 1)
- Threshold classes are set to: $< 1$, 1 - 5, 5 - 10, 10 - 50, 50 - 100 and $> 100$

### F.4.3 Output

The contamination plume is visualised as follows:

- The threshold classes are coloured by means of a bromide colour ramp
- The bromide colour ramp ranges from 0 to 100 in rainbow colours
- The threshold classes, from low to high, are consecutively set to less transparent
- The borehole traces and ground level are added as reference
- The plume is sliced in half to visualise the core of the contamination

## F.5 Civil Engineering Design

This working method explains the steps taken to visualise a civil engineering design combined with subsurface data.

### F.5.1 Input

The civil engineering file is imported as designs as follows:

- The files are imported as AutoCAD files (.DWG, .DXF)

### F.5.2 Processing

The georeferencing of the civil engineering design is done as follows:

- The files are moved by shifting the axes and entering the coordinates

### F.5.3 Output

The civil engineering design is visualised as follows:

- The design is flat coloured in grey
- Smooth faces and edges are disabled