3D MODELLING OF UNDERGROUND SPACE FOR URBAN PLANNING AND MANAGEMENT – PROVIDING BASIC PLANNING INSIGHT

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ABSTRACT

One of the current trends in urban planning and design is the promotion of more compact, intensive, and multi-functional space use. The realization and sustainable management of intensive urban development require a good understanding of interactions between land surface developments, their supporting infrastructures and subsurface conditions. A good understanding of surface and subsurface conditions and their interactions depends on communication of various professions due to different characteristics of surface/subsurface structures. Specialised language, probable divergent perspectives, and different levels of knowledge through a multidisciplinary communication have led scientific attentions toward creation of an integrated context for intensive urban developments. In principle, 3D city models should provide a means for information integration, interpretation, simulation, and simplification. However, the integrated storage, management, and presentation of complex data on surface and subsurface features and conditions are not straightforward. Relatively few investigations about integrated modelling of surface and subsurface structures for effective knowledge sharing and communication among specialists have been carried out so far. This study aims to enhance multidisciplinary communication between urban planners and subsurface specialists by raising their awareness of key interactions between surface and subsurface structures, connecting their multi-disciplines based on their demand, and providing their integration with a three-dimensional model. In this regard, five successive steps are operationalised in this research. First, interactions between surface and subsurface structures are studied. Actual and potential are formulated categories of surface/subsurface interactions by this study. The actual interactions by means of any physical connection between surface/subsurface structures reveal their potential interactions in terms of bilateral solution finding toward optimal urban development. Solutions could be either productive, protective, or provisional depending on the context. Second, several in-depth interviews with planners and specialists are conducted to narrow the focus of study on a specific subject. The solution is specified based on the information from these sources regarding any issue of the context which persuades them to communicate. Third, based on the demand of specialists and planners, related data with the capability of describing conditions of surface and subsurface and their interactions regarding the issue is collected, harmonised, and transformed. Data harmonisation in terms of spatial unit, scale, format, and projection; and data transformation in terms of creating a coherent and understandable set of information from specialised data for a multidisciplinary communication. Specialised data are transformed to understandable contents by developing indices and defining correlations between different data and their impacts on each other using Principle Component Analysis (PCA). The understandable contents refer to a meaningful interpretation of surface and subsurface conditions and their interactions for both parties (planners and specialists). Fourth, a 3D modelling approach for an integrated-object-generation is proposed. Existing 3D modelling methods are compared based on visual efficiency, level of detail, and understandability. A new approach, named “procedural modelling” based on the L-system technique, was evaluated as the most effective 3D modelling technique for an integrated platform of surface and subsurface features and structures. The L-system modelling technique supports integrated 3D object-oriented concepts with a range of levels of detail, based on rule scripting. The ESRI CityEngine platform is used to develop a 3D rule-based model. Existing spatial data for the Bloemhof neighbourhood, Rotterdam, is used to test the model and demonstrate its capabilities. Fifth, the usefulness of the model is validated through a focus group discussion and questionnaire involving several planners and specialists who are involved in a current development project of Bloemhof. The result shows an improved visualisation of surface/subsurface features and structures, flexibility in the provision of appropriate levels of detail, data updating opportunities, improved interaction, and adaptability of the model to different applications. Further enhancements can be made according to expressed user demands. However, the test also shows that the model has quite high demands in terms of information processing infrastructure.

Keywords: 3D modelling, subsurface, multidisciplinary communication, planning, CityEngine.

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GLOSSARY OF TERMS

Underground structure:	Artificial and natural underground environments (i.e., foundation, heritage, transport, and utility as artificial environments; and space, groundwater, geomaterial, and geothermal energy as natural environments).
Urban need:	A need of any involved expert in urban (re)development to understand and utilise any information related to social, environmental, and economic aspects of a (re)development plan in a city (Mielby et al., 2017).
Subsurface specialists:	Groups of specialists such as civil engineers, geologists, hydrologists, geo-technicians, and archaeologists.
Data transformation:	Transformation of specialised data (e.g., archaeological, geological, and hydrological) to comprehensible contents for urban planners and subsurface specialists regarding the implementation of several spatial, statistical, and geostatistical analytical techniques.
Information enrichment:	Integration of various types of information describing actual and potential interactions between surface and subsurface structures in terms of a realistic visualisation, an effective interpretation, and efficient technical support.
Surface/subsurface interactions:	A cyclic process that surface and subsurface structures (natural and artificial) affect each other. The effects could be positive or negative, and regarding (re)development purposes of an area, they should be managed, controlled, and effectively exploited.
Specialists interactions:	Activity of communicating (sharing knowledge), working (having collaborative discussions), and planning (making decisions) between urban planners and subsurface specialists regarding involvement of subsurface structures in urban (re)development considerations.

1. INTRODUCTION

Involvement of underground space in urban planning considerations would bring about opportunities of urban (re)development, infrastructure management/improvement, and cost-efficient constructions for cities worldwide (Broere, 2016). To this end, planners and subsurface specialists should have effective communications to exchange their knowledge (Bonsor et al., 2017). However, establishment of these communications requires a certain level of awareness regarding specialised information to understand each other. Therefore, planners and subsurface specialists need a common language to enhance their communications. The more comprehensible the communication contents, the more effective decisions might be made by planners. Thus, planners' perspective regarding underground values and subsurface specialists' knowledge regarding underground role in urban planning should be transformed into understandable concepts for their communications. To be specific, a three-dimensional (3D) model would provide planners and subsurface specialists with a demand-driven knowledge transformation considering appropriate level of detail (Houlding, 2012). Regarding the importance of mentioned issue in planning process, many scientific efforts have been taken to enhance planners' and subsurface specialists' interactions; however, an integrated and comprehensive knowledge transformation and information visualization have not been yet achieved (Liu et al., 2017; Schokker et al., 2017). This research aims to narrow the gap by developing an integrated 3D model of surface/subsurface structures and their interactions based on transformed specialised data to comprehensible contents for planners and subsurface specialists to support their communications. The model is implemented in a case area fitted with mentioned issues to examine the reliability and usefulness of the model.

This section explains background and justification of the research including social problem that research aims to address, focus of the study which explains research problem regarding unknown statements that should be discovered, and identification of research objective and sub-objectives leading to research questions. In the end, thesis structure is explained regarding the content of each chapter.

1.1. Background and justification

Integration of underground space use into city-scale planning strategies proposes a new paradigm to support urban (re)development process (Li, Parriaux, Thalmann, & Li, 2013). Currently, dynamic urban environment and the subsequent space deficiency, excessive energy consumption, and environmental changes have become several essential problems of cities worldwide. Accordingly, planning authorities sought to improve the situation regarding an optimum acquisition of potential resources. This leads their consideration toward underground space as a "societal asset" to contribute to managing these issues (Admiraal & Cornaro, 2016b, p. 214).

The underground can provide cities with space, groundwater, geomaterial, and geothermal energy resources (Li, Parriaux, et al., 2013). Meanwhile, this valuable resource is non-renewable, and its involvement in planning process should be prudent (Bartel & Janssen, 2016). Thus, in case of sound (re)development planning (i.e., balanced social, economic, and environmental urban needs), underground potential opportunities would provide cities with optimum space utilisation, efficient energy consumption, and environmental coping strategies (Broere, 2016). Consequently, an integrated (re)development paradigm including both above- and under-ground space would be resulted.

For a simultaneous consideration of above- and under-ground space in (re)development process, inclusive and integrated planning is required (Kaliampakos, Benardos, Mavrikos, & Panagiotopoulos, 2016). Indeed, the transference of some urban functions and services to the beneath of the surface would form a complex underground structure (Kaliampakos et al., 2016). Therefore, planners should notice limitations and constraints assigned to the use of underground. Soil bearing capacity, probability of its subsidence, shallow groundwater depth, and subsequently water pollution are several physical subsurface challenges that might limit urban (re)development (Zhu, Huang, Li, Zhang, & Liu, 2016). Moreover, above- and under-ground structures are interconnected. For instance, aboveground constructions require foundations, and below-ground constructions require commuting networks and air conditioning systems. Therefore, planners should be able to respond to possible mutual interactions between surface and subsurface structures, since development of one regardless of the other might negatively affect both over time (Li, Parriaux, et al., 2013). Hence, inclusive analysis of current situation regarding possibilities and impossibilities would guide planners toward a broad view of (re)development opportunities, consequences, and probable future status. To this end, in parallel with the analysis of observable aboveground structure, planners need a comprehensive perception of hidden underground structures.

Developing a comprehensive vision of underground structures for urban planners requires an interdisciplinary approach. Regarding heterogeneous characteristics of underground structures, several experts like geologists, archaeologists, hydrologists, civil engineers, architects, urban planners, geo-technicians, etc., are involved in underground-related studies with their specific perspectives, knowledge, and disciplines. The combination of these fragmented disciplines into one main purpose would help planners to consider point of views of all relevant professions in urban (re)development (Besner, 2016). This combination should be tailored to planners' demand and subsurface specialists' information. However, urban planners are often relatively unaware of underground structures, its contribution to overcoming mentioned urban challenges, and related specialised information (Admiraal & Cornaro, 2016a). In addition, subsurface specialists are relatively unaware of underground role in urban planning process. Therefore, purposeful communications among subsurface specialists and urban planners are required for a sufficient awareness and efficient operation.

Cross-discipline communications among subsurface specialists and urban planners would provide both with an efficient underground cognition (Bonsor et al., 2017). Planners and subsurface specialists should have interactions to exchange required information. Knowledge exchange would raise planners' and subsurface specialists' awareness of the value and role of the underground in urban planning (van Campenhout, de Vette, Schokker, & van Der Meulen, 2016). However, the exchanged information is specialised and incomprehensible to them. Therefore, required information for both parties should be transformed into an understandable and coherent content.

A common language for the transformation of specialised data to comprehensible information for planners and subsurface specialists should be created to enhance their communication and knowledge exchange. Since underground space use is rarely brought into urban planning, a common language would promote comprehensiveness of (re)development plans in terms of an inclusive involvement of both above- and under-ground structures (Admiraal & Cornaro, 2016b). Therefore, development of a common language will increase planners' awareness of underground structure, related opportunities, and constraints. In addition, it will raise the awareness of subsurface specialists of underground role in planning which would establish effective communication with planners through sharing understandable contents. Its effectiveness is subject to the extent that required information is purposefully transformed. For instance, types of soil and its level of hardness are not as useful as their constructability level for planners. Subsurface information should be easy to understand, reliable, structured, up-to-date, and possible to be integrated into planning process (Mielby et al., 2017). Although this knowledge transformation would provide planners and subsurface specialists with valuable information, its extreme variation (in terms of the heterogeneity of surface/subsurface characteristics) makes it challenging to be explored. To this end, 3D models may provide planners and subsurface specialists with useful data visualisation and interpretation (Caumon, Collon-Drouaillet, Le Carlier de Veslud, Viseur, & Sausse, 2009).

3D structural models are means of information interpretation, visualisation, simulation, and simplification (Caumon et al., 2009). 3D information in addition to two-dimensional (2D) information would provide more in-depth insight and a better understanding of information for planning consideration (Biljecki, Stoter, Ledoux, Zlatanova, & Çöltekin, 2015). A set of 3D information proposes effective/useful exploitation in terms of a holistic view, different levels of detail, and a spatial perception regarding the purpose of the use. To this end, 3D models, as "information provider tools", are more effective than two-dimensional models (Liu, Zhao, & Pan, 2016). The effectiveness in terms of understandability level, ease of utilisation, visual efficiency, well-developed cartographic design, and provision of appropriate level of detail. Regarding geological complexities and high levels of detail, 3D models effectively explain spatial features located in both above- and under-ground spaces, express cartographical contents, provide dynamic correlations among space features, etc. Therefore, 3D modelling regarding current improvements of geological underground mapping methods and computer technology development (Jorgensen, Hoyer, Sandersen, He, & Foged, 2015) is a proper way to provide planners and subsurface specialists with integrated surface and subsurface information.

These issues have received more considerations recently in urban planning process; however, there are still considerable problems that planners have to deal with regarding the multidisciplinary urban environment and its related issues. Section 1.2. explains the research problem which is concerned with this study.

1.2. Research problem

This study aims to bridge current gap in academic research and practice regarding underground information involvement in urban planning. Heterogeneous characteristics of above- and under-ground structures bring various professions together to address possible (re)development complexities (e.g., surface density, natural conservation, preservation of urban heritage) (Besner, 2016). Specialised language, probable divergent perspectives, and different levels of knowledge among involved professions in underground development have led scientific attentions toward creation of an effective and demand-based communication context (Admiraal & Cornaro, 2016b). Existing challenges assigned to the creation of a multidisciplinary communication among urban planners and subsurface specialists refer to data acquisition and exploitation.

Data quality, in general, data reliability is the main challenge of complex surface/subsurface data acquisition (Tegtmeier, Hack, Zlatanova, & van Oosterom, 2007). Recently, data exchange in a demand-driven manner lacks coherent attention to quality assessment (Hou et al., 2016); therefore, it becomes a concern of this research since data reliability is a basis of any academic research. In addition to data reliability, the way that dense sets of integrated surface/subsurface information would be exploited is another issue. Exploitation challenges refer to the understandability of information and ease of their utilisation. With respect to recent studies, an inclusive consideration of various social, economic, and environmental (re)development aspects and transformation of this information to understandable contents for urban planners and subsurface specialists remained an issue (Li, Li, & Soh, 2016). Thus, the importance of social aspects in parallel with other economic and environmental aspects of urban (re)development would be considered in this research as essential dimensions for data transformation and integration. In addition, ease of data utilisation is another issue that planners and subsurface specialists are dealing with in an integrated surface/subsurface planning. A virtual presentation of integrated surface/subsurface would be helpful to comprehend potentials of their structures in parallel with the understandability of their related information (Admiraal & Cornaro, 2016b). 3D models regarding their capabilities in 3D and 2D information supplement in parallel with more realistic visualisation has been identified as the most effective providers for information enrichment (de Rienzo, Oreste, & Pelizza, 2008);

however, development of an integrated surface/subsurface 3D model is still unresolved (Liu et al., 2017). Therefore, this research aims to develop solutions to contribute to managing this issue. Although there are several parties involved in underground related studies; plans; and actions, this research focuses on urban planners; subsurface specialists; and their interactions. The focus is on provision of the right information, at the right time, by the right visualisation. To conclude, Table 1 summarises existing academic research gap and contribution of this research in this field.

Table 1. Knowledge gaps

	Knowledge exchange		***Data transformation***	***Information enrichment***
Current state	Poor focus on data-sharing communications and their quality in terms of demand-driven collaborations.	Uncertainty and reliability of specialised data are less assessed; therefore, made decisions might have some levels of uncertainty.	Subsurface-related knowledge is mostly produced in a specialised manner for planners' use.	Supportive information for planners is presented in 2D features. In addition, mostly aboveground and underground structures are analysed and modelled separately.
Gap description	Isolated urban decision making, even within involved parties. Lack of bilateral awareness.	Lack of metadata management regarding detailed information about collection methods, date, and specialisation of data providers.	Lack of proper methods and considerations in terms of data conversion to effective information.	Lack of an integrated data provision of underground structure to involve this valuable resource in (re)development planning.
Gap reason	Lack of reported empirical issues and less concern of academic researchers to the importance of these basic steps.	Involvement of various parties in provision of underground-related data which result in a variation of resources and increase of uncertainties.	Lack of scientific involvement in planning process since it takes time and might be far from political and economic concerns. Lack of well-developed and well-explored methods for transformation issue.	Complexity of dynamic urban environment and hidden underground structure. In addition, existing mismatches between modelling methods for above- and under-ground since their real characteristics are different.
Gap impact	Uncoordinated underground development and consequent probable maldevelopment regardless of other professions' consideration.	Uncertainty about the reliability of information and further decisions. Decisions might lead to unexpected (re)development results.	Exclusion of underground information from urban planning considerations. Less effectiveness of urban planning decisions since some valuable resources (underground space, groundwater, geomaterial, and geothermal energy) are not involved.	A discrete perspective of actual (re)developments and potentials. Complexities of considering both above- and under-ground structures in planning process since detecting corresponding locations and their characteristics are hard to achieve.
Desired state	Participation of facilitators to guide planners and subsurface specialists toward demand-oriented communications.	Greater consideration of data quality before making any uncertain decision.	Specialised data should be transformed into planning contents and be easy to digest for urban planners.	Presenting required information of both above- and under-ground structures in a 3D context; proper, coherent, and more realistic visualisation; along with a simultaneous understanding of possible impacts of any changes in the environment.

Following sections 1.3. and 1.4. state the contribution of this research to the described research problem.

1.3. Research objective

1.3.1. General objective

To develop an integrated 3D model of subsurface/surface conditions and their interactions to support communication and knowledge exchange between planners and subsurface specialists.

1.3.2. Specific objectives

1. To identify key surface and subsurface interactions;
2. To prepare a demand-driven set of surface/subsurface specialised data for urban planning insight;
3. To transform specialised data into comprehensible contents for urban planners and subsurface specialists;
4. To develop an integrated 3D model of surface/subsurface conditions;
5. To evaluate the usefulness of developed integrated 3D model.

1.4. Research questions

1. To identify key surface and subsurface interactions.
    - 1.1. What are the types and characteristics of underground structures (i.e., natural and artificial)?
    - 1.2. How are different components of urban structure connected to the underground?
2. To prepare a demand-driven set of surface/subsurface specialised data for urban planning insight.
    - 2.1. What types of surface/subsurface information are required for urban planners and subsurface specialists to develop an integrated (re)development plan?
    - 2.2. How to relate corresponding surface and subsurface information?
    - 2.3. What are the quality specifications for required data?
3. To transform specialised data into comprehensible contents for urban planners and subsurface specialists.
    - 3.1. How to harmonise and categorise surface/subsurface data across urban need aspects (i.e., social, economic, and environmental)?
    - 3.2. How to assess the effectiveness of transformed data?
4. To develop an integrated 3D model of surface/subsurface conditions.
    - 4.1. What are the existing methods to develop a 3D surface/subsurface model?
    - 4.2. What is the most suitable method to have high interoperability level among data?
5. To evaluate the usefulness of developed integrated 3D model.
    - 5.1. How does the model contribute to planners' and subsurface specialists' communications?
    - 5.2. What are the strengths, weaknesses, opportunities, and threats of the model?
    - 5.3. How to maintain the model?

1.5. Thesis structure

The structure of this report contains 6 chapters: introduction, literature review, field of study, methodology, results/discussions, and conclusion/recommendations.

Chapter 1, introduction, explains the background and justification of the topic; the focus of the study contributing to the current gap in academic research considering weaknesses in practice and the desired state; and the object of study containing objective, sub-objectives, and research questions.

Chapter 2, literature review, gives an overview of related previous studies and current state of academic research in field of underground involvement in urban planning. In addition, it provides insights of surface/subsurface interactions, required information to be shared among urban planners and subsurface specialists, and comparison of 3D modelling methods based on literature review.

Chapter 3, field of study, explains the rationale for study area selection, its considerable issue, the state of development and natural situations related to this issue, the current state of responsible authorities for actual issue of the area, and description of collected data for further analysis.

Chapter 4, methodology, explains the used methods in this study. It separately describes methods for qualitative (i.e., expert interview) and quantitative (i.e., data harmonisation, data transformation, and 3D information modelling) data collection and analysis.

Chapter 5, result/discussions, presents the results and discussions related to the concern of urban planners and subsurface specialists for the (re)development considerations of the study area. Moreover, it discusses the results of data transformation explaining how specialised data are transformed into comprehensible contents for urban planners and subsurface specialists. In addition, it explains how useful a 3D model visualises and analyses the integrated surface/subsurface information.

Chapter 6, conclusion/recommendations, provides conclusions on the role of an integrated 3D model of surface/subsurface structures in knowledge exchange among urban planners and subsurface specialists. Moreover, the answers to the research questions are concluded, and suggestions for further research are proposed.

2. LITERATURE REVIEW

This chapter provides an overview of substantive research findings on previous studies about involvement of subsurface in urban (re)development. Findings are explained in three sub-categories regarding the focus of this study: knowledge exchange, data transformation, and information enrichment which their proper and effective combination led to the novelty of this study. In addition, definitions and concepts regarding the proposed state-of-the-art approach of this study and related theoretical and methodological contributions are explained. Concepts are operationalised considering research sub-objectives and the synthesis of studies on surface/subsurface interactions, data transformation, and proper 3D modelling method selection is explained in this chapter.

2.1. Review of related works

In terms of subsurface development, an early consideration was proposed over 100 years ago by Hénard (1911), a French architect and planner. Hénard explained a new structure as "Future cities" highlighting the role of underground space in urban development. He made several attempts to classify underground structures regarding variation of their functions, characteristics, and opportunities in contribution to urban development. In the same period, the importance of subsurface area was also emphasised by Webster (1914), a surveyor and chief engineer. His focus was on possible state of anarchy that cities might fall into in case of the exclusion of underground from urban development plans. Since then, many engineers tried to set up projects to transfer possible urban functions to the subsurface. Starting underground projection in various development plans throughout the world highlights variant functionalities of the underground. The variant functionalities of underground belong to different professions and lead to the necessity of engaged planning which would involve experts, planners, decision-makers and other relevant participants to avoid fragmented developments (Utudjian & Heim de Balsac, 1985).

Addressing fragmented approaches in underground (re)developments among various stakeholders with different perceptions and perspectives goes back to 1937 where Edouard Utudjian started to promote underground related planning (Utudjian & Heim de Balsac, 1985). His thinking pointed out potentials of integrated development of above- and under-ground space by founding an international association for communication of various experts and planners (Besner, 2016). His achievement led several researchers toward finding proper ways to integrate knowledge, information and ideas of underground specialists in urban development considerations. However, there are still some shortcomings in their communication and knowledge sharing since they require a comprehensible contribution rather than a pure data exchange.

The following subsections explain recent related works on this subject and provide an overview of existing shortcomings. Considering the main mentioned steps of underground involvement in urban (re)development, previous studies are categorised into three themes as knowledge exchange, data transformation, and information enrichment. Although combination of these three themes is not rare, their explicit review helps this research with more concise conclusion (in terms of finding its effective contribution to scientific research gap). These steps respectively refer to the transparency of need and knowledge, a specialised knowledge conversion to an easy and understandable set of information for involved parties, and a comprehensive information provision.

2.1.1. Knowledge exchange

Although knowledge sharing among urban planners and subsurface specialists is an essential step for underground involvement in urban (re)development, the quality of required information is more crucial (Tegtmeier et al., 2007). This necessity was clarified after difficulties in managing various amount of underground-related information provided by different specialised sectors. Academic researchers for knowledge exchange, initially focused on the amount of data transference and its quantity while recent tendencies are more toward data quality.

Milton (2000) emphasised knowledge exchange for effective operation by converging multi-disciplines of various involved professions in underground development. He introduced communication sessions to guide planners and subsurface specialists through demand and knowledge expressions. However, misunderstanding of definitions may still occur. Jacobs (2002) explained basic rules for decision makers and specialists' communications by clarifying different perspectives, defining standard terminologies, and prioritising demands during feedback sessions. This approach, in addition to sharing different ideas, creates a proper context for better communications since specialised terminologies will be well-defined for all participants. In addition, Liu et al. (2008) mentioned some factors that should be considered by specialists to prepare their information more useful for planners. Those factors are "reliability", "legitimacy", and "saliency" which lead considerations toward data quality and its importance in knowledge exchange.

Formerly, this issue was explained by Tegtmeier et al. (2007) in terms of reliability and uncertainty assessment of data. He discussed that during communication sessions, urban planners are fed by plenty of information, requiring their usefulness and quality to be assessed. He assessed quality of information according to "imprecision", "inconsistency", and "uncertainty" aspects. These aspects could be improved by adding essential considerations to metadata of exchanged information by indications. In addition, this improvement could be made by doing specialised interviews and reviewing available geo-portals. To improve this approach, Howard, Hatton, Reitsma, and Lawrie (2009) introduced a framework to assess the quality of information. This framework is based on an information exploitation process in a cyber-infrastructure which will raise the effectiveness of knowledge exchange and its reliability. Therefore, consideration of data quality in underground (re)development would support reliability of geological studies. However, variation of geological information over space makes their quality assessment challenging. Quality assessment of data would be helpful for this research to manage and provide metadata of exchanged information before any utilisation. This would support in lessening uncertainty of data; however, it is not always considered in empirical knowledge exchange. In parallel with the importance of information quality, their usefulness and comprehensibility are essential as it will facilitate further discussions among planners and subsurface specialists. These observations lead scientific research toward determination of proper methods to transform specialised data into comprehensible information regarding users' perception.

2.1.2. Data transformation

Utilisation of underground resources requires status analysis of its different structures (i.e., space, groundwater, geothermal energy, and geomaterial) to recognise the extent of development opportunities. Li, Parriaux, et al. (2013) integrated underground space in development process of four pilot cities; Zurich, Geneva, Bern, and Lausanne by assessing quality of groundwater, geothermal energy, geomaterial with respect to urban population, living density, and GDP per capita. Their focus was on constructability assessment and visualisation of the result which was done in 2D maps with fuzzy boundaries of values. The fuzziness of values was due to limited available sample points and data interpolation. Although 2D maps are useful in decision-making process, their utilisation requires a minimum level of map-reading ability which may not be possessed by all planners and decision makers. As an upgrading consideration for data acquisition, Kaliampakos et al. (2016) developed an electronic database; a web service and a mobile app, based on different categories of underground structures for the engineering community to collect experiences and knowledge submitted by other experts on this app for a specific location throughout the world. Although this database could provide planners with a focal point of subsurface-related information, understanding of specialised concepts is still a concern.

A more comprehensive study was done by Li et al. (2016) in terms of a more plenary assessment of underground structure. Regarding urban needs, they considered urban economic and environmental aspects for effective underground development. The assessment was done based on two major concepts; “resource supply potential” and “economic demand potential” with focus on various underground-related features such as geo-risk, sensitive soil thickness, sensitive aquifer flow, existing foundation, archaeology discovery, ecology protection level, topography, faults buffer, civil defence need, commercial land prices, residential land prices, land use type, population density, and transport accessibility. Despite various analysis of essential aspects, they did not consider social related aspects of underground development that might be important for urban planners. Social aspects in terms of safety perception, nature accessibility, and other physical-related aspects of urban structure (e.g., light and windows) which might affect social behaviour (Lee, Christopoulos, Lu, Heo, & Soh, 2016). In addition, Li et al. (2016) implemented their analysis in a real context, and the results were presented in integrated potential 2D maps differentiating by depth levels. Beside mentioned positive aspects of their work, involvement of above-ground structure to a certain extent is a considerable opportunity to provide planners with a partly integrated perspective of urban (re)development potentials. However, ease of information acquisition in terms of a comprehensible and more realistic visualisation was failed in this assessment.

These articles for integrating underground space in planning process focused on assessment of subsurface features and their level of constructability regardless of visualisation and presentation issues (e.g., understandability, and level of detail). Therefore, next section contains reviews of some current studies regarding a more realistic underground integration in planning process by using well-developed assessment and visualisation methods.

2.1.3. Information enrichment

Although there are few studies in this field for a definitive conclusion, some tried to cover essential aspects of underground features and their integration into a planning process.

Hou et al. (2016) developed a 3D geological model of underground space containing information of soil condition, bedrock condition, and faults buffer which are not all urban needs. Their achievement was a precise provision of 3D information; however, understandability of specialised data was not considered. In addition, this research did not consider integration of aboveground features in analysis which is an essential aspect of reality. These weaknesses affect completeness and the subsequent effectiveness of provided information for planners.

In a supplementary approach, Jorgensen et al. (2015) tried to develop a 3D model by combining different methods to provide proper details about geological architecture. They added high-resolution seismic data based on a large-scale survey to borehole data in order to cover their individual insufficiency in assessment of a massive amount of data. It showed that combination of modelling methods would be beneficial regarding significant amount of data and their complexity. However, there is still sense of a gap in scientific research that information transformation is not involved in a well-developed 3D information provision. This issue goes back to the first reviewed subject; lack of a well-designed communication among different stakeholders. This deficiency exacerbates the level of planners’ knowledge and understanding of subsurface-related information since proper data regarding their planning purpose are not presented coherently and realistically.

Following the shortcomings of scientific research in this field, Liu et al. (2017), a recent article, aimed at integrating above- and under-ground structures. To this end, they tried to integrate Building Information Modelling (BIM), as a 3D design of aboveground structure; and Geographic Information System (GIS), as a 3D design of underground with respect to various challenges. These two 3D modelling methods regarding their focused areas have differences in terms of formats, application, users, spatial units, methods of accessibility, etc. Considering these differences, Liu et al. (2017) had analysed possible methods to integrate BIM and 3D-GIS. They proposed "semantic web technologies" as the most effective, extensible, and flexible approach; however, the mentioned differences (e.g., scale, unit, format, application, etc.) to some extent remain as unsolved challenges. They proposed their integrated model to provide planners with support for site selection, resource management, and environmental impact assessment. Despite the value of their achievements, they identified isolated development of each model as the key obstacle to integrated modelling.

To conclude, integration of surface and subsurface information in an understandable manner is required for urban planners to manage (re)development issues considering underground contributions. Deficiencies in multidisciplinary communication between planners and subsurface specialists in terms of knowledge exchange and information provision highlight the absence of a common language for a better understanding of specialised information providing by both parties. Development of an integrated 3D model presenting transformed specialised data to comprehensible information is the state-of-the-art approach of this study which had been remained unresolved in scientific research. In addition, transformation of specialised data to comprehensible information for urban planners and subsurface specialists would deal with scale-, unit-, format-, and application- related issues of heterogeneous data obtaining (since data will be harmonised in a unique manner). A 3D model with realistic visualisation and computational/analytical opportunities may provide insights of effective (re)development decisions for planners and subsurface specialists. In addition, dynamic visualisation and analytical opportunities of a 3D model could provide urban planners and subsurface specialists with a simultaneous understanding of possible impacts of any changes in the environment. Therefore, this study considers communication gap and contributions of the 3D modelling.

2.2. Review of research concepts

"Awareness", "connection", "interaction", and "integration" are the important sequential concepts to exchange, transform and enrich information about subsurface/surface structures and their interactions regarding (re)development planning purposes (Figure 1). These concepts are adapted from van Campenhout et al. (2016) which explained them as factors that support multidisciplinary communication between planners and specialists for the purpose of knowledge sharing. This study considered these concepts through a comprehensive enhancement of communications between urban planners and subsurface specialists. In other words, the process of the enhancement of communications between these two parties is subdivided into three main steps in this study. Knowledge exchange, data transformation, and information enrichment are steps of this study that operationalised mentioned concepts (i.e., awareness, connection, interaction, and integration).

In this study, these concepts respectively refer to understanding the importance of underground involvement in urban (re)development planning, revealing limitations and opportunities of subsurface, an occasional involvement of subsurface specialists in urban planning process, and integration of subsurface information in planning issues (van Campenhout et al., 2016). Considerably, development of the latter requires cyclic consideration of the former phase. It would improve collaborations between isolated involved parties in underground development. To this end, according to Figure 1, knowledge exchange and its quality assessment; data transformation into useful planning contents; and information enrichment by an integrated 3D modelling of surface/subsurface structures are respective steps. However, there are possible and required interconnections between these steps to fulfil the aim.

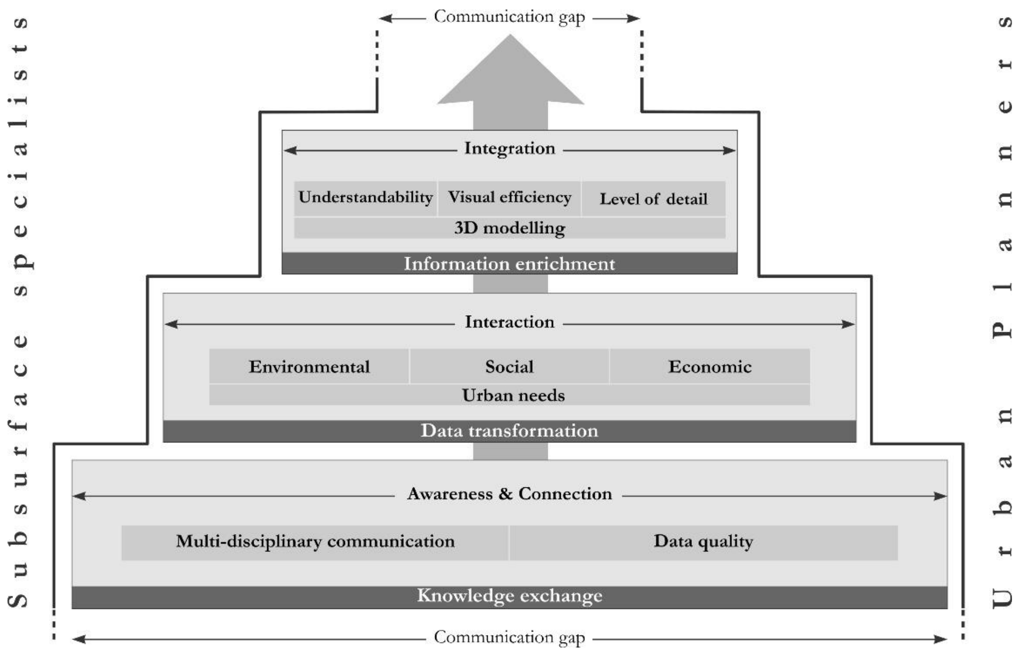


Figure 1. Initial research concepts and their interactions

Operationalisation of research concepts requires interconnections between research sub-objectives. Figure 2 shows the contribution of research sub-objectives and questions to the operationalisation of research concepts.

“Awareness”, meaning the importance of underground involvement in urban (re)development, is linked with questions assigned to surface/subsurface interactions. Review of subsurface structure, belonged types, their specific characteristics, and possible connections with surface structure clarify surface and subsurface potential interactions for further urban (re)developments.

“Connection”, referring to limitations and opportunities of subsurface structure, is revealed by creating a setting for knowledge exchange and information sharing between planners and subsurface specialists. Clarification of planners’ demand concerning context-based issues and respectively the provision of effective information about subsurface solutions may enhance multidisciplinary communications between planners and subsurface specialists.

“Interaction”, proposing the occasional involvement of subsurface specialists in urban (re)developments, refers to the transformation of specialised data to comprehensible information for urban planners and subsurface specialists.

“Integration”, meaning the combination of surface/subsurface information, provides analytical considerations for planners and subsurface specialists through an integrated surface/subsurface 3D model.

Concept	Sub-objective	Question
Awareness	Surface/subsurface interactions	Characterising subsurface components
		Understanding surface/subsurface connections
Connection	Demand-driven knowledge exchange	Identifying specialised urban need information
		Relating corresponding information
		Exploring quality specifications for data
Interaction	Data transformation	Harmonising/categorising information regarding urban needs
		Assessing the effectiveness of transformed data
Integration	Integrated 3D modelling	Exploring the existing 3D modelling methods
		Designating an integrated 3D modelling method
	Model validation	Evaluating model effectiveness
		Validating the model
		Maintenance procedure

Figure 2. Operationalisation of research concepts

Considering the contribution of research sub-objectives to research concepts, following subsections give information about research concepts and related sub-objectives based on literature review. The review provides information about surface/subsurface interactions, contextualised urban need and required information based on the demand of planners and subsurface specialists, and exploration of 3D modelling methods in terms of integrated surface/subsurface structures. This piece of literal information is synthesised by qualitative explorations (i.e., expert interviews) presenting by section 5.1.: results on connection through a demand-driven information set. The results lead to development of a conceptual framework of concepts of demanded information for urban planners and subsurface specialists for a particular setting. Section 2.2.1. and 2.2.2. explain this framework in detail.

2.2.1. Awareness of surface/subsurface interactions

The importance of an integrated (re)development planning of surface and subsurface structures has been raised recently throughout the world where increasing land utilisation is one of the main soil and groundwater threats (Norrman et al., 2016). Urban planners and subsurface specialists have different considerations regarding urban (re)development. Urban planners generally concern opportunities for enhancement of the socio-economic status of urban areas. While, subsurface specialists and engineers deal with technical issues of physical (re)developments (ISOCARP, 2015). However, a widespread concern of social, economic and physical aspects of urban (re)development is required for effective action. Therefore, the individual considerations of both parties should be integrated. This integration is based on raising their awareness of interactions between surface and subsurface structures which requires a comprehensive understanding of their types, characteristics, and (re)development contributions.

The surface structure contains two environments: natural and artificial (built) with possible interactions (Bonsor et al., 2017). The natural environment contains steady/stagnant water, and vegetation; and the built environment encompasses buildings, utilities, and transit networks (Clayton, 2009; Goel, Singh, & Zhao, 2012a). Rapid development of the built environment throughout urban areas may affect usual condition of the surface natural environment since land taking dominates undeveloped areas. Surface built environment is constructed with various levels of connection with subsurface structure, from small-scale constructions in shallow to large-scale infrastructure projects in a deep level of subsurface structure (Broere, 2016; Goel et al., 2012a). These connections indicate the actual interactions between surface and subsurface structures. Accordingly, the subsurface structure is also affected by urban (re)developments. Therefore, exploration of the hidden characteristics of subsurface structure is essential for understanding surface/subsurface contributions to urban (re)development since they are spatially interconnected.

Subsurface structure has considerable resources contributing toward exacerbating environmental, physical, social, and economic urban problems (e.g., natural disaster, environmental degradation, space deficiency, safety and security, and ageing infrastructure). Generally, the subsurface structure contains two main natural and built environments. In addition, the natural and built environments can be classified into subcategories based on different parameters of site features such as "position", "shape", "geometry", and "use" for more specific focuses (Goel et al., 2012a). Since the focus of this research is on subsurface contribution to urban (re)development, the "use" factor is considered for sub-categorisation of subsurface natural and built environments. The natural environment of subsurface structure comprises space, groundwater, geomaterial, and geothermal energy (Parriaux, Tacher, & Joliquin, 2004). The built environment of subsurface structure regarding the "use" factor includes foundation, heritage, and transport/utility subcategories. These subcategories contribute differently in urban (re)development. Table 2 explains characteristics of the subsurface structure and its contribution to urban (re)development.

Table 2. Subsurface structure, types and characteristics

	Type	**(Re)development contribution**	**Characteristic**
Natural environment	Space	Service facility/activities placement	Space use rate, area of developed spaces, use diversity, activities adjacency.
	Groundwater	Soil filtering	Soil ecology, soil permeability, amount of organic matter.
		Water storage	Natural saltation, rainfall.
		Drinking water supplement	Depth of aquifers, range of replenishment.
	Geomaterial	Mineral resources	Type of soil, quality of soil, alteration of soil types, sedimentation rate.
		Crop production	Soil fertility (chemical, physical, and biological), natural vegetation of the area, nutrient level.
		Geomorphological diversity	Erosion, sedimentation, peat formation.
		Ecological diversity	Presence of birds (or other flora and fauna)
	Geothermal energy	Thermal energy storage	Open systems in aquifers, soil permeability, boundaries of fresh and salt groundwater, presence of containment, demand for cooling/heating in the region, adjacent thermal storage systems, sealing layers.
		Fossil fuel supplement	Water salinity, types of surface activities (nuisance activities).
		Thermal energy supplement	Depth and permeability of available space for demanded energy extraction, building density
Built environment	Foundation	Stable structure	Load bearing capacity, water and wind erosion, soil type, vegetation coverage, groundwater level.
	Heritage	Archaeological values	Likelihood of existing of cultural/valuable structures, proximity to groundwater level and the quality of closest ones.
	Transport/utility	Storage	Subsurface stability, leaking of sealing layers.
		Sewerage, cables and pipes	Groundwater flows, location of subsurface objects, system capacity, surface connections.
		Transit network	Load bearing capacity, sealing layers, soil type, adjacent utilisation, groundwater level.

Source: adapted from Clayton (2009); Goel et al. (2012a); Mielby et al. (2017); The Municipality of Rotterdam (2017); Rogers (2009); Zargarian, Hunt, Braithwaite, Bobylev, and Rogers (2016)

Table 2 shows that subsurface structure can contribute broadly to urban (re)development considering its diverse characteristics. These contributions may cause potential interactions with surface structure which can be classified in different schemes of solutions to urban need (Figure 3).

Production, protection, and provision are schemes of the potential interactions between surface and subsurface structures. Production refers to economic benefits of material and energy extraction (Broere, 2016; Parriaux et al., 2004). Protection belongs to environmental benefits of ecological preservation, rainfall retention, natural landscape conservation, landform and water flow control; social benefits of containment of hazardous process, secure limited access, control of noise, pollution, vibration, industrial accidents, and archaeological protection (Broere, 2016; Goel et al., 2012a; Goel, Singh, & Zhao, 2012b; Parriaux et al., 2004). Provision relates to social benefits of mobility and utility infrastructures; economic benefits of heat and sound reservation, land cost and energy saving, natural caves for tourism; and environmental benefits of land use efficiency (Goel et al., 2012a; Mielby et al., 2017).

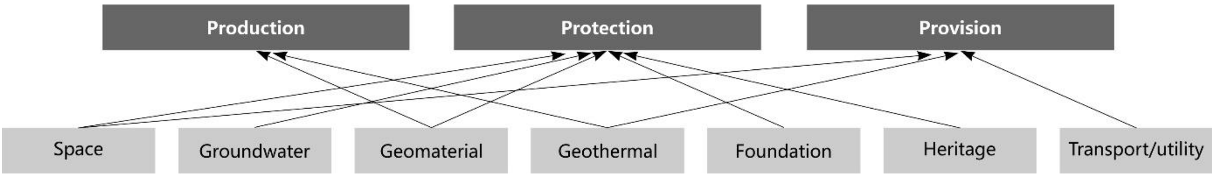


Figure 3. (Re)development contributions of subsurface structure

In summary, natural and built environments of subsurface structure, in addition to their "actual" interaction with surface structures, have "potential" interactions resulting possible solutions to urban need (i.e., production, protection, and provision). The actual interactions between surface and subsurface structures (i.e., natural and built environments) occur spatially across various depth levels (Bonsor et al., 2017). Gradual development, extraction, and utilisation of subsurface structure may result in probable impacts on surface structure (e.g., stability of constructions, soil subsidence, and flows of polluted groundwater). Therefore, optimum utilisation and effective (re)development contributions of subsurface structure attract human concerns to surface and subsurface potential interactions. Figure 4 illustrates surface/subsurface structures and their actual and potential interactions.

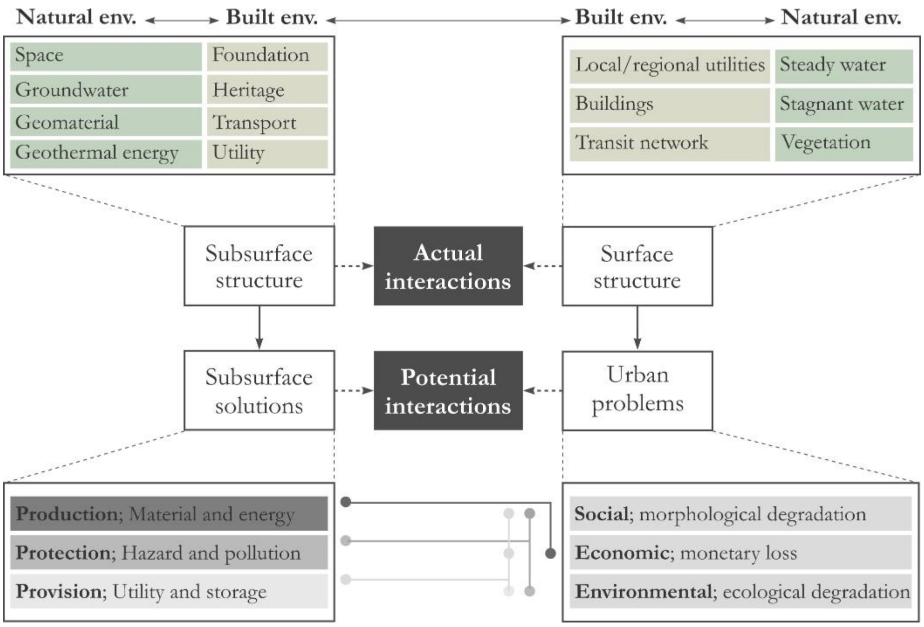


Figure 4. Synthesis conceptual model of surface/subsurface interactions

A beneficial utilisation of the actual and potential interactions between surface and subsurface structures depends on required/context-based level of urban (re)development (ISOCARP, 2015). Section 2.2.2. explains levels of (re)development and contribution of subsurface structure to this process. This investigates context-based demand for information about subsurface involvement in (re)development which leads to effective knowledge exchange between planners and subsurface specialists.

2.2.2. Connection through a demand-driven knowledge exchange

To create a connection between urban planners and subsurface specialists for knowledge sharing, understanding the required level of urban (re)development for the desired area is needed. To this end, a brief explanation of general urban (re)development levels and the contribution of subsurface structure to these levels are presented by following statements. Then, regarding the (re)development issue of the desired area in this research which is extensively described by chapter 3, the schemes of demanded information for an integrated surface/subsurface (re)development are explicated (to be shared among urban planners and subsurface specialists).

The level of urban (re)development varies across urban areas considering their actual and potential surface/subsurface interactions. The more an urban area could benefit from its subsurface structure, the more (re)developments might occur at its surface structure (Broere, 2016). From large to small-scale, vision; plan; and design are respective levels of urban (re)development with specific contributions of subsurface structure (Table 3) (Norrman et al., 2016).

The vision level corresponds to general "master planning" of urban areas. Considering level of decisions that might be made at this stage, analysis of subsurface structure and its contribution to (re)development process will be made at macro scale. Resource allocation, demand estimation, and identification of possible utilisation are key contributions of subsurface structure at this level of urban (re)development (Bartel & Janssen, 2016; ISOCARP, 2015; Norrman et al., 2016).

The plan level corresponds to "regulatory planning" of urban areas. This level consists of meso-scale considerations for control provision of subsurface planning. The control provision refers to a holistic perspective of subsurface structure and its status. In addition, it provides information for a planned utilisation of subsurface structure (i.e., space, material, energy, and water). Moreover, the plan level provides possible planning alternatives for an integrated surface/subsurface (re)development (ISOCARP, 2015; Norrman et al., 2016).

The design level corresponds to "detailed site plan" of an urban area. This level of (re)development process consists of implementation and design suggestions. Various criteria for the best-localised solution should be considered at this stage. "Climate security", "energy saving", "land efficiency" are some of the important criteria in design level (Norrman et al., 2016); however, the criteria should be selected regarding context-based issues. Table 3 shows levels of urban (re)development and contributions of subsurface structure to this process.

Table 3. Urban (re)development and subsurface planning

(Re)development Level, scale	(Re)development process	Subsurface contribution
Vision, macro	Master planning	Resource allocation
		Demand forecasting
		Key utilisation
Plan, meso	Regulatory planning	Control provision
Design, micro	Site plan	Implementation-based design

Source: adapted from Admiraal and Narang Suri (2015); Bartel and Janssen (2016); Goel et al. (2012a); Norrman et al. (2016)

Consequently, the contribution of subsurface structure in urban (re)development depends on the level of planning in an area. Section 5.1., regarding 5 expert interviews with urban planners and subsurface specialists, identifies that the level of urban (re)development in the desired area of this research is at macro level since they are currently working at the vision phase of (re)development process. In addition, Chapter 3 gives an extensive explanation of the desired area in this research. Generally, it identifies that the main concern of urban planners and subsurface specialists in this area is "risk[1] of surface water flooding" and "the contribution of subsurface structure" to managing this issue. Therefore, regarding Figure 4, the issue of the desired area in this study is an "environmental" urban problem with social and economic impacts. Moreover, regarding Figure 4 and the environmental issue of the desired area in this research, "protection" (against surface water flooding) and "provision" (of water storage) are the main aspects of subsurface potential solutions in this study.

Following statements explain the schemes related to the issue of "surface water flooding" and a macro scale study of subsurface contribution to this issue (explained by Figure 5).

Surface water flooding mostly occurs in paved areas with inadequate drainage system (Jenkins, Surminski, Hall, & Crick, 2017). Paced urbanisation, developing artificial structures, climate change and the subsequent challenges of precipitation are significant factors that affect surface water flooding (Willems, Arnbjerg-Nielsen, Olsson, & Nguyen, 2012). Exacerbating status of these factors requires attention of urban planners to the management of flooding risk.

Surface water flooding risk management depends on interactions between "hazard", "vulnerability", and "exposure" elements. The hazard of surface water flooding refers to climate-related physical events assigned to rainfall intensity (IPCC, 2014). The vulnerability element describes susceptibility and sensitivity of population to the impacts of surface water flooding (i.e., physical, social, economic, and environmental impacts) (IPCC, 2014; Kaźmierczak & Cavan, 2011). Therefore, along with physical explanation of the event by the analysis of "hazard", "vulnerability" will provide an understanding of urban community status facing possible events. As a complementary element, "exposure" expresses the presence of different types of urban structure (e.g., demographic, artificial and environmental structures) in the pathway of an event (IPCC, 2014; Kaźmierczak & Cavan, 2011). Assessment of these elements will describe potential risk of an urban area to surface water flooding. Although this information provides an understanding of urban status in flooding management for urban planners, awareness of solutions to reduce the risk is essential.

In addition to solutions that surface structure offers regarding the management of surface water flooding risk (e.g., land use/zoning regulations, building codes, and the enabling environment), subsurface structure provides urban (re)development with considerable potential solutions. Subsurface potential solutions contain protective and provisional schemes. In this study, protective scheme refers to environmental considerations, and provisional scheme refers to technical considerations. These considerations contribute differently toward the management of surface water flooding risk.

Environmental considerations contribute to managing "hazard" and "exposure" elements of surface water flooding risk (Goel et al., 2012b; Mielby et al., 2017). Regarding the concern of current study, analysis of this management is done through a "supply inventory" factor. "Supply inventory" describes the feasibility of subsurface contribution to urban (re)developments regarding surface water flooding issue. It refers to environmental considerations of both subsurface natural and built environments such as man-made structures, and geological conditions. However, involvement of environmental considerations in (re)development process raises the need for technical and engineering considerations. In addition, "vulnerability" factor is remained to be involved in subsurface solutions to the management of surface water flooding risk.

[1] In this study, whenever word "risk" is used, it refers to "risk of surface water flooding" regarding the issue of the study area.

Technical considerations contribute to managing "exposure" and "vulnerability" elements of surface water flooding risk. Regarding the concern of current study, this management is done through a "demand targeting" factor. This factor combines the theoretical understanding of construction with practice (Goel et al., 2012b). The implementation of any monitoring, controlling, and management approaches require specific knowledge on detailed surface and subsurface structures, their potential interactions, and optimum techniques. "Demand targeting" includes these types of technical considerations in categories of land utilisation management and engineering difficulties. Considerably, the way that this information is related is important.

Figure 5 explains the developed framework of this study for assessing the issue of surface water flooding in the desired area and the contribution of subsurface structure to managing this issue. In addition, it provides the way that corresponding surface and subsurface information are related (environmental considerations are related to hazard, and exposure components of surface water flooding risk assessment; technical considerations are related to vulnerability, and exposure factors of surface water flooding risk assessment). Therefore, required types of information for urban planners and subsurface specialists in (re)development process of the desired area are specified.

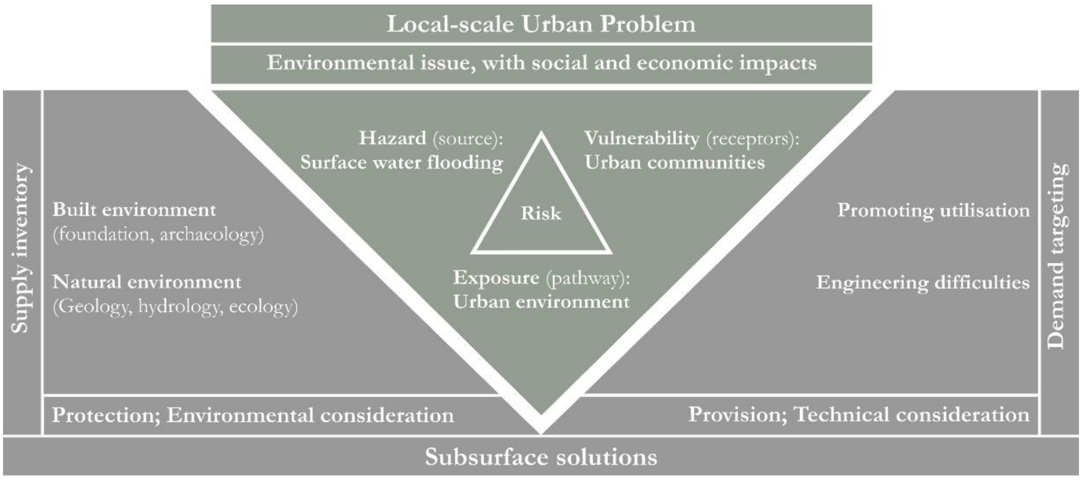


Figure 5. Demand-driven information framework

In summary, risk assessment in parallel with the appraisal of subsurface potential solutions (i.e., environmental considerations, supply inventory; and technical considerations, demand targeting) are considerable factors of surface water flooding management in the desired area of this study. In this study, risk assessment consists of analysing vulnerability of an urban community and exposure of related urban environment to a source of hazard (i.e., surface water flooding) (Kaźmierczak & Cavan, 2011). subsurface potential solutions to the management of surface water flooding consist of environmental and technical considerations. The environmental considerations refer to potential supply inventory of subsurface structure, and the technical considerations refer to potential demand targeting of the urban environment for improvement and (re)development. The potential supply inventory illustrates feasibility of subsurface structure in urban (re)development and the potential demand targeting shows the level of current engineering difficulties and required utilisation promotion in urban (re)development (Li et al., 2016). Therefore, environmental and technical considerations regarding potential subsurface solutions illustrate how corresponding information of surface and subsurface structures are related. Providing urban planners and subsurface specialists with this information may facilitate the involvement of subsurface structure in urban (re)development. Provision of this information depends on various indicators of surface water flooding risk, environmental considerations, and technical considerations.

Following section identifies indicators for each factor (i.e., surface water flooding risk, environmental and technical considerations). Therefore, categorisation of required information is presented.

2.2.3. Interaction through data transformation

This section explains related indicators to the three factors of surface water flooding management regarding subsurface contribution (i.e., surface water flooding risk, environmental consideration, and technical consideration (Figure 5)). Table 4 identifies related indicators for the analysis of surface water flooding risk and the contribution of subsurface structure to this issue. As a result, required information for urban planners and subsurface specialists are categorised based on a demand-based communication.

Several studies have been done on risk assessment related to environmental events such as flooding. Crichton (1999) developed a triangular risk assessment framework containing "hazard", "exposure", and "vulnerability".

Considering the studied environmental issue in this research (surface water flooding), hazard is categorised in probability and severity dimensions. The probability dimension explains occurrence (frequency) of experienced rainfalls in desired area. Moreover, severity explains the intensity of experienced rainfalls (Fedeski & Gwilliam, 2007). However, the measurement of rainfall for the case of this study is conducted at city level (Table 9). Therefore, for this case, the "hazard" factor is eliminated from the risk assessment index of this study since the available data contain similar values for the whole area. In addition to hazard, exposure is another critical factor in surface water flooding risk assessment.

Regarding the extent of flooding in an area, a various number of structures might be prone to the event. Bollin and Hidajat (2006) pointed out the important dimension that should be analysed under the study of exposed areas to flooding. They identified man-made structures as the most important dimension in exposure analysis. Regarding the potential space and storage provision of subsurface structure, population and valuable lands could be protected against massive water flows. Therefore, "structure" containing housing, soil characteristics, land usage, geographical structure, and controlling measurements is the main dimension of exposure in this study. In addition to exposure, vulnerability of urban structure in various social, physical, environmental, and economic aspects is important while lower vulnerability levels result in better reactions of community in flooding occurrence.

Vulnerability, another factor of risk assessment, includes social, environmental, economic, and physical dimensions (Birkmann, 2007; Bollin & Hidajat, 2006). However, the concern of the desired area in this study is mostly on physical issues in relation to environmental aspects (see Chapter 3). Therefore, in this study, social and economic dimensions are removed from the vulnerability factor. Regarding the characteristics of the desired area in this study (see Chapter 3), following indicators are assigned to the desired vulnerability dimensions (i.e., physical and environmental). First, the physical dimension contains unsafety and cultural heritage in the area which show the susceptibility of urban structure to flooding. It describes how sensitive the exposed structures are to surface water flooding. Second, the environmental dimension contains water infiltration rate relating to soil permeability and the status of undeveloped areas (e.g., green lands and unpaved gardens) throughout the area. This indicator highly emphasises on surface water flows and possible opportunities for infiltration and adding to groundwater storages (Kazakis, Kougias, & Patsialis, 2015).

In addition to the importance of urban problem analysis (risk of surface water flooding), subsurface structure could support urban (re)development with some protective (environmental) and provisional (technical) solutions. In this study, environmental consideration is considered as a protective solution for surface water flooding. This type of consideration contains potential supply inventory of subsurface structure to the urban issue. In addition, technical consideration is considered as a provisional solution for surface water flooding. This type of consideration includes potential demand targeting of urban environments for possible improvements (Goel et al., 2012b; Li et al., 2016).

The potential supply inventory refers to natural and built environments of subsurface structure. These indicators indicate feasibility of subsurface contribution to the issue of surface water flooding. The natural environment refers to space provision regarding characteristics of subsoil, and water provision regarding the status of groundwater storages. In general, these indicators present potential offers of subsurface structure for orienting surface water flow to suitable subsurface conditions. In addition, the built environment discusses the artificial structures of subsurface regarding density of developed area. Although mentioned indicators of supply inventory provide urban structure with potential capacity of subsurface structure against risk of surface water flooding, demand forecasting of the urban area is essential since an effective supplement depends on a sensible demand (Li et al., 2016).

The potential demand targeting refers to promoting land utilisation and engineering difficulties. The promoting land utilisation contains monetary and demographic characteristics of the area. This information identifies the distribution of urban wealth throughout the area regarding population dispersion. In addition, it provides information for (re)development demand forecasting of at-risk areas. The engineering difficulties refer to the status of existing surface and subsurface constructions which might be affected by heavy rainfall and increasing groundwater level (Mielby et al., 2017). Foundation resistance and water flow control are studied indicators for this dimension in this research. These indicators show how difficult the challenge of surface water flooding could be dealt in the area.

Table 4 presents the demand-driven information set (containing indicators and their detailed explanation) and required information for urban planners and subsurface specialists to enhance their communication and knowledge sharing about surface water flooding risk and the contribution of subsurface structure to this issue. Description of required data and their quality specification is presented respectively in sections 3.3. and 4.1.2.

Next section, 2.2.4., explains the way that an integrated analysis of surface and subsurface data along with an effective visualisation and information acquisition is done through an integrated 3D modelling approach in this study.

Table 4. Information categorisation for transformation

	Contribution aspect	***Factor***	***Dimension***	***Indicator***	***Abb.***	***Unit***	***Definition***	***Functional relationship with factor***	***Source of references***
Urban problem	**Risk of surface water flooding**	Exposure	Structure	Housing	E1	-	Density of housing units	Positive	Kaźmierczak and Cavan (2011)
				Soil subsidence	E2	m^2	The mean of decreasing area	Positive	Balica, Wright, and van der Meulen (2012)
				Land cover	E3	%	Ratio of green spaces to the total area	Negative	Zou, Zhou, Zhou, Song, and Guo (2013)
				Topography	E4	Degree	Slope (maximum)	Positive	Wang, Li, Tang, and Zeng (2011)
				Passing flood	E5	m	Shortest distance from river	Negative	Balica et al. (2012)
				Control project	E6	m	Distance from any dyke/canal	Negative	Wang et al. (2011)
		Vulnerability	Physical	Unsafety	V1	m^2	Area of houses in buffer (50m) of hazardous area	Positive	Kaźmierczak and Cavan (2011)
				Cultural heritage	V2	m^2	Area of historical buildings	Positive	Balica et al. (2012); Zargarian et al. (2016)
			Environmental	Infiltration rate	V3	mm^3 per m^2	Average daily amount of water infiltration	Negative	Broere (2016); Mielby et al. (2017)

	Contribution aspect	*Factor*	*Dimension*	*Indicator*	*Abb.*	*Unit*	*Definition*	*Functional relationship with factor*	*Source of references*
Underground solution	**Environmental consideration**	Supply inventory	Natural environment	Space provision	S1	m^2	10% of built-up areas (3 floors)	Positive	Li, Parriaux, et al. (2013)
				Soil thickness	S2	m	Thickness of soil layers above clay soil	Positive	Li et al. (2016)
				Penetration condition	S3	m	Thickness of clay soil layer	Negative	Li et al. (2016)
				Soil quality	S4	-	Average Soil pollution (categorical)	Negative	van Der Meulen et al. (2016); van Campenhout et al. (2016)
				Groundwater condition	S5	m	Average groundwater level (depth)	Negative	Zargarian et al. (2016); Li, Parriaux, et al. (2013)
				Water provision	S6	mm^3 per m^2	Volume of daily groundwater outflows	Positive	Li, Parriaux, et al. (2013)
			Built environment	Density	S7	-	Volume of physical assets located underground divided by volume of respective area	Negative	Bobylev (2016); Li, Parriaux, et al. (2013)

	Contribution aspect	*Factor*	*Dimension*	*Indicator*	*Abb.*	*Unit*	*Definition*	*Functional relationship with factor*	*Source of references*
Underground solution	**Technical consideration**	demand targeting	Promoting utilisation	Land pressure	D1	-	Ratio of unbuilt area (i.e., greenery/water) to built area (i.e., building/paved path)	Negative	Li, Parriaux, et al. (2013); Zargarian et al. (2016)
				Monetary values	D2	1000 €	Growth rate of average housing value	Positive	Li et al. (2016)
				Population	D3	p/hectare	Population density	Positive	Li et al. (2016)
			Engineering difficulties	Water flow control	D4	mm^3 per m^2	Water infiltration rate (average daily value)	Negative	Kazakis et al. (2015)
				Foundation resistance	D5	-	Ratio of wooden/steel foundation to concrete/or any stronger types (the ratio of buildings area)	Positive	Mielby et al. (2017)
				Densification demand	D6	-	Average floor area ratio	Positive	Li, Parriaux, et al. (2013)

2.2.4. Integration through 3D modelling

This section designs a framework to compare various 3D surface/subsurface modelling methods. Then, by explaining the proper state of involved factors regarding the purpose of this study, a most suitable method for an integrated 3D modelling of surface and subsurface structures is selected.

Regarding heterogeneous, multi-object, multi-scale and multi-structural characteristics of surface and subsurface environments, knowledge sharing between urban planners and subsurface specialists requires an integrated spatial information acquisition (Yanbing, Lixin, Wenzhong, & Xiaojuan, 2006). Concerning the use, various 3D city modelling methods are explored for the analysis and visualisation of spatial data (Biljecki et al., 2015).

In general, "geographical" and "geological" are the main types of 3D modelling methods regarding their spatial contributions to surface and subsurface structures (Yanbing et al., 2006). The geographical models state the condition of surface structures and the geological models present the condition of subsurface structures. 3DFDS (Three-Dimensional Formal Data Structure), SSM (Simplified Spatial Model), UDM (Urban Data Model), OO3D (Object-Oriented 3D), and City GML (Geography Markup Language) are examples of geographical 3D modelling methods. On the other hand, Octree, TEN (Tetrahedral Network), 3D-TIN (3D Triangulated Irregular Network), GTP (General Tri-prism), and CSG (Constructive Solid Geometry) are examples of geological 3D modelling methods (Biljecki et al., 2015; Tuan, 2013; Yanbing et al., 2006). Table 5 briefly explains advantages and disadvantages of mentioned modelling methods.

Table 5. Introduction to 3D modelling methods

Type	Method	Advantage	Disadvantage
Geographical model	3DFDS	Adjacency between spatial and non-spatial objects could be made easily	Expression of complex objects is difficult
	SSM	Easy simplification of primitive objects, small data size (storage capacity)	Difficulty and complexity of dynamic updates and modification of the model, multi-value objects
	UDM	Easy simplification of primitive objects, facial visualisation	Difficulty and complexity of dynamic updates and modification of the model
	OO3D	Provision of complex objects, LOD, facial visualisation	Uncertain provision of topological information, few possibilities in 3D spatial analysis
	City GML	Solid representation of objects, ability to compute volumes, an application independent geospatial information modelling method, format exchange	Large data storage capacity (regarding used level of detail)
Geological model	Octree	Attribute transformation, simple structure	Difficulty in geological objects expression, massive data, data redundancy, difficulty in geometrical boundary expression
	TEN	Facial visualisation, complex object structure (face and body)	Difficulty in the visualisation of complex objects, large data storage capacity
	3D-TIN	Facial visualisation	No provision of attributes for objects
	GTP	Topology modelling, 3D expression of geology (based on drill hole data)	Difficulty in visualisation of complex geological structures
	CSG	Calculation of the volume of objects, focusing on global scale structure modelling	Object definitions cannot be reused, unable to represent objects with unusual geometry, useless in local modelling

Source: adapted from Yanbing et al. (2006, pp. 102–103)

In addition, Table 6 compares described geological and geographical 3D modelling methods based on some factors which adequately describe their differences. This table leads to an effective method selection for 3D objects generation regarding the purpose of this study (integration of surface and subsurface structures).

The main factors for selection of an appropriate 3D modelling method for this study are "level of detail", "visual efficiency", and "understandability level" (Biljecki et al., 2015; Gröger & Plümer, 2012; Tuan, 2013; Yanbing et al., 2006). Appropriateness by means of integration of surface and subsurface structures to enhance communication between urban planners and subsurface specialists. Figure 6 presents a framework for comparison of 3D modelling methods for the purpose of this study.

"Level of detail" (LOD), states the ability of a model to provide different levels of information. Multi-value objects, provision of an attribute for objects, storage capacity, and complexity of model modification are independent criteria varies across different LODs (Gröger & Plümer, 2012; Tuan, 2013; Yanbing et al., 2006). "Visual efficiency" states effectiveness of the model utilisation and how close the information is presented to the required information. Adjacency of spatial objects, simplicity of model's concept, and integration of two separated surface and subsurface models in one user window are considerable criteria describing visual efficiency of a 3D model (Glander & Döllner, 2009; Tuan, 2013; Yanbing et al., 2006). "Understandability level" refers to expression of complex spatial objects and ability to spatially assign new information to original attributes (Biljecki et al., 2015; Yanbing et al., 2006).

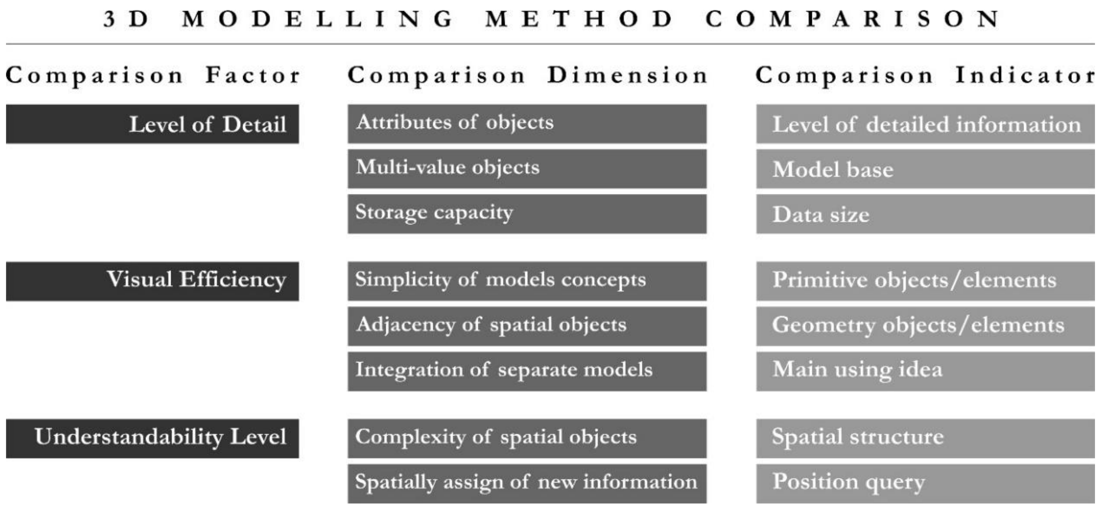


Figure 6. Framework for 3D modelling method comparison

In addition to geographical and geological 3D modelling methods, Table 6 presents possible integrated 3D modelling methods for simultaneous representation of surface and subsurface structures.

Table 6. 3D modelling methods comparison

Type	Style of model	Method	Primitive elements	Geometry elements	Model base	Main using idea	Spatial structure	Position query	Level of Detail	Data size
Geographical model	BREP (Boundary Representation)	3DFDS	Point, line, surface, body	Node, arc, face, edge	Single value map	3D city model	Vector	Yes	1	Large
		SSM	Point, line, surface, body	Node, planar, face	Simplex concept	Web-oriented visualisation, query	Vector	Yes	1	Small
		UDM	Point, line, surface, body	Node, triangle	Triangulation	City visualisation	Vector	Yes	1	Small
		OO3D	Point, line, surface, volume	Node, segment, triangle	Object-oriented modelling, triangular	City visualisation	Vector	Yes	1	Large
		City GML	Point, curve, surface, solid	Polygon, line string	Define the standards of object	3D city model	Vector	Yes	5	Large
Geological model	Voxel	Octree	Cube	None	Body divide	Geology, sea	Raster	No	1	Very large
	BREP (Boundary Representation)	TEN	Point, line, surface, body	Node, arc, triangle, tetra	Simple concept, tetrahedron	Geoinformation, pollution cloud	Vector	Yes	1	Large
		3D-TIN	Point, line, surface, body	Node, segment, triangle	Single value map, FDS (Formal Data Structure)	Geology, terrain	Vector	Yes	1	Large
		GTP	Point, line, surface, body	Node, line, face, diagonal	Body divide	Geological engineering	Vector	Yes	1	Large
	CSG	CSG	Basic 3D blocks like cube, cylinder, cone, prism, and sphere	NULL	Combine basic 3D block	Civil 3D visualisation	Vector	Yes	1	Small

Type	Style of model	Method	Primitive elements	Geometry elements	Model base	Main using idea	Spatial structure	Position query	Level of Detail	Data size
Integrated model	Combination modelling	BREP + CSG	Point, line, surface, body, basic 3D block	Line string, face	OO modelling, triangular, Combine basic 3D block	3D city model and visualisation	Vector	Yes	1	Large
		TIN + CSG	Point, line, surface, body, DEM	Node, segment, triangle	Surface divide	3D city model	Vector	Yes	1	Large
		TIN + Octree	Body; pyramid	Node, segment, triangle, cube	TIN express, surface, Octree express inside	3D city model, geological engineering	Vector/Raster	Yes (partially)	1	Very large
		TEN + Octree	Body; pyramid	Cube, node, arc, triangle, tetrahedron	Octree express (whole), TEN expresses (part)	Geological engineering	Vector/Raster	Yes (partially)	1	Very large
		OO3D-ISDM; OO3D + GTP + TIN	Point, line, surface, body	Node, face, diagonal, segment, triangle	Integrated 3D concepts, surface divide, object-oriented triangular	3D city model and visualisation, geological and topological engineering	Vector	Yes	1	Large
	Procedural modelling	L-system	Point, line, surface, body	Node, segment, face, triangle, diagonal	Integrated 3D object-oriented concepts, surface divide	3D city model and visualisation, geological and topological engineering	Vector/Raster	Yes	5	Large

Source: adapted from Biljecki et al. (2015); Gröger and Plümer (2012); Parish and Müller (2001); Smelik, Tutenel, Bidarra, and Benes (2014); Tuan (2013); Yanbing et al. (2006); Wu (2004)

According to Table 6, "OO3D-ISDM", a combination of geological and geographical methods (i.e., OO3D, GTP, and TIN); and L-system, a procedural modelling method are identified alternatives for an integrated 3D modelling of surface and subsurface structures.

Yanbing et al. (2006) introduced OO3D-ISDM (object-oriented 3D integral spatial data model) based on the combination of OO3D, TIN, and GTP. This method develops integral 3D spatial structures with Visual C++, OpenGL and SQL server. In addition, it provides a similar type of geometrical element with different attributes in geographical level. In this model, point, line, surface, and body present all spatial objects (Yanbing et al., 2006, p. 101). The involvement of GTP method in this model helps with different borehole data to ensure the reliability and quality of 3D geological information (Wu, 2004).

L-system, a procedural modelling technique, provides semi-automatic generation of various surface and subsurface 3D objects such as terrain, vegetation, buildings, utilities, landscape, transit network, and geological layers (Smelik et al., 2014). This method is based on shape grammar which directly defines rules for object modelling (Parish & Müller, 2001). Data amplification and data compression are considerable advantages of this 3D modelling method (Smelik et al., 2014). On the one hand, data amplification refers to the capability of this method in producing various types of models by using a few input variables or shape grammar rules. On the other hand, data compression states the capability of the model to generate complex geometries only when simulation is needed, while related statistical information is provided. In addition, this method provides various levels of detail regarding the use. For instance, in urban planning at the early vision stage, LOD 1 presenting general schemes of surface/subsurface structures is sufficient. By deepening the focus at design stage of planning, higher levels of detail are required which this method is also supportive.

To select the most proper modelling method for this study, required states of comparison factors (presented in Figure 6 and Table 6) are identified. In order to model the built and natural environments of surface and subsurface structures, several primitive objects are required to be integrated. For instance, point for location of trees; line for infrastructure networks; surface for geological layers; and body for buildings, foundations, and water body. Moreover, topological raster files are required for visualisation and analysis of surface condition. In addition to the integration of vector and raster spatial structures, query is required for assigning new transformed data to corresponding locations. Therefore, the procedural L-system modelling method is selected for the purpose of this study. Considerably, L-system method could support 3D urban modelling with specialised analytical tools.

A GIS (Geo-Information Science) software platform, CityEngine in combination with ArcGIS Pro are selected for an integrated 3D modelling of surface and subsurface information in this study. L-system method in CityEngine is generated based on a programming language specified for 3D concepts, CGA (Computer Generated Architecture). This shape grammar enables combination of different geometrical elements (e.g., node, face, segment, and triangle). CityEngine shape grammar is utilised for development of 3D geological and geographical objects. In addition, spatial analysis of interactions between surface and subsurface structures is needed for this study. L-system method supports a combination of different geo-based software. Therefore, for further analysis, the generated 3D model is used in ArcGIS Pro platform for spatial analysis of interactions between surface and subsurface structures. Table 7 identifies the interactive utilisation of CityEngine and ArcGIS Pro in this study. Cells in highlight present aspects that each (i.e., CityEngine and ArcGIS Pro) is more powerful regarding the use of this study.

Table 7. Combination of CityEngine and ArcGIS Pro in an integrated 3D modelling

Stage		**ArcGIS Pro**	**CityEngine**
Procedural geometry	2D to 3D procedural engine	Yes	Yes
	Interactive design tool (Dynamic reports, handles, local edits, etc.)	No	Yes
	Rule authoring	No	Yes
	Dynamic 3D streets and blocks	No	Yes
3D data types	BIM import	Partly	Partly
	Multi-patch editing	No	Yes
	3D export	No	Yes
3D visualisation	Scales	Global and local	Local
	Rendering	Streaming, adaptive	In-memory
	Animation	Yes	No
	Analysis	Yes	No

Source: adapted from Deol and Wittner (2017)

In summary, this study develops an integrated 3D model based on procedural L-system 3D modelling method using CGA shape grammar. For this purpose, CityEngine software is used for procedural geometry and 3D visualisation, since the focus is at local scale. Then, ArcGIS Pro software is used for 3D analysis (Table 7).

2.3. Concluding remarks

This chapter, explains interactions between surface and subsurface structures. On the one hand, an actual interaction is happening spatially among both natural and built environments of surface and subsurface structures. On the other hand, there are potential interactions among surface and subsurface structures which might lead to productive, provisional, and protective subsurface solutions to urban problems. Considerably, risk of surface water flooding is the main problem of development situation of the focused study area in this research related to its natural situation. Contribution of subsurface structure to this issue, in this study, is analysed by a developed index containing three main aspects: risk of surface water flooding, presenting current state of the issue in the area; potential demand targeting, referring to the needs of urban area to managing this issue; and the potential supply inventory, presenting the contribution of subsurface structure (both natural and built environments) to managing the issue of surface water flooding. To implement this analysis in a 3D visualisation and analytical platform, a procedural modelling method is selected to generate an integrated 3D surface/subsurface model. CityEngine based on CGA, a specified shape grammar, is selected to generate the integrated 3D model since it provides semi-automatic model development within a real visualisation at local scale. Then, for spatial analysis, ArcGIS Pro which is compatible with exports from CityEngine, is selected for 3D spatial analysis.

Next chapter explains the area that this study aims to examine these issues for.

3. FIELD OF STUDY

This study aims to investigate role of an integrated 3D model in dealing with the issues of knowledge exchange and development situations (i.e., physical and social developments) in a particular setting. This setting was identified by the City of Rotterdam, where all these issues are actual and have come together. They are looking exactly now at what to do with this area and how to improve it. Following sections explain the location of the setting and related information to its natural and development situations. In addition, current state of the Municipality of Rotterdam in this (re)development project is explained. In the end, description of collected data is presented.

3.1. Study area

Bloemhof is an old neighbourhood located in the district of Feijenoord, central to south part of the Rotterdam city. Figure 7 shows the location of this neighbourhood in the city of Rotterdam (on the left) and its general structure (on the right). As a brief overview, the neighbourhood with an approximate 79 hectares area is located with approximate 200 meters distance to the south from the main river of the city. The edges consist of mostly private properties along main roads, Putselaan in the north, Hillevliet and the Green Hill in the east, south the Strevelsweg and Dordtselaan on the western side of the neighbourhood. A 1 km-length canal divides the neighbourhood into two north and south parts. Bloemhof south is the main concern of the City of Rotterdam regarding its natural and development situations.

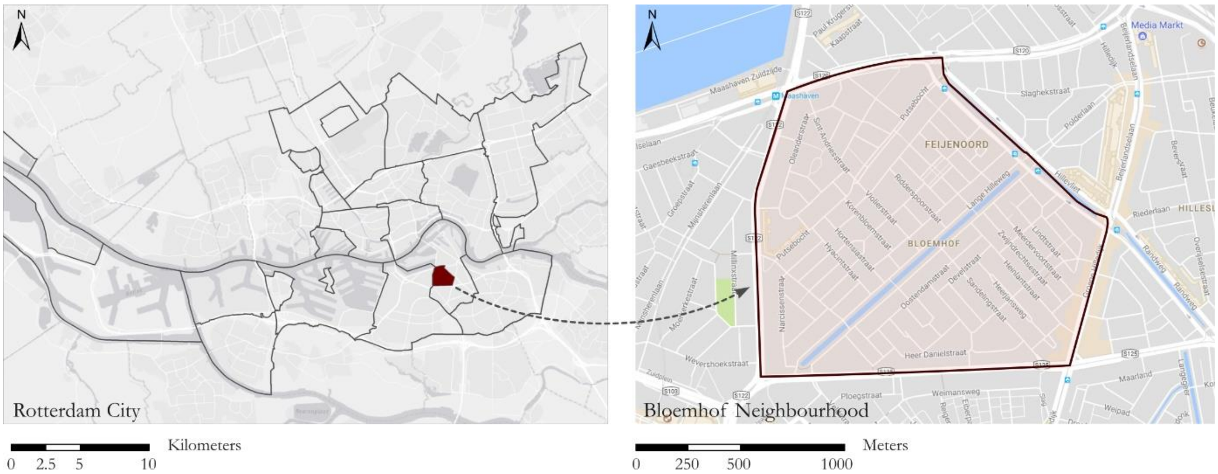


Figure 7. Bloemhof neighbourhood, Rotterdam city
Source: Data from Open street map and Google maps

The agreement of Bloemhof with other neighbourhoods in the Feijenoord district is multicultural and relatively young people. This offers opportunities. However, a significant proportion of the population is now limited by low education, low income and relatively high unemployment. In addition, the safety and living conditions are under pressure (van Wijk, Bahadoer, & Kuijpers, 2013). Throughout the neighbourhood, there is a variety of experiences within compact urbanisation along narrow streets, a long canal, and small squares. The accumulation of these aspects causes multiple issues and has been the reason that makes Bloemhof one of the 7 focus areas within the framework of the "National Program of Rotterdam South" (Steenhuismeurs, 2016). Since this study is about natural situation related to development situation, following subsections give related information of the Bloemhof neighbourhood. On the one hand, development situation states the condition of physical and demographic developments in Bloemhof. On the other hand, natural situation explains the natural surface/subsurface conditions that the city is dealing with in this neighbourhood.

3.1.1. Development situation

Bloemhof is one of the most densely populated areas in the Netherlands (Steenhuismeurs, 2016). On average, residential streets have a width of approximately 6.5 meters between the front gardens. This means that in the residential streets next to a lane and one-sided long-car parking there is hardly any space for sidewalk. In addition, there is a shortage of green area which creates a stony appearance for the neighbourhood. There are little green and considerable lack of parks throughout the neighbourhood. The layout of parks, squares and plantations in the neighbourhood is very uniform in view and use. Almost all are hardened and lacking in greenery. In recent years, efforts have been made to make the neighbourhood greener (The Municipality of Rotterdam, 2015). However, significant increasing physical and demographic issues over time affect the development process. Following statements explain gradual physical development of the neighbourhood and its social changes.

Physical development of Bloemhof goes back to 1981 when it was designated as urban renewal area due to a high housing demand of new workforce. The neighbourhood was ruined, and homes were in poor condition. For the biggest part of the neighbourhood, housing improvement was the satisfactory solution. Regarding historical values, mostly in eastern part of the neighbourhood, renovation was applied, and in case of failure, replacement of structures by new constructions was decided. Large-scale innovation was found at places with lower construction quality (van Wijk et al., 2013). The centre of the neighbourhood was radically renewed, and subsequently, the high housing density was significantly reduced by halving the housing number to eight hundred. The new spatial structure brought new squares and wider streets. Figure 8 shows the gradual physical development of Bloemhof over time before twentieth.

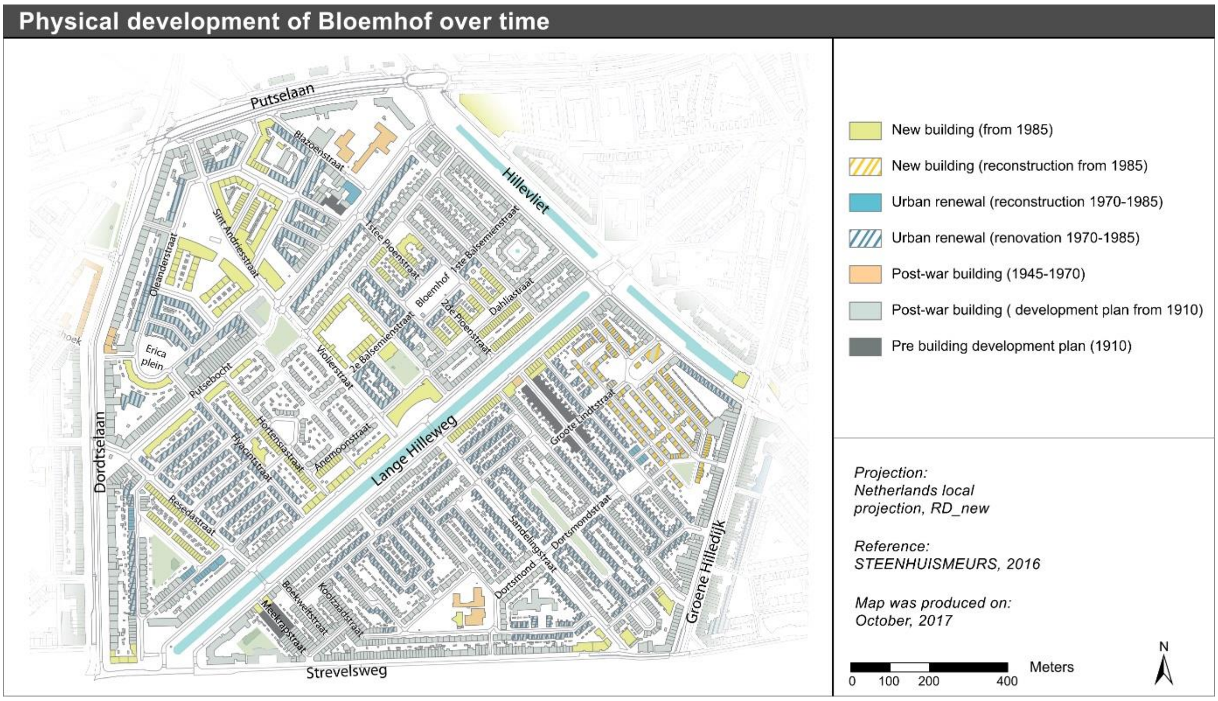


Figure 8. Physical development of Bloemhof over time
Source: adapted from Steenhuismeurs (2016)

Although the neighbourhood was considerably (re)developed over the last century, the constructions were mostly done in poor conditions. According to Figure 9, more than half of the buildings have steel constructions and the rest wooden. Strong structures are rarely found in the neighbourhood.

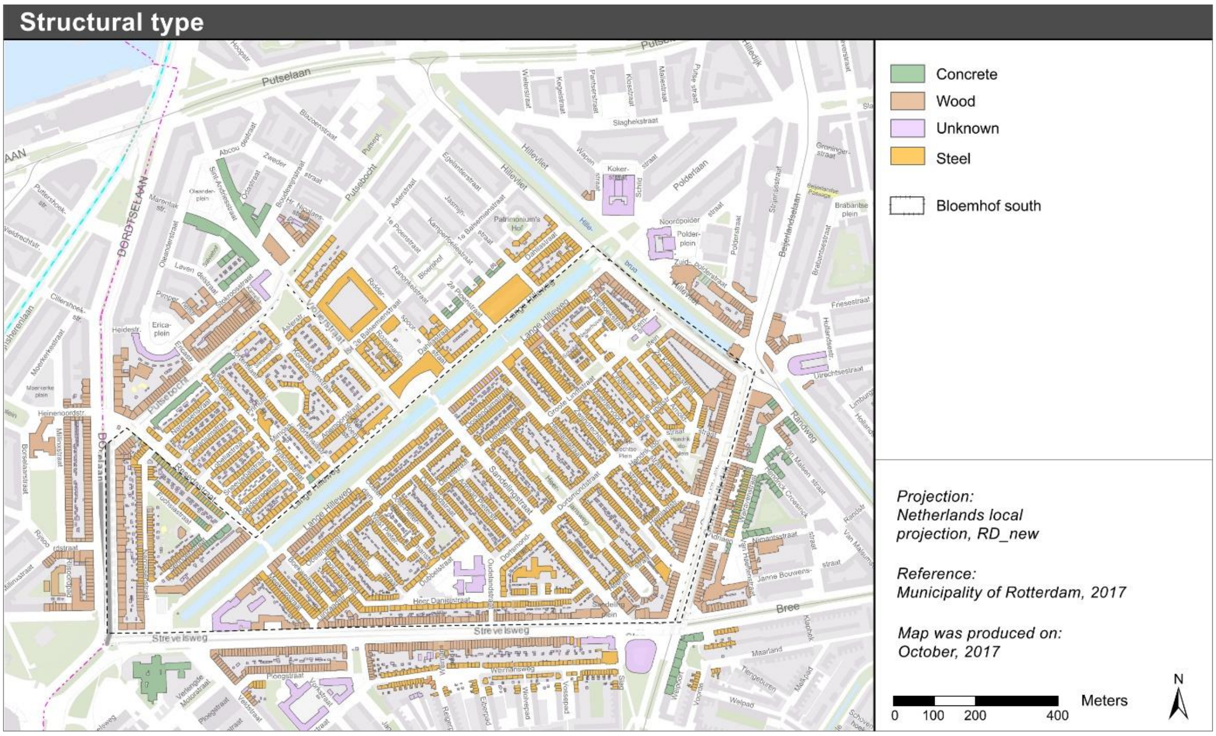


Figure 9. Structural type of building in Bloemhof neighbourhood
Source: Data from Provided datasets by The Municipality of Rotterdam

This matter is worsened in the southern part of the neighbourhood where most of the buildings are founded without piles or on wooden piles and less experienced stringer types of foundation (i.e., concrete piles) (Bloemhof south mostly had renovation plans rather new constructions) (Figure 10).

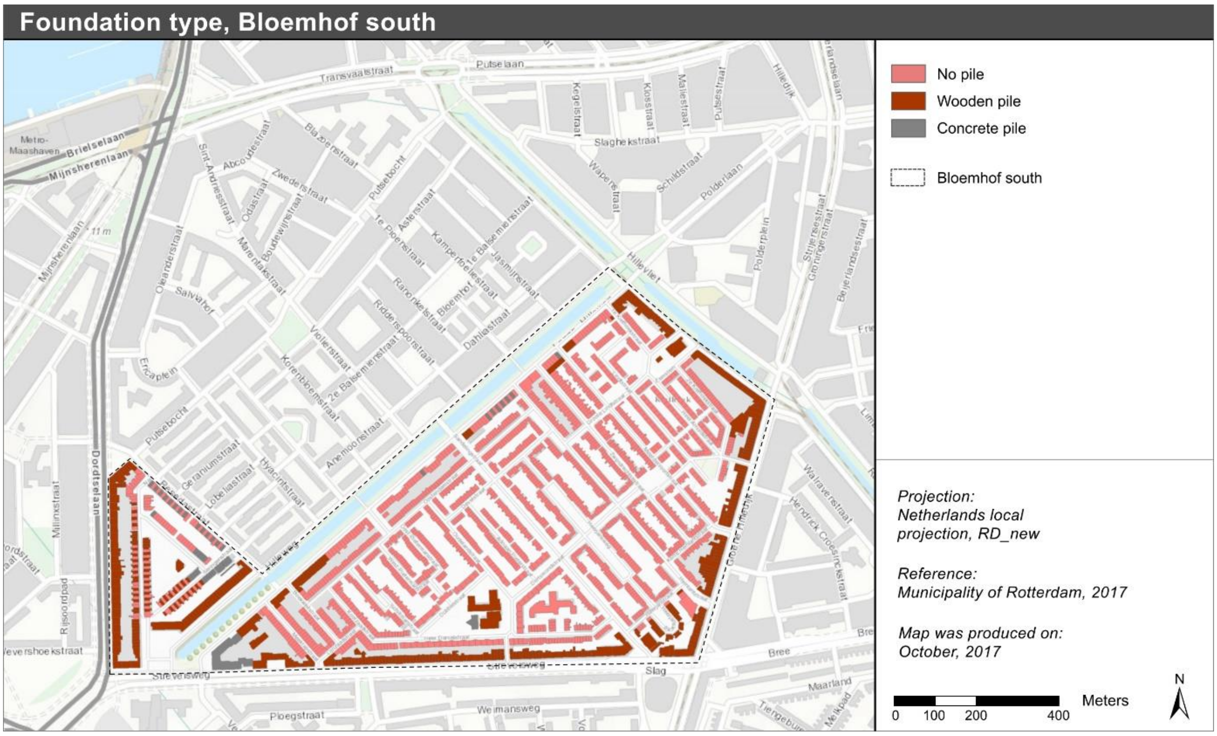


Figure 10. Foundation type of buildings in Bloemhof south
Source: Data from Provided datasets by The Municipality of Rotterdam

These issues were proved by a field survey and discussion with The Municipality of Rotterdam. Figures 11 and 12 respectively illustrate cracked and collapsed buildings in Bloemhof south due to poor quality of constructions. However, issues related to natural situation of the neighbourhood are highly influential in this matter (explained by subsection 3.1.2.).

Figure 11. A cracked building in Bloemhof
Source: Private photo by the author, 20 July 2017

Figure 12. A collapsed building in Bloemhof
Source: Private photo by the author, 20 July 2017

Over time, the quality of buildings and subsequently the social structure of the neighbourhood have been degraded. However, regarding cost-effective housing values comparing to surrounding areas, Bloemhof became the host of new immigrants (Steenhuismeurs, 2016). By gradual movements of immigrants to this neighbourhood, housing development increased, and building density[2] reaches 0.74 at 2017 which is relatively high compared to other neighbourhoods of Rotterdam with nearly similar size (Centraal Bureau voor de Statistiek, 2017). Thus, the neighbourhood is currently almost fully developed. The northern part of the neighbourhood characterises three- to four-floor housing, while southern part consists mainly low-rise buildings with many small streets (Steenhuismeurs, 2016). Noticeably, physical developments have affected social and demographic developments of the neighbourhood.

Demographic development of the neighbourhood represents a deterioration trend of social development (The Municipality of Rotterdam, 2015). The neighbourhood faces considerable immigrants' movements in the last century which according to Centraal Bureau voor de Statistiek (2017) is about 77% of total population in 2016. So, Bloemhof is now a multicultural district with more than 150 different nationalities. Of 14,000 inhabitants in 2016, about 70% have a different cultural background (Steenhuismeurs, 2016). In addition, demographics state that in 2016, 77% of the Bloemhof population are immigrants and 70% are below 45 years old (Centraal Bureau voor de Statistiek, 2017; Steenhuismeurs, 2016).

Figure 13 shows demographic changes of Bloemhof over time (2004-2016). According to figure 13, it is concluded although the population of Bloemhof has not experienced significant fluctuations, the gradual increase of immigrants' arrival to the area results in the departure of native residents to other areas. These demographic changes have the result of being characterised by low level of education, low income and relatively high unemployment.

[2] Building density is calculated by dividing total area of built up lands by total area of the neighbourhood.

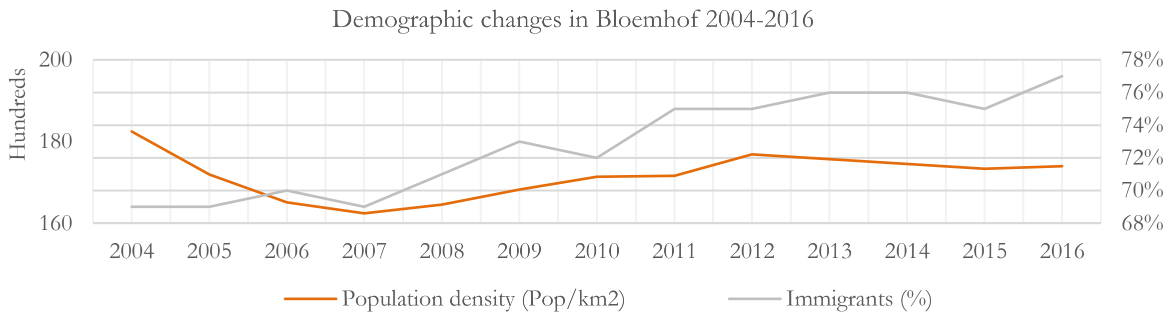


Figure 13. Demographic changes in Bloemhof 2004-2016
Source: Data from Provided data by The Municipality of Rotterdam, CBS 2004-2016

In summary, Bloemhof, over time, has experienced physical developments by means of high building density and social degradation in terms of a community with low level of education, low income and relatively high unemployment (Steenhuismeurs, 2016; van Wijk et al., 2013). These issues have led the attention of urban authorities toward physical interventions in order to monitor and upgrade current condition. Therefore, in 2005 a physical development vision of Bloemhof for 2020 has been drawn up by The Municipality of Rotterdam. This document adopted a plan to the tackle problems and utilise opportunities (The Municipality of Rotterdam, 2007). They explored “the protection of natural situation” as a possible opportunity for the provision of physical developments. However, considerable weaknesses of the plan in physical development indicates the current natural situations of the neighbourhood which requires improvement. Following subsection provides information about natural surface and subsurface situations of Bloemhof. On the one hand, natural surface situation explains state of green spaces, and on the other hands, natural subsurface situation states the condition of groundwater and soil in Bloemhof.

3.1.2. Natural situation

Although the natural situation of Bloemhof has been influenced by physical developments over time, it has considerable impacts on development process. The natural situation of the neighbourhood consists of water, vegetation, and soil at above- and below- ground level. On the one hand, its situation at surface (above-ground) level has faced increasing degradation since building constructions, and the subsequent surface pavements have paced. Therefore, the neighbourhood has been confronted with a gradual loss of greenery. On the other hand, its natural situation at subsurface (below-ground) level has a poor condition. Considerably, almost all soils at shallow level are clay which inevitably brings about less water infiltration and soil moisture. This matter has been worsened due to the low level of groundwater throughout the area. Accumulatively, low groundwater level, dominant clay soil type, and great amount of buildings with poor foundation quality (mostly without pile or on wooden piles) bring about development difficulties such as soil subsidence, reducing groundwater recharge, rotting wooden piles, and building collapse (The Municipality of Rotterdam, 2015).

Following statements provide detailed information about mentioned issues related to the natural situation of the Bloemhof south (i.e., soil subsidence and groundwater discharge).

Soil subsidence is a considerable geological issue of Bloemhof. This neighbourhood is a low-lying area characterising as a swamp with noticeable sinking probability (The Municipality of Rotterdam, 2007). Figure 14 shows the average annual height of soil subsidence (meter) throughout the south part of the neighbourhood. Along with foundation information presented by Figure 10, it is concluded that buildings which are constructed without pile are more prone to subsidence than those buildings on wooden piles. However, both have a poor condition and requires improvement/consideration. In other words, the absence of piles in building structure leads to more pressure on soil. It shows absence of development solutions to this issue.

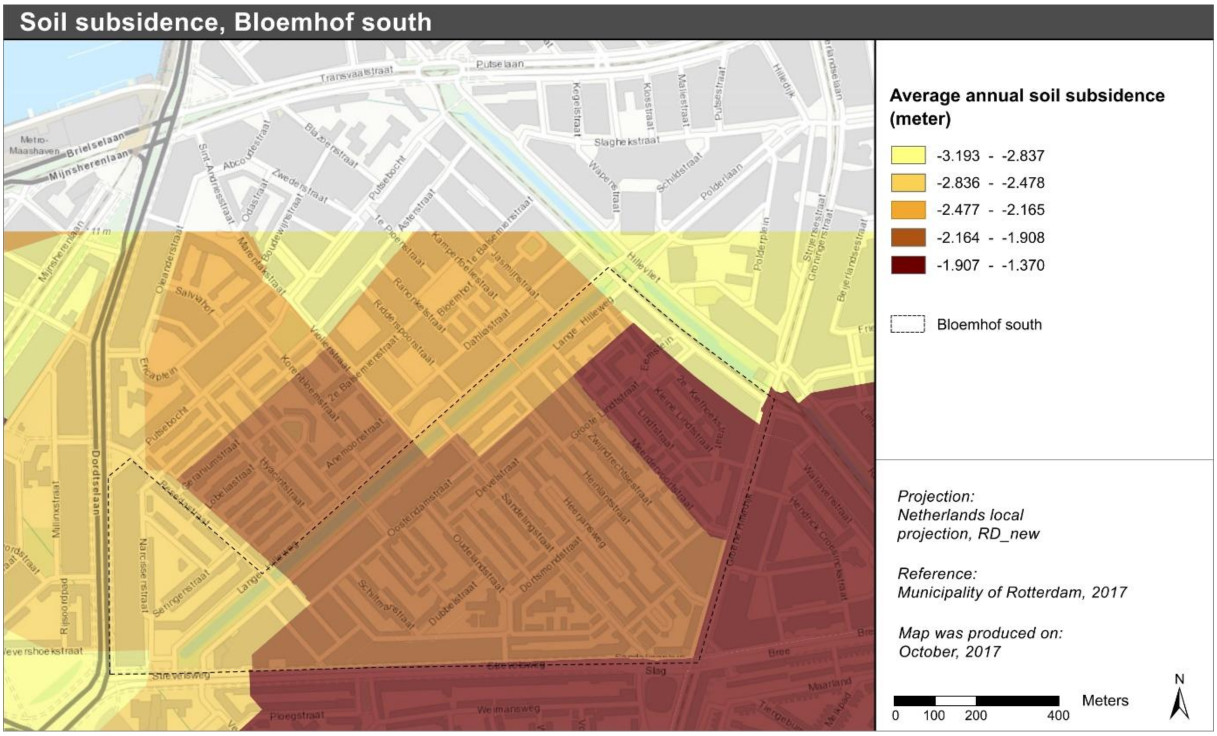


Figure 14. Soil subsidence in Bloemhof south 2017
Source: Data from Provided datasets by The Municipality of Rotterdam

However, type of soil is not an issue that could be solved by replacement resolutions. Therefore, controlling and monitoring solutions might help the area with soil-related issues. Foundation type is a development related concern. More into natural-related aspects, groundwater is an essential concern which might affect sinking of buildings over time.

The groundwater level affects development process in Bloemhof neighbourhood, especially southern part. According to Figure 10, 97% of buildings in Bloemhof south are those 'without pile' or with ' wooden pile' (The Municipality of Rotterdam, 2015). Considerably, these types of foundation are directly affected by soil moisture since wood is prone to rot in the absence of water. Therefore, groundwater level and water infiltration rate which are main factors of soil moisture should be considered. The closest the groundwater to building foundation (for wooden piles), the better the building resistance against sinking. Figure 15 shows the highest level of groundwater throughout Bloemhof south. It shows the absence of groundwater level in shallow level (i.e., less than 1.5 meters below ground level where piles are constructed) in almost all areas in Bloemhof south. In the absence of groundwater, water infiltration may positively influence soil moisture. However, according to Figure 16, soil moisture and water infiltration in Bloemhof south is too low, 0.1 to 1 mm per day (since the neighbourhood is fully developed and lacks green spaces) (Steenhuismeurs, 2016; The Municipality of Rotterdam, 2015). These facts clarify that the soil in Bloemhof south would be dry and the gradual increasing collapse of buildings should be expected.

Along with all mentioned soil- and groundwater- related issues in Bloemhof south, there are plenty of complaints against surface water flows throughout the neighbourhood. Surface water flooding is the result of rapid development and lowering green spaces. In addition, the clay soil reduces water infiltration and along with the considerable paved lands result in surface water flow/stagnant. This matter is worsened by the high possibility of heavy rain in the area (Ministerie van Infrastructure en Waterstaat, 2017).

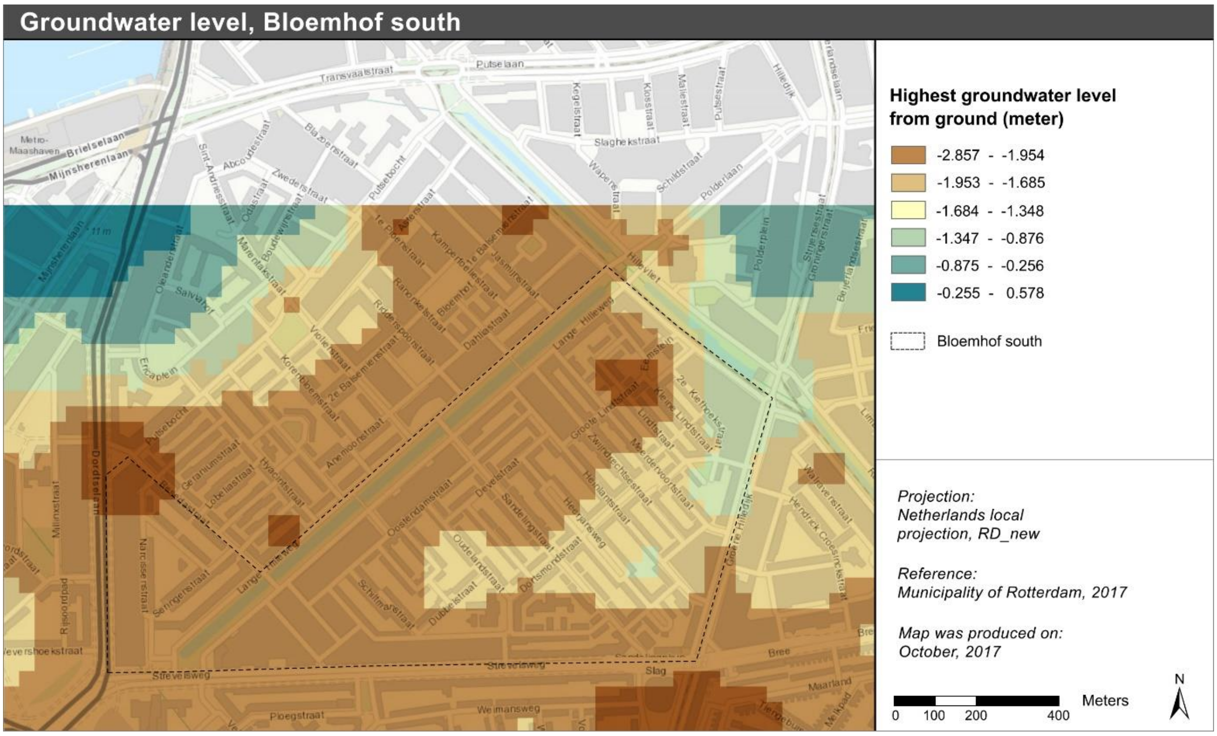


Figure 15. Groundwater level in Bloemhof south, 2017
Source: Data from Provided datasets by The Municipality of Rotterdam

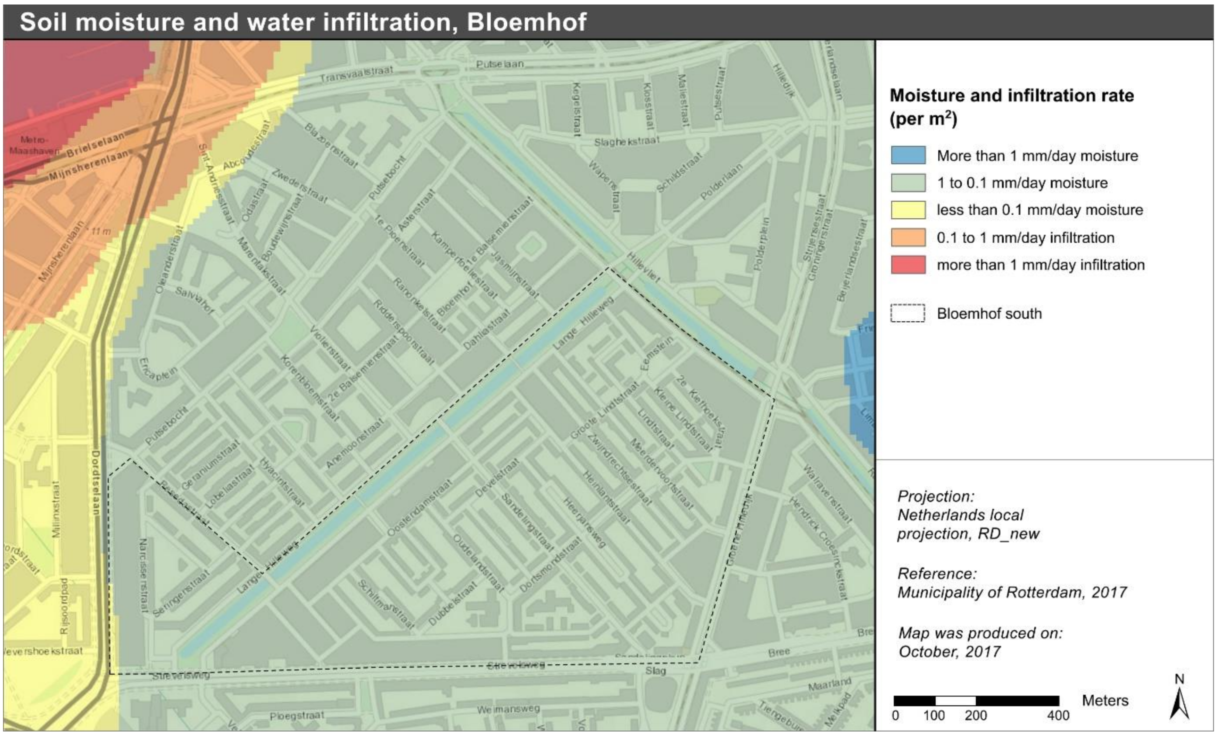


Figure 16. Soil moisture and water infiltration in Bloemhof
Source: Data from Provided datasets by The Municipality of Rotterdam

Table 8 briefly concludes weaknesses, strengths, threats, and opportunities of Bloemhof based on Steenhuismeurs (2016); The Municipality of Rotterdam (2017); and van Wijk et al. (2013).

Table 8. SWOT analysis of Bloemhof south

Internal environments		**External environments**	
Strength	**Weakness**	**Opportunity**	**Threat**
• Quiet urban living environment • Grounded homes • 1km-length canal	• Low social characteristics; unemployment, low education level, and low income • Low security rate; unsafety • High building density • Lack of green space • Clay soil • No groundwater available in the first 2-meter depth below ground level • 97% of buildings were constructed without pile or on wooden piles	• Young population • Monuments • Employment in the area • Subsurface space	• Neglect as a result of cut (trees) • Decreased safety • Decreasing economic state of the area • Heavy rainfall • Surface water flooding

Source: adapted from Steenhuismeurs (2016); The Municipality of Rotterdam (2017); van Wijk et al. (2013)

To conclude, clay soil with low infiltration rate, extensive land development, little green space, deep groundwater resources, low soil moisture rate, and great amount of buildings without pile or with wooden pile are main factors which bring about development difficulties in Bloemhof south. The three former factors result in issues related to surface water flooding. Risk of surface water flooding along with the latter three factors makes Bloemhof one of the 7 focus areas of the city.

This conclusion along with results of expert interviews about the main concern of planners for Bloemhof development (section 5.1.) identify the focus of this study for analysis and modelling. However, it is required to know about current state of the city in Bloemhof (re)development process. Following subsection presents a brief overview of what the Municipality of Rotterdam has done to integrate natural situation (subsurface) with development situation (surface) of Bloemhof.

3.2. State of Bloemhof (re)development

Regarding (re)development plans of Bloemhof, the City of Rotterdam develops considerable number of specialised models to explore geological, hydrological, and engineering information. However, for integration of surface and subsurface information, there is a developed 3D Voxel model containing land cover types (i.e., buildings, transit network, and water), elevation, groundwater depth, foundation, and geological information (i.e., soil layers).

Figure 17 illustrates a bird view (on the left), and a cross-section (on the right) captures of this model. This model offers three adjacent layers named anthropogenic layer, groundwater fluctuation layer, and geological layers. The anthropogenic layer contains water, road, sidewalk, and buildings. The model was presented to groups of urban planners and subsurface specialists. However, according to the Municipality, the model does not effectively contribute to the enhancement of interactions between urban planners and subsurface specialists. On the one hand, although urban planners were interested in spatial adjacency of surface and subsurface structures, their demand for analysed information and simultaneous calculation of different urban concerns (e.g., flooding risk) was not met. On the other hand, subsurface specialists did not find the geological information more useful than their own specialised model with considerable level of detail. Therefore, this study aims to develop a procedural 3D model including concerns of both planners and subsurface specialists for an integrated surface and subsurface development. Next section (3.3) explains exact spatial focus of this study for modelling and analysis. In addition, it provides detailed description of obtained data for further modelling and analysis.

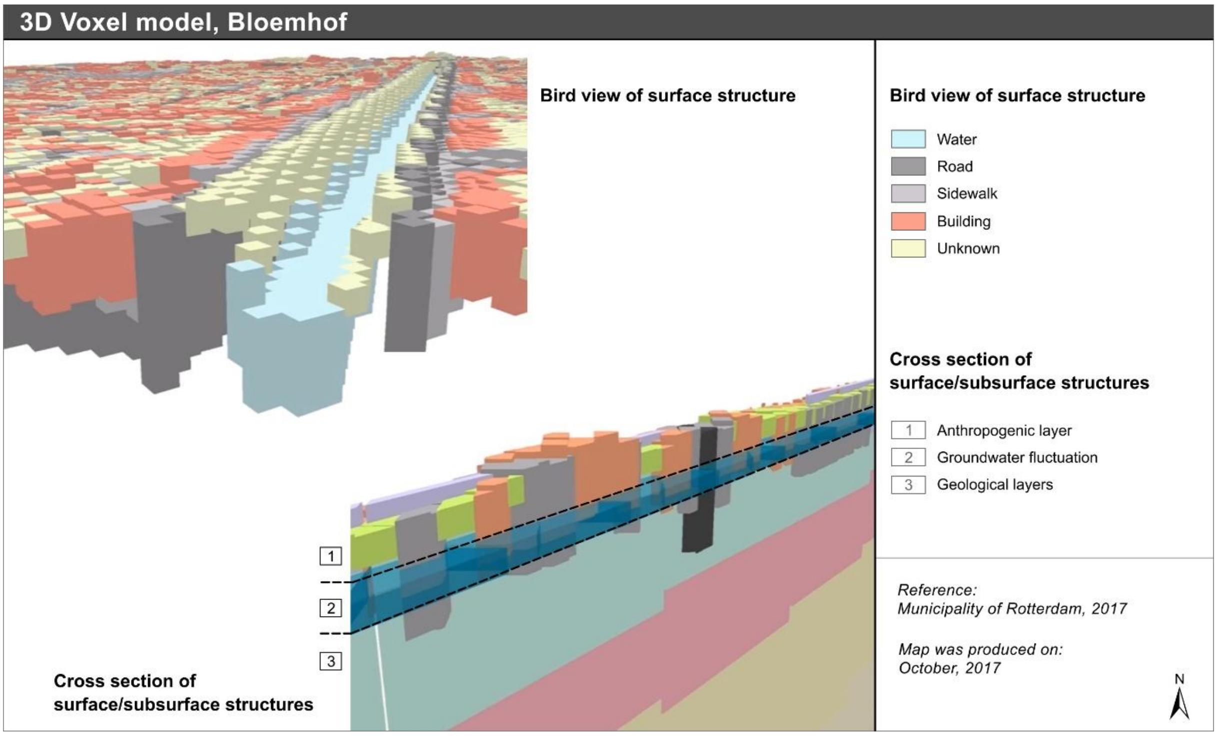


Figure 17. 3D Voxel model of Bloemhof
Source: adapted from Vuijk (2017)

3.3. Data description

Data availability; focus area of the Municipality for planning; and administrative boundaries are main factors that specify spatial focus of this study in modelling and analysis. Figure 18 shows effect of these factors in selection of the desired area in this study.

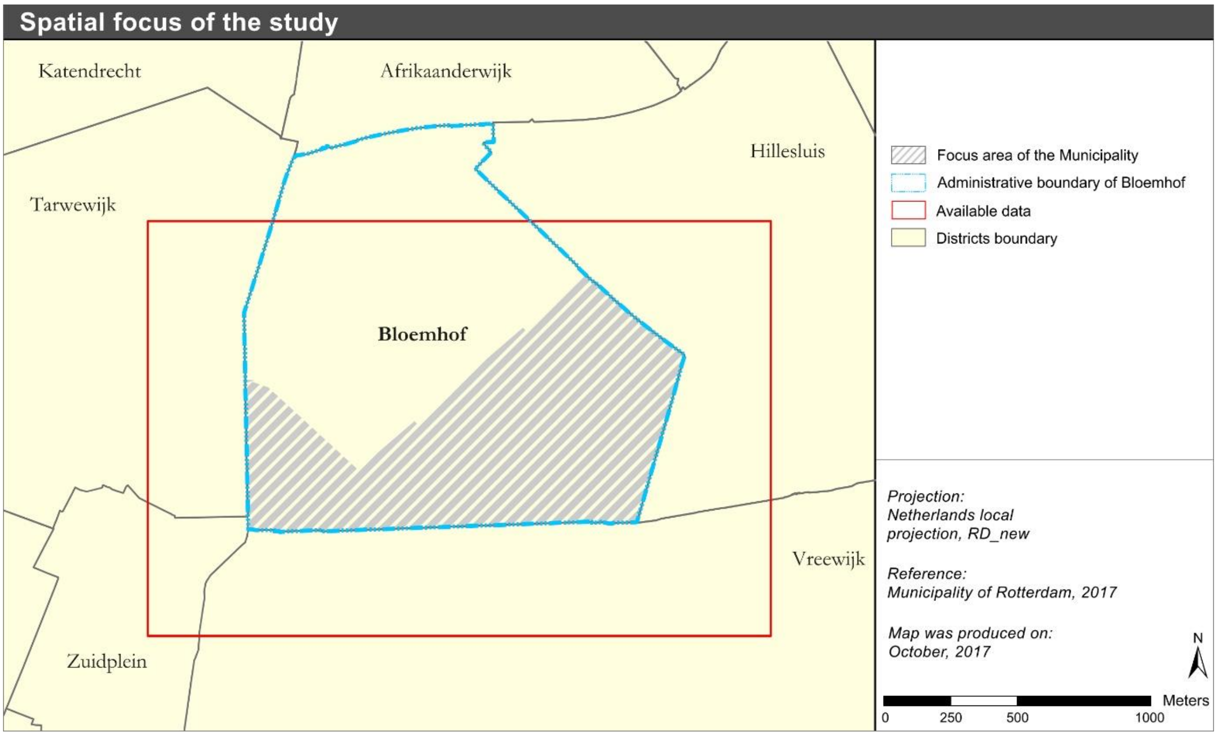


Figure 18. Specification of study area
Source: Data from Provided datasets by The Municipality of Rotterdam

According to section 5.1., the concern of this study is on surface water flooding which is a matter not only influenced by issues within an area, but also surrounding areas will also be involved in its changes. Therefore, the area of available data (red box in Figure 18) which also covers the focus of the municipality is identified as the desired area for this study.

Required secondary data for this study is collected from several sources such as the Municipality of Rotterdam and some online national geo-datasets (e.g., PDOK, DINOloket, Waterloket and Funderingsloket[3]). Table 9 presents descriptions of the collected data.

Table 9. Data description

Name	Description	Format	Accuracy	Source	Extent
Rainfall frequency	Number of rainy days in a 30-year period (1987-2017)	Text	Per day	KNMI[4]	Rotterdam
Rainfall intensity	Highest amount of precipitation in a 30-year period (1987-2017)	Text	In 0.1mm	KNMI	Rotterdam
Parcels	Land use types; road, green, water, built area, and dyke (canal)	Vector (polygon)	By dwelling	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre[5]
Drainage network	All cables and pipes networks with connection points with buildings	Vector (polygon)	By postcode	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Soil subsidence	The average amount of soil sinking in 2017	Vector (polygon)	By dwelling	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Digital Terrain Model	Surface elevation of the area	Raster	1m * 1m	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Main river	Core and protection zone of the river	Vector (polyline and polygon)	In mm	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Population	Detailed demographic information; per age, gender, and ethnicity	Vector (polygon)	By neighbourhood	CBS 2009-2017	Bloemhof
		Vector (grid)	100*100 m	CBS 2009-2017	The Netherlands
		xlsx.	By postcode	CBS 2016	Rotterdam
Surface water complaints	Complaints of various sources for flooding to the Municipality	Vector (point)	Not applicable	The Municipality of Rotterdam	Rotterdam

[3] Some of these portals such as Funderingsloket and DINOloket were used to check data quality and certainty of collected data regarding description of different sources.

[4] See (Ministerie van Infrastructure en Waterstaat, 2017)

[5] Red box presented by Figure 18

Name	Description	Format	Accuracy	Source	Extent
Cultural heritage	Monuments by different value scale; national, municipality, and future	Vector (polygon)	Not applicable	The Municipality of Rotterdam	Rotterdam
Water infiltration rate	Water infiltration rate in mm per day	Vector (polygon)	In mm per day	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Soil characteristic	Thickness of different soil layers	Vector (point)	100m * 100m	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Groundwater	Groundwater highest and lowest depth level	Raster	25m * 25m	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Wells	Location of wells and their average annual capacity	Vector (point)	Not applicable	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Foundation	Type of buildings' foundation	Vector (polygon)	By dwelling	The Municipality of Rotterdam	A 1500 km^2 area containing Bloemhof south in centre
Sewerage	Pipelines and sewerage connections	Vector (polyline) Vector (point)	By postcode By dwelling	Waterloket, and The Municipality of Rotterdam	Rotterdam
Monetary value	Average house value	xlsx.	By neighbourhood	CBS 2009-2017, PDOK	Rotterdam
Poverty	Average household income, low-income households, and households below social minimum	xlsx.	By neighbourhood	CBS 2009-2017, PDOK	Rotterdam

4. METHODOLOGY

The overall approach of this study is a mixed qualitative-quantitative method. To be specific, different data collection, process and analysis methods were applied to address each sub-objective and related questions of this study. Figure 19 explains the overall approach of the research and following statements explain choice rationale.

Data collection phase contains different qualitative methods regarding variety of required data. This study requires specialised information related to geological properties; groundwater; underground infrastructure; surface buildings; surface infrastructure; terrain; etc. Therefore, literature review and expert interview are appropriate data collection methods to deploy an integrated and a multidisciplinary set of information in addition to efficient feedbacks on process (Liu et al., 2008). In addition, focus group discussion involving experts and questionnaire is the aimed techniques for validation of the result. Model validation indicates usefulness of research output (the 3D model).

Data process phase contains mixed qualitative-quantitative data preparation methods such as data harmonisation and data quality assessment. Data harmonisation led the study to an effective distinction of natural and built environments of surface and subsurface structures, and supported inclusion of all various surface/subsurface uses (Kaliampakos et al., 2016). In addition, data quality assessment eased generation of a valid and real representative set of information (Tegtmeier, Zlatanova, van Oosterom, & Hack, 2014).

Data analysis phase includes both qualitative and quantitative methods. A mixed information transformation was applied on both surface- and subsurface- related data to provide effective communication between involved specialised participants (Xu, Ding, Luo, & Ma, 2014). This was done through several spatial, geospatial, and statistical analytical methods to analyse planning consideration variables in relation to specialised data by use of obtained weights through Principle Component Analysis technique. Moreover, the analysed and transformed data was visualised in 3D using rule-based modelling technique. Furthermore, the usefulness and effectiveness of the generated 3D model were evaluated by SWOT analysis method.

Specific objective	*Data collection*	*Data process*	*Data analysis*
Surface/subsurface interactions	Literature review Semi-structured expert interview		
Demand-driven knowledge exchange	Semi-structured expert interview	Data quality assessment	
Data transformation	Literature review	Data harmonisation	Geospatial analytical techniques Principle Component Analysis Point-biserial correlation
Integrated 3D modeling	Literature review		Method comparison 3D model development
Model validation	Focus group discussion Questionnaire		SWOT analysis

Legend: Qualitative Quantitative Mixed

Figure 19. Overall research approach

To give an overall view of research methodology, Figure 20 presents a flowchart of general implemented methods and techniques across research specific objectives.

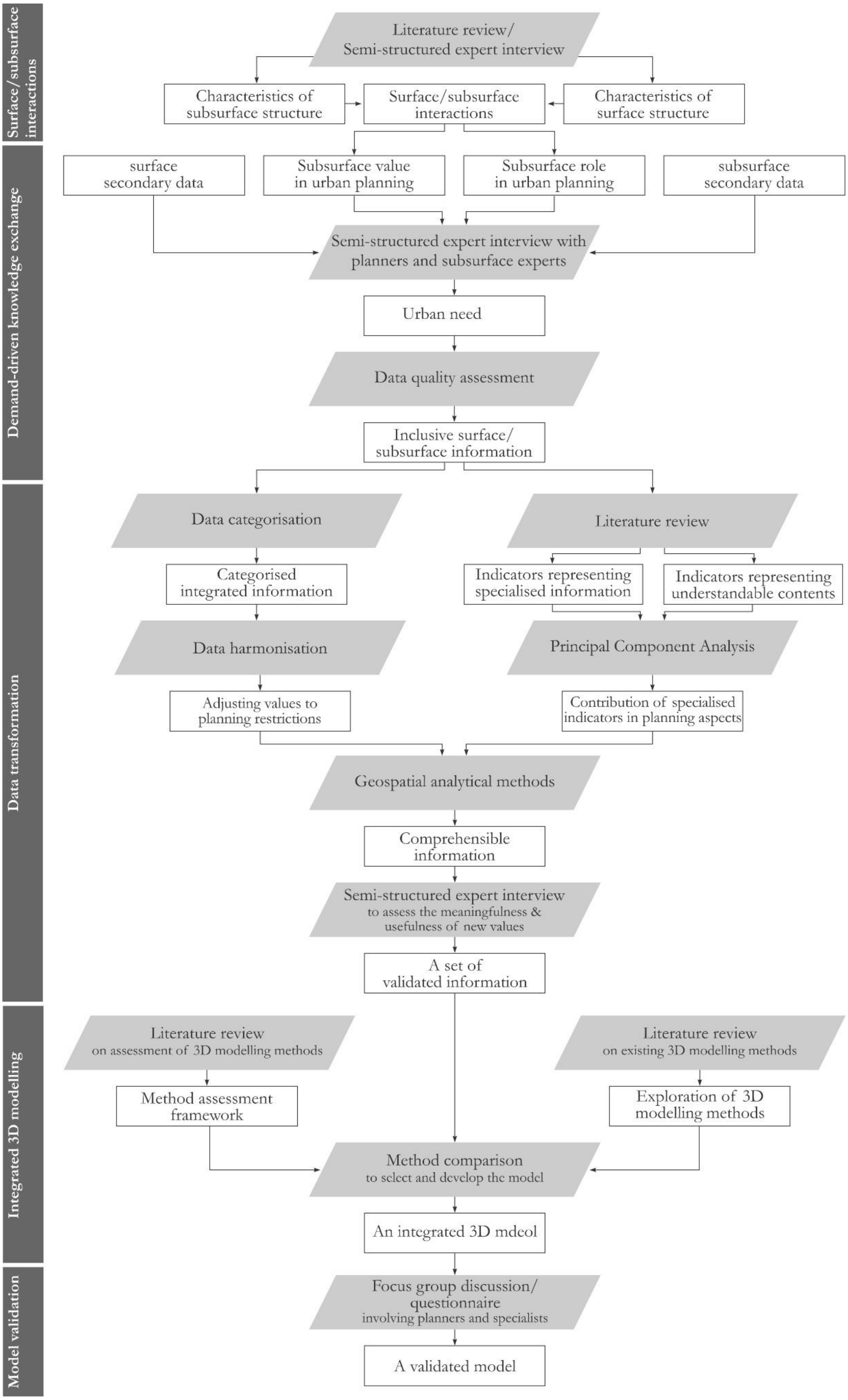


Figure 20. Flowchart of general research methodology

Following sections 4.1 – 4.3 explain applied methods for each research specific objective in detail. Note, first specific objective is analysed through literature review, and its discussion was presented by Chapter 2.

4.1. Method of connection through a demand-driven knowledge exchange

This section explains used methods in preparation of a demand-driven set of information. To this end, "expert interview" is used to get the idea of experts in terms of their main concern for (re)development process of Bloemhof.

4.1.1. Expert interview

Expert interviews were developed to address main concern of urban planners and subsurface specialists in (re)development process of Bloemhof. Interviews were conducted in a semi-structured manner to provide optimum geo-information sources (Tegtmeier et al., 2014). This method was selected since experts were expected to discuss their knowledge and experiences regarding the main issue of Bloemhof rather being limited by some exact questions (Annex 1 presents template of expert interviews in this study). So, prepared questions for the interview were continued by some follow-up questions retrieved during the discussion. The interviewees were selected among representative groups of subsurface specialists (e.g., civil engineers, geologists, hydrologists, geo-technicians, and archaeologists) and urban planners who are currently involved in (re)development project of Bloemhof. This selection was done based on a combination of "snowball" and "maximum variation sampling" methods to ensure representativeness of samples (Bogner, Littig, & Menz, 2009). The snowball sampling started based on the current developed connections with the Municipality of Rotterdam. Then, each interviewee was asked to introduce another relevant expert in terms of their profession and involvement in Bloemhof project. This approach refers to maximum variation to involve several professions in discussion. For an effective discussion, interviewees received questions in advance. In addition, interviews were recorded by notes and voice recorders in case of the agreement of the interviewees since accurate understanding of specialised concepts requires replay. Analysis of the notes was done based on several steps. First, content of discussion was transcribed. Second, transcripts were coded based on general thematic categorisation. Then, categories were labelled by primary and sub-primary themes. Finally, connection between categories was described. Therefore, priority of categories was derived, and the main concern of (re)development process in Bloemhof was concluded based on experts' consensus. According to Bogner et al. (2009), to ensure correctness of researcher's understanding of the interviews' contents, conclusions of interviews were checked with interviewees.

4.1.2. Data quality assessment

Since some data was provided by the Municipality of Rotterdam from various sources and some was collected from different online national geo-datasets (e.g., PDOK, DINOloket, and Funderingsloket), their quality was specified to ensure data reliability/certainty (Tegtmeier et al., 2007). Data quality specification was done by reviewing metadata of geo-portals as existing data provider tools and asking data providers about certainty of data collection and interpretation methods. Geo-portals contain information about producer of data, data collection method, and date of production. According to "DINOloket" (2016), "FunderingsLoket" (2017), and "PDOK Geodatastore" (n.d.), the collected online data was developed by experts from the government, the municipality, and private companies. With a high certainty (explained by interviewees), each group of experts works on data related to their own profession and final data was checked with other expert groups. All data which was downloaded online from geo-portals has metadata. So, the user could understand definition of parameters and used methods for data collection and interpretation. This study mostly used pure data without interpretation (e.g., demographic and geographic data). So, the risk assigned to uncertainty of data interpretation is reduced. In addition, description of used variables in this study (Table 4) was adapted to the metadata of collected datasets.

Moreover, a 2D analysis of "surface water flooding risk" index (Table 4) was done, and the result was compared with real data (see section 5.2.). To ensure the representativeness of selected variables in addition to the reliability of used data. So, the quality of data was specified for this study. Next sections explain used methods in different steps of this study (regarding research sub-objectives).

Section 4.2. describes used methods for the analysis of needed information. It explains methods for transformation of specialised data to comprehensible information for urban planners and subsurface specialists. In addition, section 4.3. explains applied techniques for 3D model generation, and process of model validation.

4.2. Method of interaction through data transformation

To create comprehensible information by transforming specialised data, data harmonisation is the first requirement. Since specialised data (e.g., geological, hydrological, and archaeological data) were collected from variant sources, they might have differences in scale, format, unit, and projection. Therefore, data harmonisation should be done to convergent required data for the analysis and be able to integrate data (Kaliampakos et al., 2016). Then, it is possible to transform data to comprehensive sets of information according to presented relations by Table 4.

4.2.1. Data harmonisation

Data harmonisation was done based on four main factors: scale, range of values; format, type of data; unit, spatial structure of data; and projection, coordinate system of data. According to Table 4, each factor has several dimensions containing various indicators. In addition, for explanation of each dimension and subsequently each factor, indicators need to be combined. However, their combination depends on their similarity in scale, unit, format, and projection. Therefore, this study first harmonised data to prepare the context for further analysis.

Figure 21 describes how different data were harmonised in this study. First, for harmonisation of data based on unit, a square-based tessellation was implemented to create a spatial unit (grids) which could obtain values from all range of data accuracies (from small units like values per dwelling to large units like values per zone/block/neighbourhood). Second, for harmonisation of data based on scale, relevant normalisation methods were implemented regarding types of data. Linear normalisation was used for data which were continuous and not affected by their spatial location. For those data which were influenced by their spatial location, in other words, "distance", a decay function was used to normalise data. Third, for harmonisation of data based on format, several spatial analytical methods (e.g., zonal statistics, extract values to points, format conversion like excel to table (. dbase)) were applied to extract values and assign to correspondence spatial locations. Fourth, for harmonisation of data based on projection, all collected data were checked to be projected on the Netherlands local projection system (i.e., RD_new).

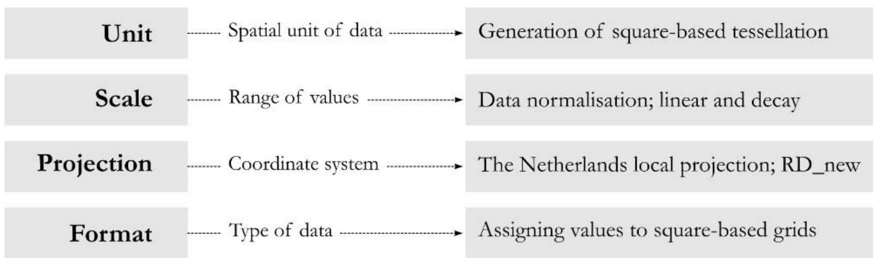


Figure 21. Data harmonisation

All mentioned steps were fundamental bases for further analysis which are explained by the next section in detail. Next section describes implemented analytical methods on data transformation regarding identified important factors for this study (presented in Table 4).

4.2.2. Data transformation

Data transformation has four steps. First step is to develop map of surface water flooding risk. This map was developed to be compared with real surface water nuisance. Therefore, in case of correlation, it is concluded that the index is reliable and is presenting real-based information. Second and third steps are to develop "supply inventory" and "demand targeting" indices to analyse contributions of subsurface structure to the issue of surface water flooding. Fourth step refers to analysis of vision map aggregating results of second and third steps. The result shows priority of planning considerations regarding urban needs and potential support of subsurface structures. The four described analytical steps were done by using ArcGIS Pro software.

First step: risk of surface water flooding

To generate map of "surface water flooding risk", exposure and vulnerability as the main dimensions were calculated based on Equation 1.

$$RI = E * \mathrm{V}$$

Equation 1. Risk Index

Source: Balica et al. (2012)

Where RI indicates risk index, E identifies exposure dimension, and V identifies vulnerability dimension.

Each indicator was generated based on 1000 m^2 grids[6] throughout the study area. The value of indicators was analysed through several geospatial analytical techniques. Annex 10 shows flowchart of the analytical steps for each indicator of risk assessment of surface water flooding (E1 - E6 as exposure indicators, and V1 - V3 as vulnerability indicators). For a detailed explanation, following statements describe the process of analysis for each indicator:

- E1: To calculate density of housing units a dataset containing land use types was used. Those features with land use type of "building" were selected and a "union" function was implemented between selected building features and generated 1000-m^2 grids. Then, to calculate the area of "buildings" per grid, a "dissolve" function was applied based on Grid_IDs, and the shape area was summed. The result is the area of buildings per grid. So, a new attribute field was created, and building density based on the ratio of building area to grid area was calculated.

- E2: Value of soil subsidence was assigned to the grids regarding the same process as E1 (respective "union" with grids dataset and "dissolve" functions). Used dataset contains range of soil subsidence per pre-defined zones by the Municipality of Rotterdam. In this analysis, the mean value of soil subsidence was averaged across grids while implementing dissolve function.

- E3: Calculation of greenery land cover ratio to the total area was done by using the previously mentioned dataset containing land use types (in E1). Similar to applied methods for E1, here the land use types "green" and "garden" were selected. After implementing a union function between selected features and grids dataset, a dissolve function was applied to sum the area of green lands. Then, by adding a new attribute field, ratio of green areas to the total area of the spatial unit (grid) was calculated.

- E4: Slope degree was considered for the analysis of topographical structure of the desired area. A Digital Train Model (DTM) raster dataset was used by a "slope" function to create slope raster. Values of the created slope raster were generated by degree. Regarding the studied subject, risk of surface water flooding, higher slope degrees result in better conditions for water flow. Therefore, a "zonal statistics" function was implemented by using slope raster and grid dataset to get the maximum slope degree of all

[6] In this study, when the word "grid" or "grids dataset" is used, it refers to the generated 1000m^2 square-based tessellations. This grid dataset was generated based on the union of spatial areas of all obtained data. 1000 m^2 is the smallest size which is proper for presenting the largest features in datasets. Grids has sides of 31.62 meters.

intersected pixels within the zone of each grid. Then, the resulted raster was used to assign pixel values to grid point by applying "extract values to points" function.

- E5: To calculate shortest distance from river, "near" function was used by adding polygons of grid features and line feature of river (centre line) as input datasets. Result is proximity information between each grid and river centre line. Therefore, each grid has the value of its shortest distance from existing river in the area.
- E6: Proximity to existing canal within the desired area was calculated for each grid by implementing a "near" function using polygon features of canal dataset and polygon features of grid dataset as inputs.
- V1: To analyse exposure of the desired area (in terms of water flooding), locations with measurements of surface water flooding nuisance were identified as hotspots. These locations regarding surrounding buildings within a radius of 50 meters from their centre points, through a "buffer" function, were considered as unsafe areas. Next, all houses located within the generated buffer zones gained value 1 in a new attribute field to be separated from other (safe) buildings. Then, a "union" function between the result of previous step and grids dataset and then a "dissolve" function was implemented to calculate sum of unsafe areas within each grid zone.
- V2: Calculation of cultural heritage was done through a respective implementation of "union" and "dissolve" functions between a dataset containing buildings with a level of historical value and grids dataset. The result is sum of historical buildings' area per grid zone.
- V3: To assign value of water infiltration to each grid, a "zonal statistics" function was applied by adding polygon feature of grids dataset and infiltration raster as inputs. The output raster contains mean value of daily water infiltration rate with pixel size of 150 meters. Then, respectively a "raster to polygon" and a "spatial join" function were applied to extract mean infiltration value for grid size.

The calculated values of exposure and vulnerability indicators vary in range and in units of measurement. Therefore, data were normalised to enable combination of different indicators of each dimension. However, indicators differently affect dimensions, either positively or negatively. Thus, to involve the positive/negative effects of indicators on dimensions, values were normalised differently. On the one hand, continuous values were normalised based on a linear function (Equation 2) to rescale values in range of 0 to 1. Linear normalisation brings about a unique range of values across indicators which is a requirement for developing an index. On the other hand, a decay function was used for normalising indicators that explain distance values. Equation 3 shows normalisation method based on a decay function.

$$x\ (new) = \frac{x - \ x(\min)}{x(\max) - x(\min)}$$

Equation 2. Linear normalisation

Where $x\ (new)$ is the new normalised value, $x(\min)$ is the minimum, and $x(\max)$ is the maximum value in the range of x values.

$$x\ (new) = \frac{x^2}{r^2}$$

Equation 3. Decay normalisation
Source: Wulan, Martinez, and Sherif (2013)

Where $x\ (new)$ is the new normalised value, and r is the maximum value in the range of x values (maximum distance value).

Equations 2 and 3 were used for values (indicators) with positive impacts on related dimensions, called benefit normalisation function. For values (indicators) with negative impacts on related dimensions, results of Equation 2 and 3 were subtracted from 1, called cost normalisation function. In this case, indicators E1, E2, E4, V1, and V2 were normalised based on benefit linear normalisation function (Equation 2). However, indicators E3 and V3 have negative impacts on risk dimension and were normalised based on the cost linear normalisation function (1-Equation 2). Moreover, indicators E5 and E6 have distance values with negative impact and were normalised based on the cost decay normalisation function (1-Equation3). Then, the normalised values were used to calculate risk index. However, involved indicators (especially indicators related to exposure dimension) have linear correlations (Annex 2 and 3). Therefore, correlated indicators have to be reduced to avoid double calculation of similar values.

The Principal Component Analysis (PCA) method was implemented to reduce correlated indicators. PCA is a factor reduction method applicable for population which is the case for this study (no sampling). Some initial tests were applied to ensure applicability of the PCA method regarding data. According to Field (2013), KMO statistics greater than 0.500 for sample size and multicollinearity describing by determinant of correlation (R) matrix greater than 0.00001 for correlations between variables are initial tests for the PCA method. In this study, the KMO statistics is 0.503 which ensures adequacy of sample size for analysis. For multicollinearity, the closer the determinant value to 1 means no correlation between variables which rejects need for factor reduction. In this study, determinant value for exposure indicators is 0.412, and for vulnerability indicators is 0.938. Therefore, indicators related to exposure dimension are correlated across an adequate sample size and applicable for implementing PCA. However, indicators related to vulnerability dimension are not correlated which identifies possibility of involving all indicators in vulnerability and further risk analysis. Annex 4 illustrates results of the KMO test, and Annexes 2 and 3 show determinant values of multicollinearity analysis respectively for exposure and vulnerability.

Therefore, a PCA method was implemented for exposure indicators. According to Annex 5, 2 components which have eigenvalue greater than 1 were derived from 6 indicators of the exposure dimension. These 2 components accumulatively explain the exposure dimension around 55.64%. Annex 6 presents the regression coefficients for each indicator on each component. Accordingly, the coefficients were assigned to values of each indicator and the total exposure score was calculated based on Equation 4. In addition, indicators related to vulnerability dimension were calculated based on Equation 5.

$$E = [(0.196 * E1) + (-0.832 * E2) + (0.002 * E3) + (0.098 * E4) + (0.822 * E5) + (0.589 * E6)]$$
$$+[(0.795 * E1) + (0.147 * E2) + (0.873 * E3) + (-0.382 * E4) + (-0.012 * E5) + (0.114 * E6)]$$

Equation 4. Exposure calculation

$$V = V1 + V2 + V3$$

Equation 5. Vulnerability calculation

For vulnerability, the indicators were summed since they have no correlation and no specific contribution weight in analysis. Final calculated values for vulnerability were in range of 0 to 3 since indicators (i.e., V1, V2, and V3) were previously normalised in range of 0 to 1. Since final values of vulnerability and exposure dimensions should be multiplied for calculation of risk score (Equation 1), their final calculated values were normalised (based on a benefit linear normalisation function, Equation 2) to become in a similar range of values (0 to 1). Then, the risk index was calculated based on Equation 1. The result is shown in Figure 23.

The generated map of surface water flooding (Figure 23) was compared with real surface water nuisance[7] to check reliability of used indicators and data in risk (R) calculation. To this end, several analytical steps were implemented to enable comparison between surface water flooding risk map and surface water complaints point dataset. In general, to compare these two datasets (calculated surface water flooding risk and real surface water complaints) the neighbourhood effect was considered for both.

[7] The real surface water nuisance is available in terms of a point feature dataset containing complaints of residents against surface water flooding.

The R (risk) value of 8 surrounding grids around each grid was analysed and the maximum value was assigned to the centre grid. This fact considers effect of adjacent areas on each location. In other words, regardless of the risk value per each grid, in case of the existence of an area with high-risk value around any location, adjacent areas are highly affected and subsequently their risk get increased (Kunz & Hurni, 2008). Annex 7 presents result of surface water flooding risk regarding neighbourhood effect.

In addition, the neighbourhood effect was also considered for surface water complaints dataset. In other words, the effect of surface water stagnant and flow are not limited to the exact location of complaints and is extended across adjacent areas (within 50 meters radius). Annex 8 shows the grids with high probability of surface water nuisance.

To compare these two generated maps (Annex 7 and 8), a point-biserial correlation was implemented since the complaint dataset has dichotomous variables (Field, 2013). Annex 9 shows the correlation table.

The result of this analytical section is presented in section 5.2.

Second step: supply inventory

Supply inventory factor contains natural and built environments as the main dimensions for the analysis of environmental consideration. Calculation of the supply inventory value throughout the desired area was done based on a combination of seven indicators (described by Table 4). Equation 6 shows the way these indicators were combined.

$$SI = \sum_{i=1}^{k} \left(\sum_{n=1}^{6} \alpha_n . NE_n + \beta . BE \,) \right)$$

Equation 6. Supply inventory calculation

Where SI indicates supply inventory, NE identifies indicators of the natural environment, and BE refers to indicators of the built environment dimensions. NE contains S1-S6 and BE comprises S7 as their related indicators. k identifies number of components which were derived from the indicators (by PCA) analysis to reduce number of indicators based on their correlation if there is any (presented by Annexes 12 and 14). In addition, α and β respectively represent contribution weights of indicators of the natural and built environments dimensions which are explained further by Equation 7, and Annex 15. Moreover, n refers to number of indicators that are categorised in each dimension.

Each dimension contains several indicators that were analysed separately based on the 1000-m^2 grids throughout the study area. Annex 11 shows a flowchart of analytical steps for each indicator (S1–S6). For a detailed explanation, following statements explain methodological steps that were implemented for calculation of each indicator:

- S1: Space provision was calculated based on area of any built-up land on which building and/or nonbuilding structures are present. By using a dataset containing general types of land cover, buildings, roads, and pedestrians were selected as a group of built-up areas. The value for space provision was calculated for these selected built-up areas based on 10 percent of the area multiplied by 3 which refers to possibility of subsurface space provision in 3 floors. Calculated value was filled in a new attribute field and through a "union" function between built-up areas and grids dataset and then a "dissolve" function was summed per grid (based on Grid_IDs). The result is the amount of square meter space that can be provided by underground within the boundary of each grid.

- S2: To analyse thickness of soil layers above clay soil or in other words, depth of clay soil, a multipoint dataset containing geo-condition of different soil layers throughout the study area was used. First, the point values were assigned to 1000-m^2 grids. To this end, a "buffer" function with a radius of 50 meters (half of the distance between points) was applied. Since the buffer function generates circular boundary, a "minimum boundary geometry" function was implemented regarding selection of "envelop" as geometry type. Therefore, the result presents a square boundary for each point with sides of 100 meters. Next, soil types which identify clay layers ("strat types" 1070, 2010, and 4000) were named "clay" in a new text attribute field. These layers have different elevation (z) values. To identify depth of clay layer, the highest layer should be selected. So, a "union" function between generated square-shaped geometry boundaries and grids dataset and then a "dissolve" function was applied to get the biggest elevation value for clay layers (since elevation values are negative, the bigger the value means the closer the layer to the surface). Then, by a "select by attribute" function, soil layers with clay type were selected, and the elevation values were multiplied by -1 in a new attribute field to convert them to the thickness of soil layers above clay soil.

- S3: To analyse penetration condition of subsoil, thickness of clay soil is considered. For calculation of soil thickness for clay type, a new layer named "Stack Height" was added to the point feature of soil dataset. Stack height shows the thickness of each soil layer by subtracting elevation value of the higher layer from the elevation value of the lower layer. Note, for the first layer, the stack height was calculated by subtracting the elevation value of the bottom point of the first layer from the elevation value of the surface (which was extracted from DTM raster using "extract values to points" function). Then, clay soil layers were selected, and the stack height values were assigned to corresponding grids.

- S4: Soil quality was analysed by calculating value of soil pollution for zone of each 1000-m^2 grid. A polygon dataset containing categorical values (4 categories) of soil pollution from very slightly contaminated to heavily contaminated was used to assign values to grids. First, a new attribute field was added to convert nominal values for soil pollution to numeric values from 0.25 for the very slightly contaminated category to 1 for the heavily contaminated category. Then, by implementing a "union" function between soil pollution dataset and grids dataset and then applying a "dissolve" function based on Grid_IDs, maximum value of the numeric soil pollution field was assigned to each grid. The maximum value was selected since the presence of a higher level of pollution throughout a small area (1000-m^2 grid) has a considerable effect on the points with lower pollution value within that area.

- S5: For analysing groundwater condition, average value of groundwater level was assigned to grids. A raster dataset presenting average values of groundwater level with pixel size of 25 meters was used and the values by using "extract values to points" function were assigned to the point dataset of grids.

- S6: For analysing water provision, volume of groundwater outflow was calculated throughout the study area. A raster dataset presenting values of groundwater outflow (negative values) with pixel size of 150 meters was used and through applying "extract values to points" function value of groundwater outflow was assigned to point dataset of grids. Then, the negative values were converted to the positive values (to be identified as volume) by multiplying the field values by -1 using "field calculator". The resulted values show daily volume (mm^3) of groundwater outflow per m^2.

- S7: To calculate density of physical assets located subsurface, three classes of structures were categorised as subsurface built environments. Buildings, streets, and infrastructures are three classes that their volume was calculated and summed per grid. First, for buildings and streets, the used dataset for S1 (which considered buildings, streets, and pedestrians as built areas) was used as the input of a "union" function with grids dataset and then a "dissolve" function was applied to calculate sum of areas regarding general land use classes (built and unbuilt). Then, by applying a "select by attribute" function, grids that were identified with land use class of "built" were selected, exported and joined with grids (based on Grid_IDs) as the first class of subsurface structure. Then, a new attribute field was created, and the volume of this class was calculated by multiplying shape areas by 1.5 as an assumption for minimum depth of foundation in a flat area such as the desired area in this study. For the second class, infrastructure, cables and pipes were used as line features. The radius of each infrastructure type as sewerage system, gas pipes, drinking water pipes, and electricity cables was assigned to their features regarding the literature reviews and technical reports on pipes' types and characteristics. Next, a new attribute field was created to calculate the volume of each line regarding their shape length, and radius of pipes and cables (volume = shape length * radius^2 *3.14, it was assumed that all pipes and cables are designed as regular cylinders). Then, by implementing a "spatial join" function with grids dataset, sum of the volumes per each grid zone was calculated and assigned to each grid based on Grid_IDs. Then, to calculate subsurface built density, these two volume fields (for buildings and streets, and infrastructure) were summed and divided by the volume of grids (it was assumed that grids are cubes with equal sides).

According to Equation 6, calculated indicators should be combined regarding their contribution weight. To this end, values of all indicators, both categories of NE and BE, were normalised since range of values were different and their combination relies on similar range of values. Considering the effect of each indicator on the factor, supply inventory (presented by Table 4), Equation 2 was used for normalising indicators S1, S2, and S6 which have positive effect on the subsurface supplementary solution to risk of surface water flooding issue. In addition, indicators S3, S4, S5, and S7 were normalised by subtracting the result of Equation 2 from value 1 (1-Equation2) since they have negative effect on supply inventory aspect of subsurface. Then, a PCA was applied on normalised values of all indicators (S1-S7) to check the correlation between indicators and analyse whether reduction of indicators regarding their correlation is possible. To ensure the reliability of the use of PCA, KMO test which presents the adequacy of sample size and multicollinearity which identifies the correlation between indicators were checked. According to Annex 12, determinant of the correlation matrix for supply inventory indicators which should be greater than 0.00001 is 0.289. Therefore, indicators of supply inventory are correlated. In addition, according to Annex 13, statistics of the KMO test is 0.490 which is considerably close to 0.500 which proves the adequacy of sample size for implementation of the PCA. Considering results of multicollinearity and KMO test, use of PCA method is reliable for supply inventory indicators.

The result of PCA method (Annex 14) illustrates that 4 components with eigenvalue greater than 1 can be representatives of all 7 analysed indicators. These 4 components accumulatively explain the supply inventory factor around 81.22%. The contribution weights of each indicator across 4 components are presented in Annex 15. Accordingly, the coefficients were assigned to values of each indicator and the total supply inventory score was calculated based on Equation 7.

$$
\begin{aligned}
SI = {} & [(0.915 * S1) + (0.108 * S2) + (-0.109 * S3) + (0.075 * S4) + (-0.071 * S5) + (0.079 * S6) + (-0.911 * S7)] \\
& + [(-0.047 * S1) + (-0.035 * S2) + (0.682 * S3) + (0.106 * S4) + (-0.909 * S5) + (0.114 * S6) + (-0.058 * S7)] \\
& + [(-0.036 * S1) + (0.018 * S2) + (-0.072 * S3) + (-0.864 * S4) + (-0.024 * S5) + (0.823 * S6) + (-0.030 * S7)] \\
& + [(0.094 * S1) + (0.932 * S2) + (0.472 * S3) + (-0.192 * S4) + (0.176 * S5) + (-0.180 * S6) + (0.009 * S7)]
\end{aligned}
$$

Equation 7. Supply inventory calculation regarding contribution weights of indicators

Figure 24 shows generated map of potential supply inventory of subsurface structures regarding the issue of surface water flooding based on described analysis. As Figure 24 shows, there are some grids with NULL value. This fact refers to a concern that all grids are not applicable to the calculation of all indicators. To be specific, calculation of a NULL value of any indicator (S1-S7) for a grid, results in a NULL value for supply inventory score of that grid[8]. To have a continues surface of supply inventory factor throughout the study area, an "IDW" interpolation function was applied on calculated supply inventory values which is suitable for relatively dense features (Naoum & Tsanis, 2004). According to Equation 8, this method interpolated the values using an inverse distance weighted technique. IDW works

[8] Note, implementation of any mathematical functions on a NULL value is not applicable. Considerably, NULL value will not be considered as zero.

based on the values of surrounding values (point feature) within a predefined search radius to interpolate known values and predict unknown values.

$$Z_p = \frac{\sum_{i=1}^{n}(\frac{Z_i}{d_i{}^p})}{\sum_{i=1}^{n}(\frac{1}{d_i{}^p})}$$

Equation 8. IDW calculation
Source: Johnston, Ver Hoef, Krivoruchko, and Lucas (2001)

Where Z_p indicates pth unknown value, Z_i indicates value of ith known point, n identifies number of points for calculation of any unknown cells regarding search radius. Search radius could be explained by number of surrounding points or a distance. In addition, $d_i{}^p$ refers to distance between ith known and pth unknown cells with power of p as the exponent of distance.

In this study, 8 points were identified as the number of surrounding points explaining interpolation search radius. In addition, a power value as the exponent of distance was identified which controls the significance of surrounding points on interpolated value. Considerably, the higher the power value the more the reduction of point distance influence (Lu & Wong, 2008); therefore, in this study power was selected as 2 (range is any real number greater than 0). Annex 25 illustrates the resulted map[9] of supply inventory interpolation throughout the study area.

Third step: demand targeting

Demand targeting factor was identified by Table 4 with 6 indicators in terms of subsurface related needs of urban areas regarding surface water flooding issue. "Promoting utilisation" and "engineering difficulties" are two dimensions that compromise analysis of 6 indicators. Indicators D1-D3 were categorised as "promoting utilisation" dimension and D4-D6 were categorised as "engineering difficulties" dimension. Calculation of the demand targeting factor was done based on Equation 9 regarding its main dimensions and analysed contribution weights of each indicator (through PCA analysis).

$$DT = \sum_{i=1}^{k}\left(\sum_{n=1}^{3}\alpha_n \,.\, PU_n + \sum_{m=1}^{3}\beta_m \,.\, ED_m\right)$$

Equation 9. Demand targeting calculation

Where DT indicates "Demand Targeting" factor for the analysis of technical consideration. PU and ED respectively refer to "Promoting Utilisation" and "Engineering difficulties". In addition, n and m identifies number of indicators that were categorised in each dimension. Moreover, k indicates number of components that were derived from a PCA method to reduce multicollinearity between indicators, and α and β refer to contribution weights (regression coefficients) of each indicator in analysing "Demand Targeting" factor. Contribution weights are further explained by Equation 11, and Annex 20.

Each dimension contains several indicators that were analysed separately based on the 1000-m^2 grids throughout the study area. Annex 16 shows a flowchart of the analytical steps for each indicator (D1 – D6). For a detailed explanation, following statements explain methodological steps that were applied for calculation of each indicator:

- D1: To calculate land pressure, ratio of unbuilt areas containing greeneries and water bodies to built areas which are considered as buildings and transport networks, either motor vehicles, bicycles, or

[9] Used pixel size for IDW function was ≃4 meters according to shortest distance between objects within grids (the spatial unit of the analysis which is ≃31.62 meters.

pedestrians was analysed. The created dataset of built and unbuilt areas in indicator S1 was used and through implementation of a "union" function with grids dataset and a "dissolve" function based on Grid_IDs, area of built and unbuilt lands was summed separately. To have the built and unbuilt features separately, a "split by attribute" function was applied. The two output datasets were joined based on Grid_IDs, and the ratio of unbuilt to built areas was calculated in a new attribute field.

- D2: For analysing monetary value of buildings throughout the study area, growth rate of average housing value was calculated using a feature dataset with 100m*100m cells containing average housing values for two consecutive years (2011 and 2012)[10]. A new attribute field was added to the feature dataset table, and growth rate of the average housing value was calculated according to Equation 10.

$$Growth\ Rate = \sqrt[m-n]{\frac{Housing\ value\ m}{Housing\ value\ n}} - 1$$

Equation 10. Growth rate calculation

Where m and n refer to the year that data are related to. M explains the later and n indicates the earlier date of data.

Then, by implementing a "union" function with grids dataset and "dissolve" function based on Grid_IDs mean of housing values were calculated for grid zones.

- D3: To calculate population density, the used dataset in D2 (feature dataset with 100m*100m polygon cells, named CBS dataset) was used. This dataset has the population value of the area for 2016. To calculate population density for the grids (1000m^2 square-based tessellations), first population density for the CBS dataset was calculated by dividing population by area size of cells in a new attribute field and then a "union" function was implemented between the CBS and grids dataset. Then, before applying "dissolve" function to have the density value for grid zones, the calculated density field for the output of the "union" function was returned to the population value which is possible to be summed through a "dissolve" function (despite density value). Then, a "dissolve" function was applied based on Grid_IDs and population numbers were summed. So, each grid has a value of population 2016. Then, the population density was calculated by dividing the population by grids area.

- D4: To analyse water flow control, water infiltration rate was calculated, and corresponding values were assigned to grids. Methodological steps and used dataset are the same as the applied process inV3. So, by using the result of V3, a "join attribute" was applied between V3 and grids dataset based on Grid_IDs to add infiltration values to grid dataset.

- D5: For analysing foundation resistance, ratio of wooden/steel[11] foundations to concrete foundation was calculated. A feature dataset containing foundation types was used in a "union" function with grids dataset, and then a "dissolve" function was applied based on Grid_IDs and foundation type to sum shape area of each foundation type within each grid zone. So, the result contains area of each foundation type per grid features. Then, by applying a "split by attribute" function several feature classes were created regarding unique foundation type. Next, all the results (one feature class for wooden piles, one for buildings without pile, and one for concrete piles) were joined with grid dataset based on Grid_IDs and the ratio of wooden/steel foundation to concrete foundation was calculated in a new attribute field. To involve effect of building density in analysis, the calculated ratio was multiplied by building density per grid. Note, there are some NULL values which refer to grids that have no building within their boundary.

- D6: Calculating densification demand was made based on analysing floor area ratio (FAR). Two datasets containing area of buildings footprint and addresses (refers to individual housing units) were used

[10] There was no other available dataset that provides more updated data related to housing values per a 100*100m spatial unit.
[11] Buildings which are indicated as steel foundation have no pile belowground.

in the calculation of FAR. A "spatial join" function was applied to these two datasets indicating footprints as target and addresses as join feature and sum of the addresses' areas per footprint were calculated. Then, by dividing the sum of addresses' areas by corresponding footprint area, floor area ratio was resulted. To assign the values to grids, a "union" function between the result of described process and grids dataset and then a "dissolve" function based on Grid_IDs and calculation of mean floor area ratio was applied.

For analysing "Demand Targeting" factor throughout the area, calculated indicators (D1_D6) should be combined according to Equation 9. However, indicators values vary across different ranges which should be the same for combination. Therefore, values were normalised. According to the effect that each indicator might have on factor (demand targeting), different normalisation methods were used. Indicators D2, D3, D5, and D6 with positive effect of demand targeting changes were normalised based on Equation 2 (benefit linear normalisation). Indicators D1 and D4 with negative effect on demand targeting changes were normalised based on 1-Equation 2 (cost linear normalisation). Then, according to Equation 9, contribution weights of each indicator in analysing "demand targeting" factor should be considered since equal consideration of indicators' impact on analysis could have biased the result.

Therefore, a PCA method was implemented to understand contribution of each indicator in analysing demand targeting factor. However, sampling adequacy and indicators correlation are prerequisites of PCA method. Therefore, KMO test and determinant value of multicollinearity analysis were check for those 6 indicators of demand targeting factor (D1_D6). Annex 17 and 18 respectively describe results of multicollinearity and KMO tests. According to Annex 18, KMO test value is 0.572 which is greater than 0.500 and proves the adequacy of sample size for applying PCA method. In addition, according to Annex 17, determinant value equal to 0.655 proves that indicators are correlated. Therefore, both tests were analysed and then the PCA method was implemented. The result of the PCA is presented by Annex 19 which explains that among 6 analysed indicators, 2 components (with eigenvalue greater than 1) were derived for further analysis of demand targeting since indicators were correlated. Accumulatively, these 2 components explain the demand targeting factor by 47.51%. Moreover, each indicator gained unique weight across components which were used in calculation of demand targeting factor. Annex 20 explains contribution weights of each indicator across 2 components. Accordingly, the coefficients were assigned to values of each indicator and the total demand targeting score was calculated based on Equation 11.

$$DT = [(0.500 * D1) + (0.027 * D2) + (0.463 * D3) + (0.047 * D4) + (0.751 * D5) + (0.830 * D6)] \\ + [(0.190 * D1) + (0.784 * D2) + (0.317 * D3) + (-0.512 * D4) + (-0.342 * D5) + (-0.133 * D6)]$$

Equation 11. Demand targeting calculation regarding contribution weights of indicators

Figure 25 presents generated map of the result of described analysis on demand targeting factor explaining need of urban areas to subsurface structures regarding issue of surface water flooding (in the desired area). Similar to the generated map for supply inventory (Figure 24), analysed demand targeting factor has also some grids with NULL value. To solve this issue and have a continues surface raster of demand targeting analysis throughout the study area, an "IDW" function based on 8 surrounding points in search radius of interpolation with significance power of 2 was implemented (according to Equation 8). Annex 26 shows the result of generated interpolated raster of demand targeting value throughout the desired area in this study.

Fourth step: vision map

According to section 2.2.2, it was explained that the aim of this study is to provide urban planners and subsurface specialists with a comprehensive set of information for vision phase of urban (re)development. Accordingly, analysed "supply inventory" and "demand targeting" factors were compared to explore how potential supply inventories of subsurface structures can meet potential demands of urban structures regarding surface water flooding issue. Therefore, a vision map was generated for further planning considerations. Following statements describes applied analytical (statistical and spatial) methods on supply inventory and demand targeting values of all locations throughout the study area for the purpose of vision map generation.

To generate vision map, first, the interpolated values of supply inventory and demand targeting factors (Annexes 25 and 26) were assigned to the grid feature class (1000m² square-based tessellations) through "extract values to points" function and then both outputs were joined with grids dataset to add interpolated values in new attribute fields. Next, both added values were normalised using a linear normalisation equation (Equation 2). Normalisation enables accurate comparison between values. Then, demand targeting values were subtracted from supply inventory values in a new attribute field. The resulted values vary from positive to negative and the greatest the value shows the better the supply provision against demands. Figure 26 shows the generated vision map regarding level of differences between values of supply and demand for each grid.

4.3. Method of integration through 3D modelling

This section explains applied analytical processes for generation of an integrated 3D model of surface/subsurface structures. The model was divided into two general structures, surface and subsurface; each encompasses several types of environments. Generated environments regarding surface structures are as buildings, trees, and canals. In addition, generated environments of subsurface structures are as follow: subsoil space use of trees; soil layers; infrastructures containing sewerage system, gas network, drinking water system, and electricity; groundwater; wells; buildings foundation; soil pollution; and soil subsidence rate. To conclude, Table 10 shows generated 3D objects of surface and subsurface structures throughout the study area in this research.

Table 10. Generated 3D objects of surface/subsurface structures

Structure	Environment		Object	Data characteristics
Surface	Natural	Water	Canal	Original
		Vegetation	Tree	Transformed
	Built	Buildings	Buildings	Original/transformed
Subsurface	Natural	Space	Subsoil space use by trees	Transformed
		Groundwater	Groundwater level	Original/transformed
			Wells	Original
		Geomaterial	Soil layers	Original/transformed
			Soil subsidence	Original
			Soil pollution	Original
	Built	Foundation	Piles	Original
		Utility	Infrastructures; pipes	Original

According to Table 10, 3D objects of some surface and subsurface environments were generated using original data and some were transformed using CityEngine and ArcGIS Pro. Section 4.3.1. explains the process of 3D model generation described by Table 10 in detail. In addition, after model generation, its validation was performed through a focus group discussion where the model was presented to and used by planners and specialists who are involved in (re)development project of the Bloemhof neighbourhood.

Moreover, for model validation, a questionnaire was designed (Annex 29) and participants of the focus group discussion were asked to fill the form. Section 4.3.2 explains process of the 3D model validation.

4.3.1. Model generation

Regarding Table 10, 3D model generation was divided into two processes, surface structure generation and subsurface structure generation. Annex 21 gives detailed explanation of generation procedure for each. Regarding Annex 21, following statements describes 3D generation of each object related to surface and subsurface structures in detail.

Surface structures

- Buildings: to model 3D objects of buildings structures, a feature class containing basic registration addresses/buildings and their heights was imported into CityEngine environment. Annex 21, lines 93-96 show steps of buildings generation. Imported 2D polygons were extruded based on their height values.

- Trees: at surface level, trees have two components, trunk and crown which were separately modelled in this study. To model 3D objects of trees, first, several analytical methods were applied using ArcGIS Pro and then model generation was done based on results of the analysis in CityEngine environment.

For a detailed explanation: Urban (2008) identified a direct correlation between sizes of a tree, its trunk diameter and crown spread (regardless of trees types) (Annex 22). Using examples of Annex 22, a linear regression analysis was implemented between values of trunk diameter and crown spread area. Resulted regression coefficient (Equation 12) was applied to available values of crown spread[12] for trees throughout the study area to calculate their trunk diameter.

$$TD = 38.85 + 5.027 * CS$$

Equation 12. Linear regression model between trunk diameter and crown spread

Where TD identifies diameter of trunk in millimetre (mm), and CS refers to radius of trees' crown in square meter (m^2).

Next, a "buffer" function was implemented based on calculated trunk diameter to create circular boundary of trunks. Then, available point feature class of trees containing crown radius and polygon feature class of trunks' boundary were imported to the CityEngine environment. According to Annex 21, lines 110-121, trunk diameter was used for generation of a cylinder as trees trunk, and crown radius was used to model spheres as trees' crown. Note, height of trees was assumed as 2 meters for all throughout the study area since related data was not available.

- Canal: a polygon feature dataset of existing canal within the study area was used to model its 3D object. According to Annex 21, lines 124-127, described feature class was imported into the CityEngine environment and its name was changed to "Name__water" for an animated visualisation of water motion.

Subsurface structures

- Subsoil space use by trees: at subsurface level, trees have one component, soil volume which was modelled in this study based on Annex 22. To model 3D objects of required soil volume for trees, first, several analytical methods were applied using ArcGIS Pro and then model generation was done based on results of the analysis in the CityEngine environment.

For a detailed explanation: Urban (2008) identified a direct correlation between size of a tree and its soil space requirement (Annex 22). Using examples of Annex 22, a linear regression analysis was implemented

[12] Available dataset of trees has values of crown radius, and the crown spread was calculated by assuming the crown as a sphere.

between values of soil volume and crown spread. Resulted regression coefficient (Equation 13) was used to calculate required soil volume for trees throughout the study area.

$$SV = 0.246 + 0.387 * CS$$

Equation 13. Linear regression model between soil volume and crown spread

Where SV indicates volume of required soil for trees in cubic meter (m^3), and CS indicates spread of trees crown in square meter (m^2).

Next, regarding Equation 14, depth of required soil space for trees was calculated for its 3D generation. Note, space of required soil for trees was considered as a rectangular cube as wide as trees crown.

$$D = SV/(2 * CR)^2$$

Equation 14. Calculation of depth of required soil space for trees

Where, D indicates depth of required soil space for trees in meter, and CR refers to crown radius in meter.

Then, a "buffer" function based on CR (radius of trees' crown regarding Equation 14), and then a "minimum bounding geometry"[13] function was applied to generate square-based boundary of soil space for trees with width of trees crown (its diameter). Then, generated square-based boundaries of trees' soil space were imported into the CityEngine environment and related rule (Annex 21, lines 130-150) was assigned to features. To differentiate generated cubes of soils for each tree, type of its related soil was used to give different colours to soil cubes. In addition, for top side of the cubes, a satellite image of the area was used for their coverage instead of using assigned colours to different soil types. This fact improved visualisation quality of the model.

- Groundwater level: Two raster datasets containing values of lowest and highest groundwater level were used in this process. For generation of groundwater 3D objects, a feature dataset was required to assign raster values to corresponding locations. Therefore, by using "tessellation' function, a grid dataset with squares of 625 m^2 was generated[14]. Then, by implementing "extract multi-values to points" function, raster values were separately assigned to the created grid dataset. According to Annex 21, lines 153-160, height of groundwater layer was calculated by subtracting the lowest groundwater level from the highest groundwater level. For 3D generation, the lowest groundwater level was used as groundwater layer base, and the calculated height value was used as extrusion level. Note, fluctuation of groundwater level is important in urban decision makings; however, certain data was not available regarding groundwater fluctuation level. In this study, to avoid model uncertainty, groundwater was generated based on its lowest and highest available measurements.

- Wells: a point feature class of wells containing elevation values of their top level (z) was used in this step. Using previously mentioned raster datasets, lowest groundwater level was assigned to the wells points. Therefore, their depth was calculated by subtracting lowest groundwater level values from z value. Annex 21, lines 162-169 illustrates the rules that wells were modelled based on in 3D[15]. For a better visualisation, 0.4-meter wide cylinders were generated as connector tubes (from wells to the surface) for each well. Annex 21, lines 171-176 presents developed rules for 3D generation of connector tubes.

- Soil layers: there were two point-feature-classes available for soil layer 3D modelling, one covered a larger zone and the other covered a smaller zone than the study area[16]. However, both were used in this step since they provided different data. The smaller one had value of soil layers height and the larger one

[13] For "Minimum Bounding Geometry", geometry type was selected as "Envelop" and group option was selected as "None".

[14] Pixel size of the two groundwater raster datasets was 25 meters.

[15] Width of wells was considered as 1 meter based on assumption (cylinders of 0.5-meter radius).

[16] In their intersected area, points had same locations.

had full coverage of the study area. In this study, the larger dataset was used as the basis for modelling and the smaller dataset was used to assign height of soil layers to corresponding points to the larger dataset. To this end, several analytical steps were applied on both feature classes. The larger feature class has elevation values for soil layer with 0.5-meter precision. In this study, only the elevation value of the lowest position for each soil type was used. Therefore, a "dissolve" function was applied to the larger feature class based on its x, y, and soil type fields and the minimum elevation value was extracted. This dataset was a multipoint feature class containing several values for each point. This means that each point has values illustrating vertical position of different soil types at that location. To enable further analysis, the multipoint feature class was converted to a point feature class. Then, the larger dataset was joined with the smaller one to assign height values of soil layers to corresponding points[17] (note, there were some points that remained with no height value, since the smaller dataset did not fully cover all points of the larger dataset). Next, by using a DTM raster dataset, points of the larger dataset gained elevation value of their top layer (surface). This fact was done by using "extract values to points" function. Then, table of the larger feature class was converted to excel (using "table to excel" function) and those remained height values were calculated (for points that were located out of the intersection boundary of the two feature classes) by subtracting elevation value of lower layer from elevation value of upper layer for each point. To assign calculated height values to related points, the excel file was converted to table (using "excel to table" function), and then was joined with the larger feature class. The result was several points describing position of soil layers. To prepare the dataset for 3D generation, a "spatial join" function (one to many) was used between the larger feature class and a previously generated tessellation dataset of 100*100 meters squares[18]. To make the visualisation of 3D objects smoother, a "spatial join" function between the result of the previous step and a new generated 10*10 meters tessellation was applied. Then, the output was imported to the CityEngine environment and related rule (Annex 21, lines 179-199) was assigned to it. According to Annex 21, each soil type has specific colour which was retrieved from obtained documents from the Municipality of Rotterdam (Annex 23 and 24, both in Dutch). Annex 23 was used to get the abbreviation of each soil type, and then Annex 24 was used to find the official specified colour for each soil type using its abbreviation. In addition to generated soil layers, each soil type was generated separately in case of tendency for individual visualisation of each soil type layer. Annex 21, lines 202-235 illustrate how soil layers were generated separately.

- Soil pollution/subsidence: In this step, analysed indicators E2 and S4 which respectively shows soil subsidence and soil pollution were used. For 3D modelling (Annex 21, lines 238-245), value of soil pollution was imported to the CityEngine environment, and colour ramp of yellow to red was assigned to the dataset to describe level of pollution. In addition, to illustrate soil subsidence rate, the previous generated 3D objects of soil pollution gained values of soil subsidence and a *10-exaggeration level was applied for better visualisation[19].

- Piles: For 3D modelling of building piles, available point features of piles were imported to the CityEngine environment. Each point was converted to a cylinder with specific colour regarding type of pile (Annex 21, lines 248-261). Size and depth of piles were based on assumption since there was no available data regarding this fact. Depth of piles starts from 1.5 meter belowground where pile caps end. The pile cap was generated using polygon feature dataset of buildings. Lines 264-266 of Annex 21 were applied on imported pile cap polygons into the CityEngine software and their depth was considered as 1.5 meters (an assumption).

[17] They were joined based on a text field containing x, y and soil type values.

[18] 100*100 meters size was decided based on the existing distance between points in the larger dataset.

[19] Range of soil subsidence rate is small, from -1 to -3. In 3D visualisation, created space between surface layer and polygon features of soil pollution shows subsidence rate.

In addition, potential piles' rottenness was analysed. According to Klaassen and Creemers (2012), wooden piles that have their top point above groundwater layer are potentially exposed to rottenness. They described the best position for wooden piles as a full coverage of wooden piles with groundwater which keeps piles almost safe from rottenness. Therefore, this study analysed intersections between piles and groundwater layer. Since piles are constructed below buildings and pile caps (-1.5 meters belowground as an assumption), 1.5 was subtracted from surface elevation value to identify z values of the piles' top point. Then, calculated z value of the piles was compared with z value of highest groundwater layer. The comparison was done by subtracting z value of the highest groundwater layer from z value of the top side of the piles. The higher the resulted value from zero (positive), indicates possibility of pile rottenness over time. Annex 21, lines 269–278 show how calculated values of potential pile rot were assigned to corresponding buildings in terms of a colour ramp from brown to blue. The closer the colour to brown means the groundwater level at that location is low and building pile is exposed to rottenness, and the closer the colour to blue illustrates the full coverage of building pile with groundwater layer. According to analysis, positive values should have brownish colours and negative values should have blueish colours. Therefore, values were normalised between 0 and 1 in terms of having 0.5 for zero value of results of the potential pile rot. Thus, colours were assigned properly. Considerably, this analysis was done on wooden piles and other types of foundation were not considered. In other words, buildings with concrete pile or without pile are visualised as white buildings with a level of transparency, means no value for this analysis.

- Infrastructures: To model infrastructure, a line feature class which had data regarding material and length of sewerage, drinking water, gas, and electricity networks was used. First, a "3D buffer" function was applied in ArcGIS Pro environment on the line feature datasets using radius of pipes regarding their material[20]. Then, the created multipatch dataset of 3D cylinders for each mentioned infrastructure type was imported into the CityEngine environment. However, there was no available data regarding their exact location at underground. Therefore, their location was set based on assumptions considering their orders in depth. In addition, sewerage wells were generated as connector cylinders to the surface. Annex 21, lines 281-305, illustrates how the 3D objects of infrastructures were modelled in CityEngine.

Transformed factors

- Vulnerability/exposure factors: To visualise calculated vulnerability and exposure values, different colours were assigned to top and sides of each building. To be specific, calculated values of exposure and vulnerability (regarding Equation 4 and 5) were imported into the CityEngine environment as raster datasets and value of each pixel was assigned to corresponding buildings. The top face of each building gained the values of exposure dimension, and sides of each building gained the values of vulnerability dimension. A colour ramp was used to make the colours change from green to red illustrating buildings conditions from the best to the worst (regarding vulnerability and exposure factors, see Table 4). Accordingly, values of buildings height were used as original data, and exposure/vulnerability values were used as transformed data (which went through several analytical processes, see section 4.2.2.) for colours. Lines 97-107 of Annex 21 explains applied rule for visualisation of vulnerability and exposure values in the 3D model.

- Risk: To involve risk of surface water flooding map in the generated 3d model, its discrete values which were calculated based on Equation 1, were interpolated to have continues values within each grid (for a better understanding/visualisation of risk issue throughout the area). To this end, an "IDW" function based on 8 surrounding points in search radius of interpolation with significance power of 2 (according to Equation 8) was applied on calculated risk values of grid dataset. Annex 27 shows the result which has interpolated values of risk within each grid[21]. To be able to import the result into the

[20] Radius for electricity cables is based on assumption and considered as 0.0508 meter.

[21] Used pixel size for IDW function was ≃4 meters and size of grids (sides) was ≃31.62 meters.

CityEngine environment, the output raster should be converted to features. However, basically, an IDW output raster is not valid as input for statistical functions, since its value is not integer. To this end, before implementing "raster to polygon" function, first a "raster calculator" function was applied, and pixel values were multiplied by 10^9 regarding decimal places of raster values. Next, "int" function was implemented to make raster values integer. Then, a "raster to polygon" function was applied, and a new attribute field was added to return raster values to their origin by dividing by 10^9. Then, the created polygon feature class was imported to the CityEngine and was coloured from green to red describing lowest to highest risk rate (values were classified based on their natural break) (Annex 21, lines 308-322).

- Planning (re)development vision: To provide a comprehensive vision for planning consideration regarding surface water flooding issue of the study area, calculated vision map (described by the fourth step of section 4.2.2.) was imported into the CityEngine software. Considerably, vision map (Figure 26) contains effect of supply inventory factor on demand targeting factor. For visualisation, a colour ramp of green to red was used for vision values[22], and the closest the colour to green means the better the coverage of urban need by subsurface supply inventories (Annex 21, lines 325-331).

After generation of the 3D model, its usefulness regarding purpose of its development should be appraised. The purpose was providing a basic planning insight for urban planners and subsurface specialists for (re)development process of the Bloemhof neighbourhood. Therefore, through a validation step usefulness of the model was evaluated. Next section explains model validation process in detail.

4.3.2. Model validation

Validation process of the generated 3D model was done in two steps.

First, a focus group discussion was conducted, and the model was presented to a group of four participants[23]. The limited number of participants might not describe usefulness and effectiveness of the model properly; however, due to various factors such as time limitation, heavy workload of experts, difficulties of gathering different people at one time, etc., it could not be avoided[24]. During the group discussion session, a presentation including generation process of the model, its purpose, and a demonstration of its structures[25] was given to participants. Several questions were posed and discussion regarding each was noted by the researcher.

Second, participants were asked to fill a questionnaire (Annex 29) about the 3D model and its usefulness in terms of providing basic planning insight of surface and subsurface structures for planners and specialists. The questionnaire was designed based on Likert (psychometric) scale format. Responses (Annex 30) were analysed manually[26] in terms of transferring responses to a spreadsheet and giving them orders regarding created scale (in this case, from 1 to 6 by means of 1 for "strongly agree" to 5 for "strongly disagree" and then 6 for "no response"). In addition, the questionnaire had several explanatory questions which were analysed thematically by coding main terms of responses and analysing their repetition. In parallel with analysing questionnaire data, discussion notes were evaluated using the same method as explanatory questions of the questionnaire. Then, overall findings were concluded using the SWOT analysing method. Section 5.3. describes results of the model validation.

Next chapter presents results of the research and discusses them regarding research sub-objectives.

[22] Subtraction of normalized demand-IDW values from normalized supply-IDW values.

[23] Two urban planners and two specialists (a geologist and a cartographer) were invited to the validation focus group discussion.

[24] This matter should be considered for further developments of this study.

[25] Uploaded online via YouTube, access through this link: https://youtu.be/7b4HUyUU6pE

[26] Since number of samples (respondents) was not sufficient for doing sub sample analysis (due to possible misleading of results).

5. RESULTS AND DISCUSSIONS

5.1. Result/discussion on connection through a demand-driven information set

This study conducted five interviews with experts (i.e., two urban planners, one subsurface masterplan expert, one water manager, and one geologist). These interviews resulted in a clear understanding of the main concern of Bloemhof (re)development project for this study. Although interviews were done with limited (five) number of experts, responses achieved a consensus on most basic issues that gradually affect surface and subsurface conditions of Bloemhof. However, the limited opportunities of having discussions with experts from different professions have not been ineffective on results of this study. In addition, having ideas and opinions of several experts from same profession would bring about certainty in concluding results. To be specific, if this research had opportunities to interview with more than one expert from each group (i.e., planner, subsurface planning expert, geologist, hydrologist), the certainty of the point of views of each group was higher and would lead to a more reliable analysis. Nevertheless, this fact does not necessarily violate the reliability of the result of this research in issue specification of Bloemhof since a consensus was achieved and interviewees had several concerns in common. Table 11 explains result of conducted interviews with experts whom are currently involved in (re)development project of Bloemhof.

Table 11 explains the interviews' transcripts, coding, and their categorisation in detail regarding exact statements of interviewees. Table 11 creates categories of the content of all interviews and identifies them by different colours. In general, interviewees discussed around four main themes such as geological structure (light brown), heavy construction development (light grey), greenery (light green), and hydrological challenges (light blue) of the Bloemhof neighbourhood.

According to interviewees, issues of the geological structure of Bloemhof relate to the dominant type of soil throughout the area which is mostly clay at shallow depth of underground. The clay soil reduces infiltration rate of water since its particles readily form aggregates (Holtz, Kovacs, & Sheahan, 2005). Interviewees discussed this issue as a leading cause of constant surface water flows in rainy months and declining groundwater level in Bloemhof. In addition, increasing subsidence rate of subsoil is another issue related to the geological structure of Bloemhof. Despite soil type which is a cause of surface and subsurface related hydrological issues in Bloemhof, interviewees discussed soil subsidence as an effect of this matter. The lowering groundwater level results in an increased rate of soil subsidence.

Furthermore, interviewees discussed some issues related to the current heavily constructed structure of the Bloemhof neighbourhood and its relation to lack of greeneries and decreasing water penetration throughout the area. They described these factors interrelatedly. One the one hand, the neighbourhood is heavily constructed, and very few areas have been remained green or even reserved bare. On the other hand, usually Bloemhof has several rainy months with considerable precipitation volume[27], and the capacity of the sewerage system is limited. These issues along with the almost constant slope throughout the area and considerable number of buildings with wooden piles[28] make natural and development situations of the neighbourhood worse. In other words, groundwater resources of Bloemhof are rarely recharged and the condition gets worse in terms of gradual collapse of areas having buildings on wooden piles.

[27] Data was not available at local scale. Field observations and discussions with experts familiar with the local context prove the fact of high precipitation volume throughout rainy months in Bloemhof.

[28] Which are prone to rottenness in absence of water.

Table 11. Initial themes from expert interviews

Interviewees				
Urban planner 1	Urban planner 2	Subsurface master plan expert	Water manager	Geologist
TU Delft University	*Municipality of Rotterdam*	*Municipality of Rotterdam*	*Municipality of Rotterdam*	*StrateGIS*
Clay soil.	Bloemhof is a sinking area.	Penetration issues regarding soil type and heavy constructions.	Clay soil.	Clay soil.
Mostly polluted soil throughout the area.	Water infiltration is a fundamental issue of Bloemhof.	Planners want to know where the best location for a new tree is.	Wooden piles.	No sand in shallow subsurface levels.
Increasing soil subsidence.	Planning requires information about both aboveground and underground environments containing pipes and cables.	It is important to know where the surface water flooding is worse.	Most private buildings have paved their green spaces.	Polluted soil.
Heavily constructed.	Understanding of possible uses of underground space is essential.	A dynamic analysis of water flow is needed.	Low capacity of sewerage system.	Simultaneous analysis is required to see how a change in urban area affects subsurface environments.
Rottenness of wooden piles.	Poor foundation.	Planners want to know how much water will be infiltrated by 1m^2 of green area.	Bloemhof has risk of surface water flooding.	Dry shallow level of soil layers.
Lots of residents paved their gardens.	Bloemhof lacks green spaces.		Heavy rainfall and low water infiltration rate.	
Groundwater starts at least from 1.5 to 2.1 below ground level.	Aims to make more green environments.		Very low recharge rate of groundwater sources.	
Drained groundwater since it is rarely recharged.	Heavy rainfalls cause surface water flooding in the area.			
Calculation and analysis of water-related issues are very important for planners.	Finding solutions for flooding system is required for Bloemhof.			
There are lots of water nuisance throughout the neighbourhood.	Try to increase interactions between surface/subsurface for water related issue with green areas.			
Mapping issues related to surface water flooding is necessary.	Low capacity of sewerage system.			

To narrow down the focus of this research and specify the main concern of (re)development process in Bloemhof, Table 12 was developed to find relations between interviewees' statements. Column "weight" in Table 12 shows how different issues should be prioritised in Bloemhof (re)development regarding concerns of specialists. Tables 11 and 12 show that the frequency of concerns regarding hydrological challenges is more than other mentioned issues in the Bloemhof neighbourhood. Although it is known that the frequency of statements does not significantly illustrate prioritisation of concerns, this study considered repetition of each subject related to its importance rate. In addition, conclusions of the main issue of the Bloemhof neighbourhood regarding interviewees' concern was checked with them after each interview. Therefore, it is concluded that specialists and planners need to have more communications in field of hydrological challenges. According to Table 12, "surface water flooding" is the main concern of specialists in (re)development project of Bloemhof with the highest weight of concerns in the category of hydrological challenges.

Table 12. Primary and sub-themes from expert interviews

Primary theme	Sub-theme	Weight	
Geological structure	Condition of soil layers	12.8%	**25.6%**
	Soil quality	5.1%	
	Soil penetration	7.7%	
Heavy construction development	Foundation	7.7%	**18.0%**
	Building density	10.3%	
Greenery	Green spaces	12.8%	**12.8%**
Hydrological challenges	Water infiltration	12.8%	**43.6%**
	Surface water flooding	20.5%	
	Groundwater discharge	10.3%	

Bloemhof requires considerations tailored to natural situation along with the development situation to find solutions for "surface water flooding" issue. This neighbourhood is a low-lying and densely populated area with a high social vulnerability rate compared to other neighbourhoods throughout the Rotterdam city (Koks, Jongman, Husby, & Botzen, 2015; The Municipality of Rotterdam, 2007). The surface water flooding risk management policies and mitigation measurements should be subject to the specific need of the area. For instance, a rich area could afford flood-proofing of their houses; however, a poor neighbourhood would more rely on governmental assistance (Koks et al., 2015). Therefore, risk management measurements should be based on individual characteristics of the area.

Considering degrading potential areas for surface water infiltration due to gradual increase of pavements throughout the Bloemhof neighbourhood, planners are currently dealing with management of potential flooding risk of surface water. A comprehensive consideration containing environmental, physical, social, and economic factors can deal with specific local-based flooding issue of the neighbourhood (Table 4). The Municipality of Rotterdam has held several planning workshops regarding the status of groundwater and reintroduction of drainage system in Bloemhof. These workshops and the subsequent group discussions raised the importance of groundwater consideration while the contemporary garden pavements around the neighbourhood have compromised surface water infiltration. This matter affects groundwater level. In addition, the probability of surface water flooding will be increased during heavy rainfalls which require considerations on drainage system and canals to control water flows. Moreover, building foundation is highly affected by the absence of groundwater recharge since most of the buildings are constructed without/or on wooden piles.

Regarding the above-mentioned issues of Bloemhof discussed by interviewees, there are some cause-effective relations between them. Following parts of this section describes these relations by developing a problem tree of the main issue of Bloemhof which is specified based on the interviews (Tables 11 and 12).

Figure 22 shows the importance/problem tree of surface water flooding in Bloemhof. Therefore, by considering surface water flooding as the main issue of Bloemhof, to some extent, other issues (effect factors of Figure 22) may also get improved.

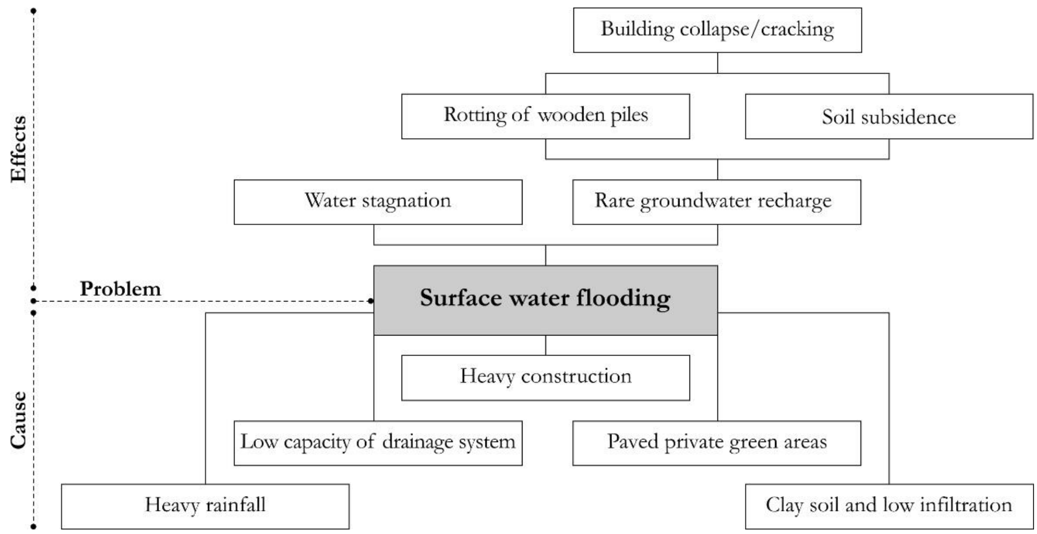


Figure 22. Problem tree of surface water flooding

To conclude, urban planners and subsurface specialists who are involved in (re)development project of Bloemhof require information about surface water flooding as well as spatial analysis of development and natural situations of Bloemhof. Since they are now working at the vision phase of (re)development process, general structure of both natural and built environments of surface and subsurface is the sufficient level of detail (LOD1) for visualisation (according to Table 3). However, they need considerable amount of information for analysis and calculation. Therefore, Table 4 containing required information for the analysis was developed in this study to provide planners and subsurface specialists with a demand-driven set of information. Following section describes analysis of surface water flooding issue and subsurface contributions to this issue based on Table 4.

5.2. Result/discussion on interaction through information transformation

This section describes analysis of the selected indicators related to the issue of surface water flooding and contribution of subsurface structures to management of this problem (according to Table 4).

Despite related previous studies, selected indicators in this research comprehensively cover different aspects of surface and subsurface structures and conditions. The comprehensiveness of indicators refers to covering social, environmental, and economic aspects of surface structures; and environmental and technical aspects of subsurface structures. Combination of these aspects in an integrated assessment of surface and subsurface structures would result in a comprehensive and broad view of their conditions and better support for decision makings. However, their combination was not fulfilled comprehensively in most of the previous studies. As the most related studies, Li, Parriaux, et al. (2013) assessed integration of underground space in development process of four pilot urban areas[29] with a focus on environmental aspect of subsurface condition (i.e., quality of groundwater, geothermal energy, geomaterial) and few considerations on social and economic aspects of surface condition (i.e., population, living density, and GDP). In addition, Li et al. (2016) did a more plenary assessment of surface and subsurface structures and their interactions; however, with a primary focus on environmental and technical aspects of subsurface structures and conditions and less emphasis on aspects related to surface structures. They did not involve social assessment of urban area in their analysis and mostly focused on its economic and environmental aspects. However, this research made a comprehensive selection of indicators related to both surface and subsurface structures and conditions. Although limitations of data availability affected selection of

[29] Cities that Li, Parriaux, et al. (2013) assessed by their work were Zurich, Geneva, Bern, and Lausanne.

indicators, almost all related aspects of surface/subsurface structures to the aim of this study[30] are covered by selected indicators. Indicators that describe surface structures and conditions are related to its social, environmental, and economic aspects; and indicators that present subsurface structures and conditions are related to its environmental and technical aspects. Following statements describe results of analysing the selected indicators.

First, quality and reliability of collected data (related to the selected indicators) were evaluated (sections 4.1.2. and 4.2.2. respectively described taken steps for evaluation of data quality and reliability in this study). Several studies mentioned the importance of these considerations before data analysis; however, each followed different approaches. Liu et al. (2008) mentioned "reliability" as a factor that should be considered for adequate preparation of specialised data for multidisciplinary communications. They, by following the approach of Tegtmeier et al. (2007), described "communication session" between whom are willing to use data as an effective approach to evaluate reliability of data. The communication sessions were explained as opportunities for data users to exchange their understanding of data, related specialised terminologies, and data collection methods with data providers. However, it might not be possible for all to have access to data providers. In addition, some studies evaluated quality of data in terms of level of uncertainty. Howard et al. (2009) evaluated the quality of data based on uncertainty of their metadata. They presented a cyber-infrastructure to provide a complete, clear, and correct set of data description regarding their constant review and update by experts. However, quality assessment of data without considering their reliability in analysis might not successfully result in accurate and certain results. Accordingly, this study combined both approaches on evaluation of data quality and data reliability to prove certainty of its analysis and results which is not always considered by most studies on geological information with complex and varied structures.

Evaluation of data quality was done by reviewing metadata of geo-portals as existing data provider tools and asking data providers about certainty of data collection and interpretation methods (see section 4.1.2 for more explanation).

Evaluation of data reliability in this study was done by comparing results of analysis with real data. To ensure the reliability of selected indicators (Table 4), the first dimension which is "risk of surface water flooding" was analysed and the generated map was compared with real complaints of residents regarding surface water nuisances (Figure 23). To this end, several steps were implemented such as preparation of data related to each indicator, rescaling of data into one similar range, development of risk index, and risk map generation. Section 4.2.2. explained applied methods for these steps in detail. Following statements interpret the results.

Figure 23 shows risk of surface water flooding throughout the Bloemhof area. Regarding comparison of this index with real complaints of residents about surface water nuisance, it is shown that there is considerable similarity in risk level. Most of the areas that are announced by residents regarding the issue of surface water flooding are assigned with a high level of risk (Figure 23). To ensure the comparison statistically, a point-biserial correlation was implemented (explained by section 4.2.2.). Annex 9 shows the implemented correlation matrix between these variables (risk index and complaints). It is shown that correlation coefficient between these two variables is 0.453 and p-value is 0.000 which shows significance of the correlation.

The correlation coefficient shows that calculated risk of surface water flooding and real surface water complaints are correlated. In other words, calculated values for surface water flooding risk and surface water complaints increase concurrently since they are positively correlated; however, increases are not all

[30] Transformation of specialised data by integrating related indicators of surface and subsurface structures and their analysis in terms of assessing the specific issue of an urban area and appraising the potential contribution of subsurface structure towards solving that issue. The transformed data result in comprehensible information for those who want make decisions on the issue.

in the same range and vary across spatial grid-based unit of the analysis. Several considerations could justify this matter. There might be some people that do not complain even if they have a problem. In addition, there might be some people that complain when there is very little problem.

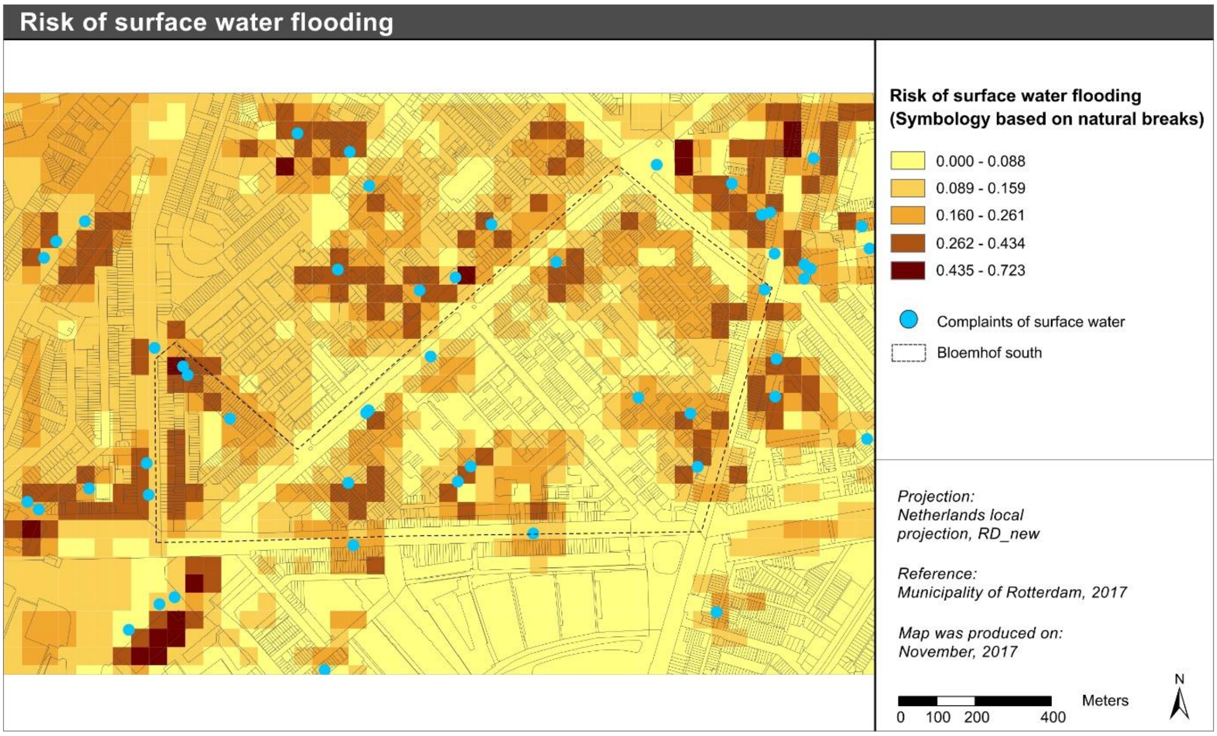


Figure 23. Risk of surface water flooding

Nevertheless, it is concluded that the analysed indicators are reliable since they are presenting real situation.

Accordingly, indicators of supply inventory and demand targeting were analysed with high confidence of data reliability. Figures 24 and 25 show results of analysed indicators of supply inventory and demand targeting factors respectively (section 4.2.2. explains methodology for related analysis).

The "potential supply inventory" and the "potential demand targeting" factors in this research were adapted from Li et al. (2016). They integrated indicators related to surface and subsurface conditions across demand and supply factors. However, in this research the "potential demand targeting" factor is assigned to conditions of surface structures and the "potential supply inventory" factor is representing conditions of subsurface structure. This leads analysis to possibilities of evaluating surface and subsurface capacities against each other. In addition, this study focused on the transformation of specialised data by evaluating correlations between different indicators and their contributions in index development, while it was not considered in previous studies. For instance, as one of the most related works to this study, (Li, Li, Parriaux, & Thalmann, 2013) analysed surface and subsurface conditions by developing an index relying on opinions of local experts. To be specific, indicator selection and their weighting for index calculation were done based on local expert opinions in their work. However, in this study, in addition to observing the views of local experts, relationships between indicators and their weighting have been calculated statistically (using PCA method, see section 4.2.2. for more detail). The used approach in this study highlights the importance of correlations between indicators which should be reduced in case of any and the contribution of each indicator to the index by giving them weights regarding the importance of their impacts on results.

Figure 24 shows potential contribution of subsurface structures to the issue of surface water flooding. For the analysis of this factor both natural and built environments of subsurface structure were analysed (Table 4). In general, analysed indicators indicate existing condition of subsoil structure since this matter positively affects surface water flooding issue. To be specific, level of soil pollution, water infiltration, and space availability describe properness of a condition for vegetation growth which might balance cause factors of surface water flooding (e.g., water infiltration, rate of development density, and surface water flow) (Figure 22).

Figure 24 provides a relative description of potential supply inventory factor throughout the study area. Values of the calculated potential supply inventory are varied from negative to positive and are describing relative capacity of each spatial unit in supplying supports from subsurface structures to urban environment. Each individual value regardless of its positive or negative sign cannot be interpreted separately. Interpretation of an index should be made relatively across all spatial grid units. In other words, the higher value indicates a better supplementary condition of subsurface structures regarding surface water flooding issue.

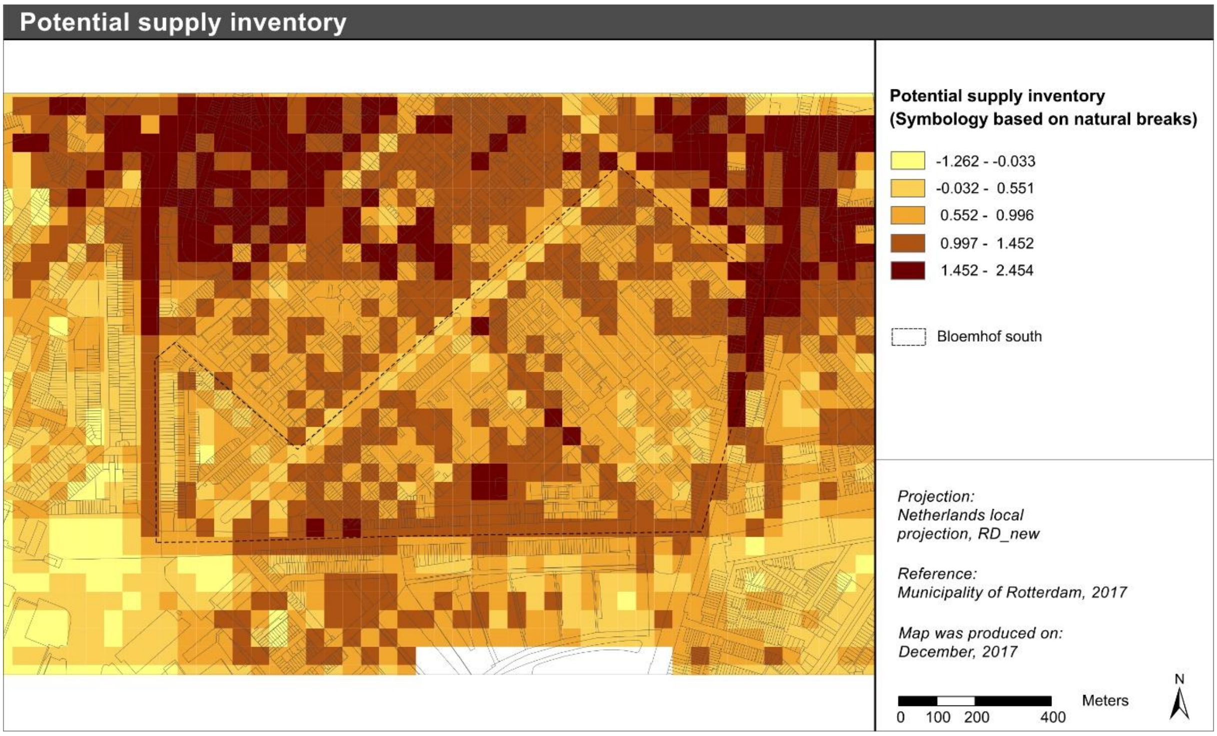


Figure 24. Potential supply inventory

However, rate of supply regardless of analysing demand side is meaningless. Therefore, Figure 25 shows result of analysing related indicators to demand factor.

The demand factor indicates potential need of the Bloemhof urban environment to its (re)developments regarding the issue of surface water flooding. The higher the value of calculated potential demand targeting factor (by Figure 25) identifies the worse the condition of urban structure in terms of surface water management and water flow control. Considerably, values are relative throughout the area and compare the condition of urban structure across generated grids.

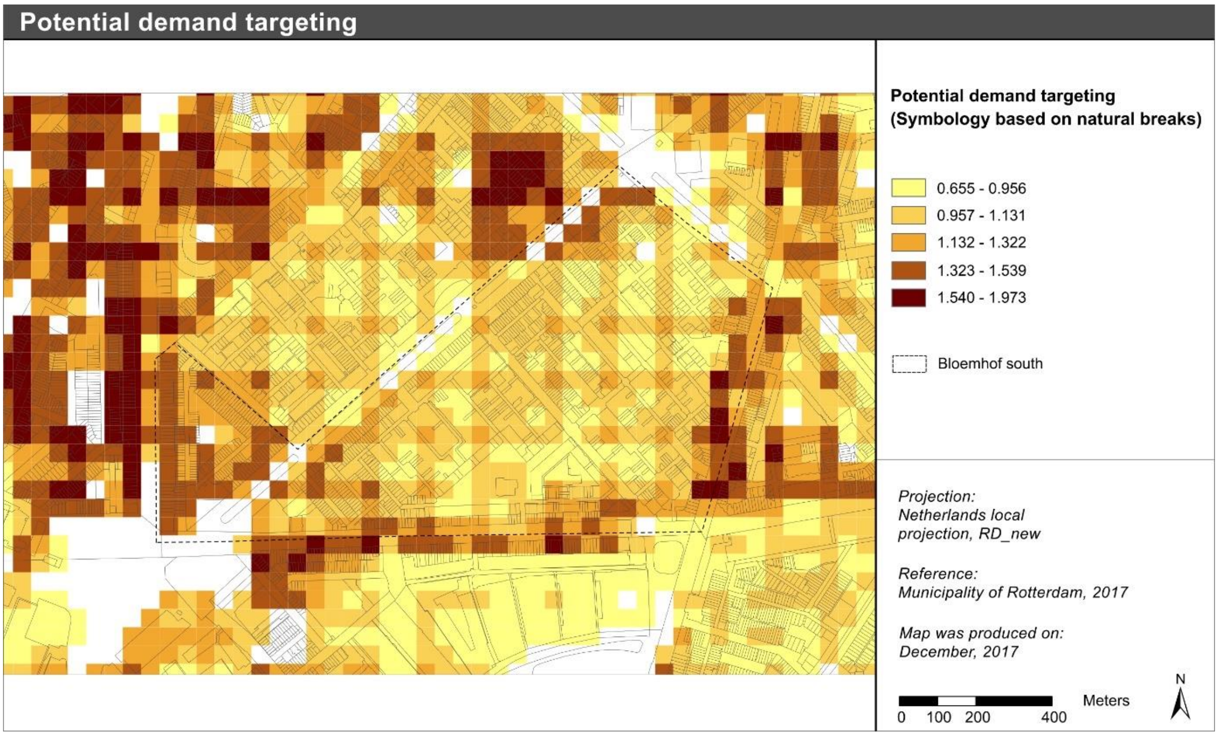


Figure 25. Potential demand targeting

To enable utilisation of calculated supply inventory and demand targeting factors in planning thoughts, their values were interpolated throughout the whole study area since there are some NULL valued grids in Figures 24 and 25 (explained by section 4.2.2.). This is due to the fact that all grids are not applicable to the calculation of all indicators. For instance, indicator D1, presenting ratio of unbuilt to built areas, is meaningful for all grids since each has a structure either artificial (built) or natural (unbuilt). However, indicator D5, presenting ratio of the wooden foundation to concrete or any stronger types per grid zone, is not meaningful for grids that have no building. Annexes 25 and 26 respectively illustrate interpolated values[31] of the potential supply inventory and the potential demand targeting factors.

Comparison between interpolated values of the potential supply inventory and the potential demand targeting factors result in a (re)development vision of Bloemhof for urban planners and subsurface specialists[32].

Figure 26 illustrates result of (re)development vision calculation. The calculated value for (re)development vision identifies how the situation between demand and supply is equilibrium. The lower the value means the weaker the supply system in meeting the demand side. To be specific, based on Figure 26, two approaches could be taken for (re)development considerations. On the one hand, if planners decide to give (re)development priority to available supplementary capacity of the area (surface/subsurface conditions), the development should be started from greener areas. The greener the area means the greater the capacity of supply system in relation to demand of the area for improvement and development. On the other hand, if decisions have focused on the importance of improving conditions of worst areas (with high risk of surface water flooding), (re)development considerations should be started from reddish areas. The redder the area means the lower the capacity of supply system in relation to demand of the urban area for improvement.

[31] Interpolation based on an Inverse Distance Weighted (IDW) method.

[32] Section 4.2.2. explains applied methodology for comparison between potential supply inventory and potential demand targeting factors in detail.

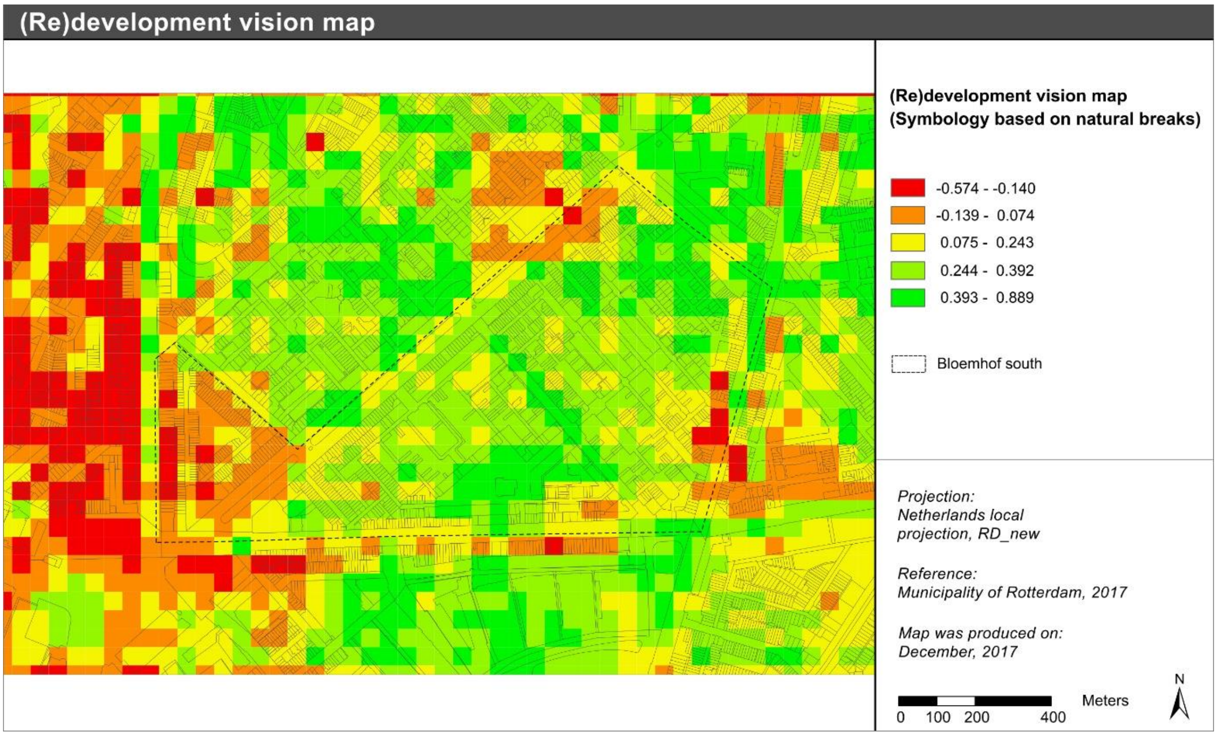


Figure 26. (Re)development vision map

Used colours for visualisation of the (re)development vision values (Figure 26) are categorised in 5 classes, from red with negative values, high priority for the second (re)development approach; to lime green with positive values, high priority for the first (re)development approach.

Figure 27 describes the extent that each class covers throughout the study area. The importance of coverage extension by each colour depends on the approach that planners and decision makers would take for (re)development considerations of Bloemhof. In case that available surface/subsurface capacities are aimed to be used for (re)development, values of yellow; light green; and lime green classes which have higher supplementary capacity than the demand, should be considered. In this case, almost 73% of the total area has efficient capacity of current surface and subsurface structures in dealing with surface water flooding issue (based on the calculation of this study). However, in case that improvement of worst-off areas is focused for (re)development, values of red and orange classes which have lower supplementary capacity of surface and subsurface structures than the demand should be considered. In this case, nearly 27% of the total study area has considerable failure of current surface/subsurface structures in dealing with the issue of surface water flooding.

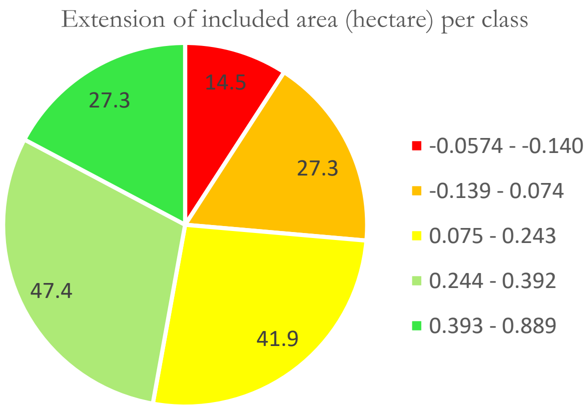


Figure 27. Quantification of (re)development vision map

Using results of Figures 23 and 26 in parallel would provide urban planners and subsurface specialists with a comprehensive understanding of the Bloemhof neighbourhood regarding surface water flooding issue. To compare with previous related works, Li, Parriaux, et al. (2013) and Li et al. (2016) described current conditions of surface and subsurface structures with the aim of planning support; however, they did not finalise their results in a way that gives planners a vision for further considerations. This study adds value to previous studies by supporting planners and decision makers with a broad vision of current surface and subsurface conditions in addition to the detailed description of their deficiencies and capabilities in an integrated improvement/(re)development.

To enhance utilisation of surface and subsurface related information for urban planners and subsurface specialists, a 3D model was generated. Following section explains and discusses the result.

5.3. Result/discussion on integration through 3D modelling

In this study, surface and subsurface structures (Table 10) were integrated through 3D objects generation using grammar-based techniques (i.e., CGA shape grammar modelling). Liu et al. (2017), the most recent work in the field of integrated 3D modelling of surface and subsurface conditions, proposed the semantic web-based technology for the purpose of integrating surface and subsurface structures. However, they developed surface and subsurface models separately due to the challenges of doing heterogeneous data integration (e.g., formats, application, users, spatial units, methods of accessibility). This study has adopted a comprehensive approach toward improving the shortcomings of previous studies in an integrated 3D modelling of surface/subsurface structures. The comprehensiveness had been fulfilled by integrating objects from above- and below-ground in a single 3D platform, providing data with an appropriate level of detail, and visualising the transformed specialised data in an understandable manner[33]. In addition, transformed data regarding analysed indices (Table 4) was visualised in the 3D model.

The generated 3D model of surface/subsurface structures of the Bloemhof neighbourhood and transformed factors in this study was published online through CityEngine web viewer[34]. In addition, a short movie of the 3D model was created and uploaded online via YouTube[35].

Table 13 describes objects of the 3D model in detail. Each object which refers to individual components of surface/subsurface structures (according to Table 10) are illustrated, provided information is explained, and resolution of used data is discussed. The resolution of data discusses limitations of data availability and data accuracy. This study had some limitations to obtain all required data which could provide higher accuracy of the analysis.

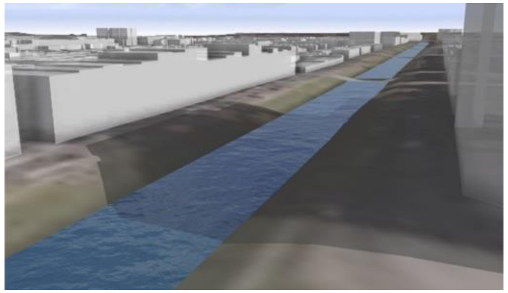
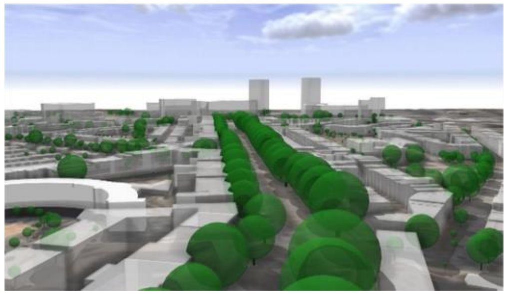
[33] Assigning information (which was produced through transformation of specialised data) to corresponding objects (of surface and subsurface structures).

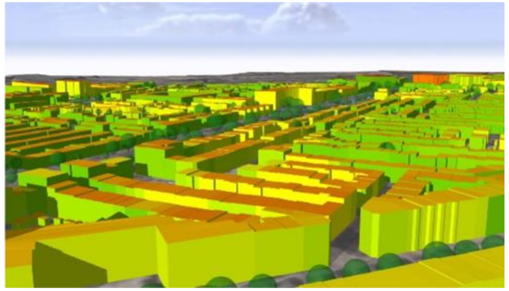
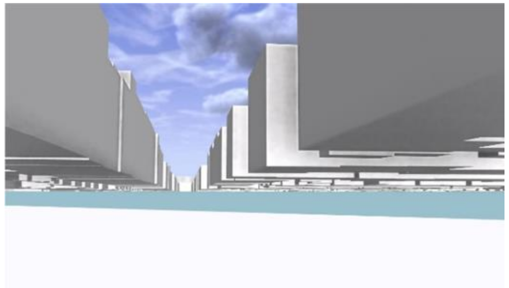
[34] http://arcg.is/2rqIegj

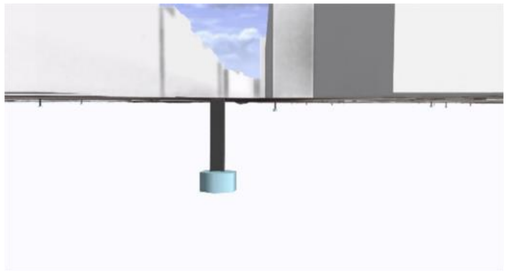
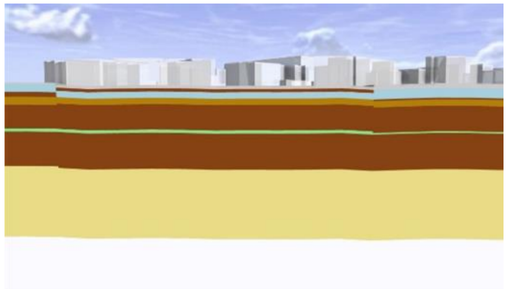
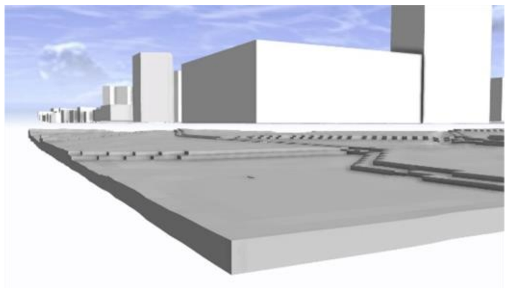
To enable visualization of the model through CityEngine Web Viewer, ESRI (2017) provides a guideline since weak system configuration and web browser setting make visualization slower and even impossible.

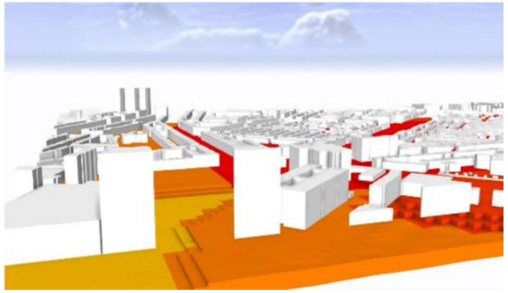
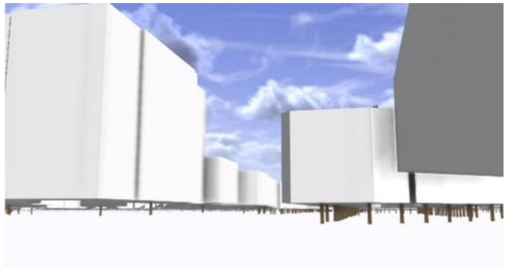
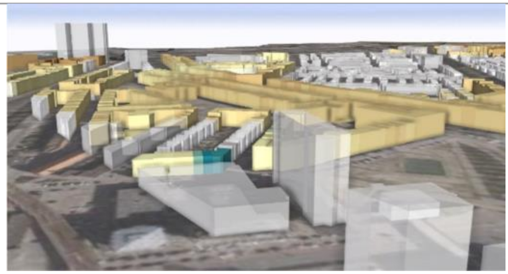
[35] https://youtu.be/7b4HUyUU6pE

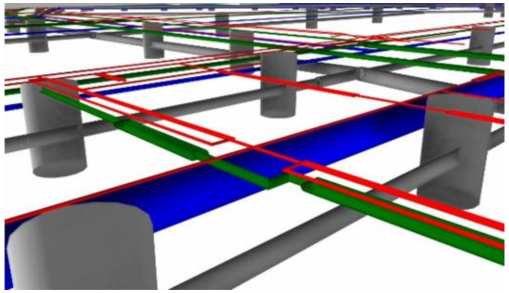
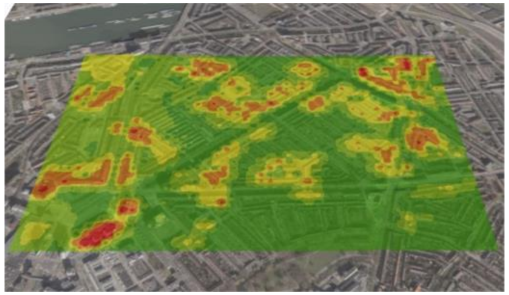
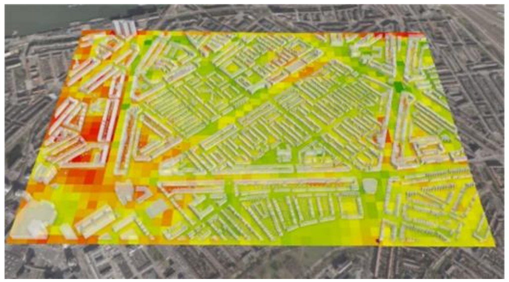
Table 13. Description of the integrated surface/subsurface 3D objects

3D object	View	Information provision	Data resolution
Canal		• Visualisation of animated water flow; • Length and width of the existing canal.	• Lack of data about canal depth; • Estimation of water parameters was not provided (e.g., wave size, and wave speed).
Tree		• Width of trees' trunk; • Spread of trees' crown.	• Trees' crowns are visualised as spheres which is an assumption; accordingly, some overlapping parts of trees with buildings are seen; • Lack of data regarding trees height; A Digital Surface Model (DSM) raster dataset was used to get values of trees height; however, since crowd spread was assumed as a circle and point locations of trees were not 100% accurate it was useless; • Size of trees was considered regardless of their type.
Building		• Building height; • Area of footprints.	• By checking height of some randomly selected buildings with street view of google map, it was concluded that data of building heights is not 100% accurate; • Many errors in sheds' height were found. Their height was adjusted to a standardised value (2.5 meters).

3D object	View	Information provision	Data resolution
Vulnerability/exposure	 See Annex 28 for legend.	• Visualisation of calculated vulnerability and exposure dimensions as wall and roof colours (respectively);	• Vulnerability and exposure factors were calculated based on grid-based spatial unit, and then an interpolation method (IDW) was applied to have values for the whole area. Resolution of the interpolated result is 4 meters. Each building gained value of pixel that has covered its centre point.
Subsoil space use by trees	 See Annex 28 for legend.	• Type and volume of required subsoil for each tree; • Visualisation of soil type that each tree is grown in by colour.	• Soil volume was calculated based on literature review and related shapes were generated as rectangular cubes which only express estimated values of soil volume rather actual dimensions of space requirement by trees' root. Soil volume was modelled in 3D based on a consideration that root growth as wide as trees crown.
Groundwater level		• Visualisation of groundwater layer with thickness of the difference between highest and lowest groundwater; • Groundwater depth, and average level of groundwater.	• Lack of data regarding possible water fluctuation; • Data was obtained using raster datasets with pixel size 25 meters.

3D object	View	Information provision	Data resolution
Wells		• Visualisation of groundwater wells at their exact location with exact thickness (regarding highest and lowest water level); • Generation of 0.5-meter wide tubes for a better visualisation of wells from above.	• Lack of data regarding wells size.
Soil layers	 See Annex 28 for legend.	• Visualisation of subsoil layers regarding their specific types, thickness, and exact location.	• Lack of data integrity; • Two separate datasets were used with different extent; • Terrain raster dataset was used, and elevation values were assigned to grids of the first layer of subsoil to calculate soil thickness since some grids have the value in advance (grids of the dataset with smaller extent). • Data resolution (100*100 meter) does not provide data matching with elevation layer.
Soil subsidence	 See Annex 28 for legend.	• Level of soil subsidence throughout the Bloemhof neighbourhood illustrating by the created distance (gap) between soil and buildings.	• Data resolution was low (polygons with minimum area of $\simeq$665 m^2), and a certain value of soil subsidence for each location was not described; • Subsidence value of each polygon was provided as the mean of all locations within its boundary; • Regarding small range of subsidence values (in terms of proper visualisation), soil subsidence values were exaggerated 10 times.

3D object	View	Information provision	Data resolution
Soil pollution	 See Annex 28 for legend.	• Level of soil pollution in 4 classes from very slightly to heavily contaminated; • Thickness of pollution layer is related to soil subsidence level.	• Low data resolution: ≃16121 m^2 (the minimum area size of polygons); • Data had categorical classification of pollution level for polygons, and the original pollution values in different depth levels were not available.
Piles	 See Annex 28 for legend.	• Type of foundations for each building footprint differentiating with colours.	• Each footprint has one cylindrical pile as its foundation; • Depth and width of foundations were not provided, and a unique value was assigned to all buildings for visualisation.
Potential wooden piles' rottenness	 See Annex 28 for legend.	• Potential pile rottenness indicates how wooden piles and groundwater layer are intersected.	• Depth level of groundwater layer was extracted from raster datasets with pixel size 25 meters.

3D object	View	Information provision	Data resolution
Infrastructures; pipes	 See Annex 28 for legend.	• Location, size, and length of subsurface infrastructures (i.e., sewerage system, drinking water system, electricity network, and gas network); • Visualisation of wells for the sewerage system at a certain depth (provided by collected data).	• Vertical allocation of infrastructures was not provided by the available data, and was considered as an assumption; • Size of sewerage wells was considered based on assumption; • Radius of pipes and cables was retrieved from literature review based on provided types and materials of pipes and cables.
Risk of surface water flooding	 See Annex 28 for legend.	• Value of calculated risk of surface water flooding for any location throughout the study area.	• Data resolution was ≃ 4 meters.
(Re)development vision	 See Annex 28 for legend.	• Rate of (re)development priority for any location/building footprint throughout the study area.	• Data resolution was ≃ 31.62 meters. This value is concluded as the smallest common spatial unit among all obtained and used data for this study. To ensure the accuracy of analysis, this value (31.62) is not rounded off.

The generated 3D model was validated using a questionnaire (Annex 29). Data provision, visualisation, ease of utilisation, and applicability are main factors of the validation questionnaire that can comprehensively describe the model. The model was validated from scientific and technical point of views.

On the one hand, scientific aspect of the model was appraised by real users[36] in terms of effectiveness[37] of data provision and visualisation. It should be noted that the visualisation aspect can be considered from both scientific and technical point of views. "Data provision" as the first section of validation questionnaire (Annex 29, questions 1-4) focuses on usefulness of transformed data for planners and subsurface specialists, and sufficiency of level of detail. In addition, "visualisation" as the second section of validation questionnaire (Annex 29, questions 5-6) discusses accurateness of the generated 3D objects geometrically, and appropriateness of used colours.

On the other hand, technical aspect of the model was evaluated regarding its ease of utilisation, and applicability. "Ease-of-utilisation" section (Annex 29, questions 7-9) explores ease of interactions with the model. Moreover, the "applicability" section (Annex 29, questions 10-13) deliberates possibilities of model generalisation.

Figure 28 provides concluded result of responses (Annex 30) to the validation questions; however, it should be considered that the number of respondents (four experts) was small for a general conclusion of the model performance (in terms of effectiveness and usefulness). The small number of consulted experts for the model validation is a limitation of this study which could not be avoided due to time limitation, heavy workload of experts, difficulties of gathering different people at one time, etc. However, this study is aware of possible changes that would have happened on the validation results in case that the respondent group had different participants with different professions than the ones who participated in this study.

To analyse responses to the validation questionnaire, percentage of chosen answers (the Likert scales) per aspect (i.e., data provision, visualisation, ease-of-utilisation, and applicability) was calculated separately for each respondent. In other words, each aspect contains few questions. Each question was designed based on 6 scaled responses. So, responses from each participant were summed across questions of each aspect and Likert scales. Therefore, the orientation of each individual respondent is determined across validation aspects. Horizontal coloured bars by Figure 28 indicate how far responses of participants are from the neutral ("neither agree nor disagree") state. The more the length of the bar from the vertical dashed line to the sides shows the orientation of responses to either agreement or disagreement with each aspect of validation. Considering dominant colour per bar and their lengths enable understanding of required improvements and changes to the model for further works.

According to Figure 28, "applicability" is the strength of the model. In other words, respondents evaluated the generated 3D model of this research highly effective in (re)development planning despite existing voxel model of the Municipality of Rotterdam (Figure 17). Moreover, regarding posed questions in the applicability section, the model is highly adaptable for further generalisation in terms of area extension and subject of study. These results generally illustrate how the model might behave in practice.

In addition, respondents found "ease of utilisation" as an aspect of the model that needs improvement. Later contact with respondents determined an external factor influenced this issue. The model was too heavy for fast loading and demonstration using a normal internet speed. Nevertheless, almost all respondents found online presentation of the model via CityEngine web viewer a good innovation. Accordingly, the improvement might be needed for extension of the area, and respectively size of the

[36] Participated planners and specialists in focus group discussion (validation session).

[37] Effectiveness of provided data (by the model) regarding the purpose of Bloemhof (re)development.

model which seems is too large for use at any location by anybody. Since the model was generated for enhancement of communication between specialists and planners, this matter needs further considerations in practice.

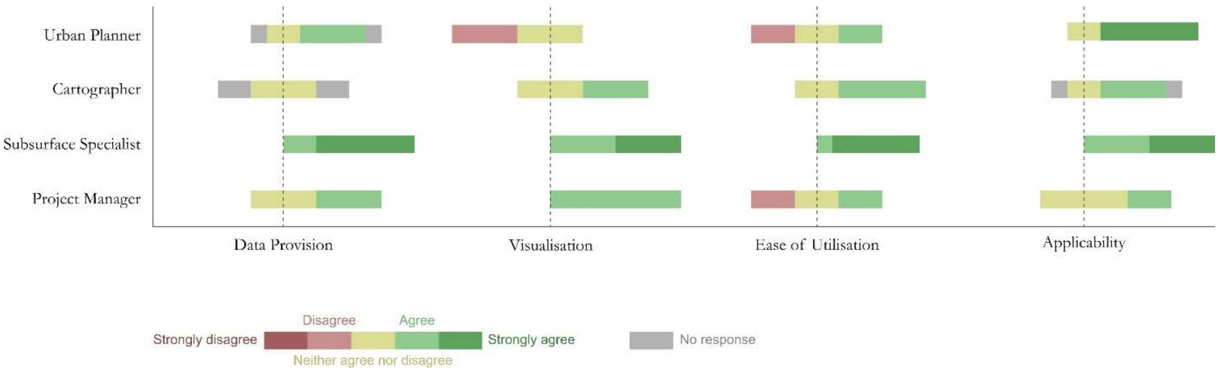


Figure 28. Analysis of responses to validation questionnaire by four experts

Beside responses to multiple-choice questions, remarks of explanatory questions and group discussions were analysed thematically. To conclude findings, Table 14 describes strengths, weaknesses, opportunities, and threats of the 3D model regarding its role in enhancement of communication between urban planners and subsurface specialists for knowledge sharing and making decisions.

Statements of the SWOT analysis are based on the validation results and group discussions. In addition to exact responses of participants, integration of their responses is also considered to develop the SWOT table. Table 14 presents some statements in highlight which refers to items that were mentioned by several respondents. This fact provides this research with most emphasised aspects of the model by users. To be specific, 3D integration of specialised data with realistic objects was positive concern of almost all respondents which shows how appropriate the model provides users with required information (in terms of visualisation and data transformation). However, the big size of the model was a challenge for most users to work with it. Although presentation of the model on internet-based web viewer service of ESRI makes its utilisation rather efficient than application-based presentation, its big size caused difficulties regarding internet speed.

Table 14. SWOT analysis of the integrated surface/subsurface 3D model

Strengths	• Possibility of layer by layer visualisation of objects; • Integrated visualisation of surface and subsurface structures; • Easy transfer from 3D to 2D (e.g., cross section generation); • Interrelated analysis of indicators using ArcGIS model builder; • Sufficient level of detail for the vision planning phase; • Realistic presentation of surface/subsurface structures; • Accurate geometric representation of objects; • Online demonstration, not relying on any application; • Provision of demand-driven information for planners and specialists;
Weaknesses	• Requirement of high computational capacity; • Huge size of the model might make its utilisation challenging at any location regarding internet connection speed; • Biased comprehension of classified information due to utilised colours which might be meaningful for some groups of expert and not for the others; • Inaccurate allocation of some subsurface-related structures due to data unavailability (i.e., pipes).
Opportunities	• Data/model updating; • Adaptability of the model to different subjects and case areas; • Scenario development; • Possibility of upgrading to a four-dimensional (4D) model.
Threats	• Extending utilisation of the model beyond the vision planning phase.

Note: highlighted statements determine items that were mentioned by several respondents.

SWOT analysis describes usefulness of the model in vision planning phase for enhancing communications between planners and specialists. However, some limitations made the model performance weak regarding accurate analysis and proper visualisation. Next section describes an overview of limitations that this research faced throughout 3D modelling process.

5.4. Limitations

Doing this research faced several limitations that might indirectly affect the results and applied methods. Table 13 explained some under “data resolution” column. To give a general description of limitations for the whole process of this research, following statements are listed.

- Experts’ availability; their willingness; time issues; and effectiveness of responses caused some constraints in doing interviews and group discussions.
- Small number of experts consulted for problem analysis and model validation.
- Data uncertainty, regarding incomprehensive datasets (e.g., dataset of gas pipes has distinct lines).
- No metadata was attached to collected data; data description was obtained by contacting data providers and searching through geo-portals.
- High computational capacity is required for complex models same as the generated model in this research since the area of study was considerably large for 3D modelling.

Next chapter provides a summary of results and discussions of this study and reflections of achievements on research objectives.

6. CONCLUSION AND RECOMMENDATIONS

This chapter presents a summary of results and discussions of this research. It refers to research objectives and questions that have been met throughout the study. In addition, it provides further studies with some recommendations.

6.1. Reflection on research objectives

This study has investigated how a 3D model can contribute to the enhancement of a multidisciplinary communication between urban planners and subsurface specialists and provide them with a broader planning insight into surface and subsurface conditions and interactions. The model was developed based on integration of data on surface and subsurface structures. 3D integration of complex data on surface and subsurface structures is not as straightforward as their individual management and 3D visualisation. Individual models of surface and subsurface structures are effectively useful for professional practices in related fields. However, a multidisciplinary communication requires understandable and useful information for all participants. This study integrated specialised data by transforming related ones into meaningful information for both parties of planners and specialists.

Understanding of conditions, characteristics, and interactions of surface/subsurface structures was a prerequisite to data transformation. Surface and subsurface structures vary across built and natural environments with different interactions. This study defined interactions between surface and subsurface structures in an urban setting as actual and potential. On the one hand, the actual interaction refers to any existing physical connection between their structures and features. On the other hand, the potential interaction refers to potential contribution of each toward improvement of the other's condition. Understanding the interactions between different structures of surface and subsurface led this study to effective categorisation of data for transformation. In addition, demand of planners and subsurface specialists guided transformation of data towards an effective provision of information. This study conducted several in-depth interviews to investigate demand of planners and specialists for integration of surface and subsurface structures. Accordingly, for data transformation, this study developed an index focusing on demand of planners and specialists, and actual/potential interactions between surface and subsurface structures. The index states the demand as an issue of an urban setting related to interactions between surface and subsurface, describes the actual interaction as existing condition of surface and subsurface structure, and indicates the potential interaction as possible contribution of subsurface structure into the improvement of surface condition. Transformed data based on the described index provided new and meaningful information for urban planners and subsurface specialists. The useful and meaningful information of surface and subsurface should be presented in an effective visualisation, easy to understand and interact, and applicable for updating and improvement context. A 3D context was proposed by this study.

This research proposes a 3D modelling approach for an integrated-object-generation. A new approach, named "procedural modelling" based on the L-system technique, was evaluated as the most effective 3D modelling technique for an integrated platform of surface and subsurface features and structures. The L-system modelling technique supports integrated 3D object-oriented concepts with a range of levels of detail, based on rule scripting. The ESRI CityEngine platform was used to develop such a 3D rule-based model. Existing spatial data for the Bloemhof neighbourhood, Rotterdam, was used to test the model and demonstrate its capabilities. The model was validated regarding opinions of real users (urban planners and subsurface specialists) on its effectiveness in terms of data provision, visualisation, ease of utilisation, and applicability. The result shows an improved visualisation of surface/subsurface structures, flexibility in the provision of appropriate levels of detail, data updating opportunities, improved interaction, and adaptability of the model to different applications. Further enhancements can be made according to expressed user demands. However, the test also shows that the model has quiet high demands in terms of information processing infrastructure.

Next section proposes possible developments of this study for future works.

6.2. Recommendations for further research

Following statements present possible directions that future studies can follow toward a progressive stage of this research.

- Development of the model in a 4-Dimensional style for scenario development and dynamic analysis;
- Interactive conversion/analysis of integrated information between 2D and 3D models;
- Improvement of modelling technique to CityGML.

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APPENDIX

Annex 1. Template of questions for expert interviews

1. What are the main issues of the Bloemhof neighbourhood?
2. What is the current focus of Rotterdam for the Bloemhof neighbourhood?
3. What do planners need to know about the spatial aspects of the neighbourhood?

Annex 2. Correlation between exposure indicators

Correlation Matrix [a]

		E1	E2	E3	E4	E5	E6
E1	Pearson Correlation	1	-.095**	-.514**	-.054*	-.017	-.070**
	Sig. (2-tailed)		.000	.000	.030	.487	.006
	N		1584	1584	1584	1584	1584
E2	Pearson Correlation		1	-.132**	-.071**	.515**	.233**
	Sig. (2-tailed)			.000	.005	.000	.000
	N			1584	1584	1584	1584
E3	Pearson Correlation			1	.183**	.026	.008
	Sig. (2-tailed)				.000	.309	.745
	N				1584	1584	1584
E4	Pearson Correlation				1	-.009	.000
	Sig. (2-tailed)					.714	.998
	N					1584	1584
E5	Pearson Correlation					1	.077**
	Sig. (2-tailed)						.002
	N						1584
E6	Pearson Correlation						1
	Sig. (2-tailed)						
	N						

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

a. Determinant = .412

Annex 3. Correlation between vulnerability indicators

Correlation Matrix [a]

		V1	V2	V3
V1	Pearson Correlation	1	.066**	-.220**
	Sig. (2-tailed)		.009	.000
	N		1584	1584
V2	Pearson Correlation		1	-.114**
	Sig. (2-tailed)			.000
	N			1584
V3	Pearson Correlation			1
	Sig. (2-tailed)			
	N			

**. Correlation is significant at the 0.01 level (2-tailed).

a. Determinant = .938

Annex 4. KMO test for exposure indicators

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.503
Bartlett's Test of Sphericity	Approx. Chi-Square	1400.771
	df	15
	Sig.	.000

Annex 5. PCA components for exposure indicators

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings[a]
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	1.775	29.579	29.579	1.775	29.579	29.579	1.763
2	1.564	26.067	55.646	1.564	26.067	55.646	1.576
3	.958	15.961	71.607				
4	.800	13.326	84.933				
5	.554	9.234	94.167				
6	.350	5.833	100.000				

Extraction Method: Principal Component Analysis.

a. When components are correlated, sums of squared loadings cannot be added to obtain a total variance.

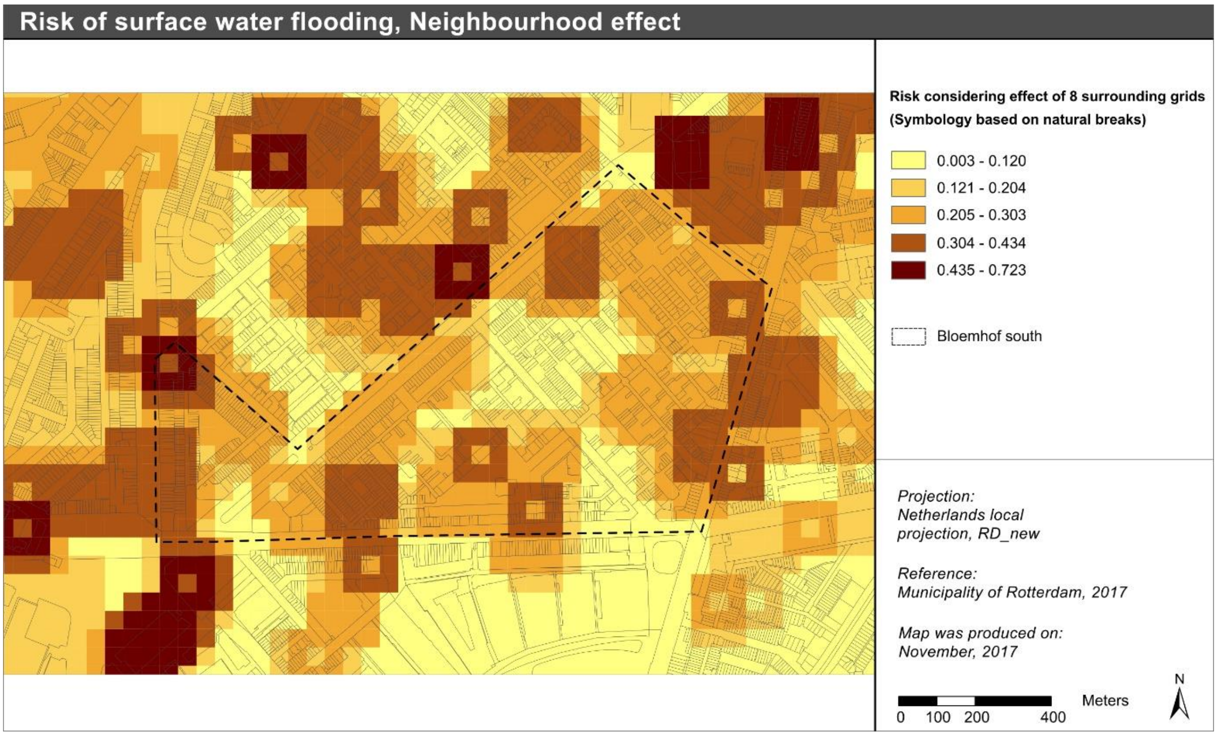
Annex 6. PCA pattern matrix for exposure indicators

Pattern Matrix[a]

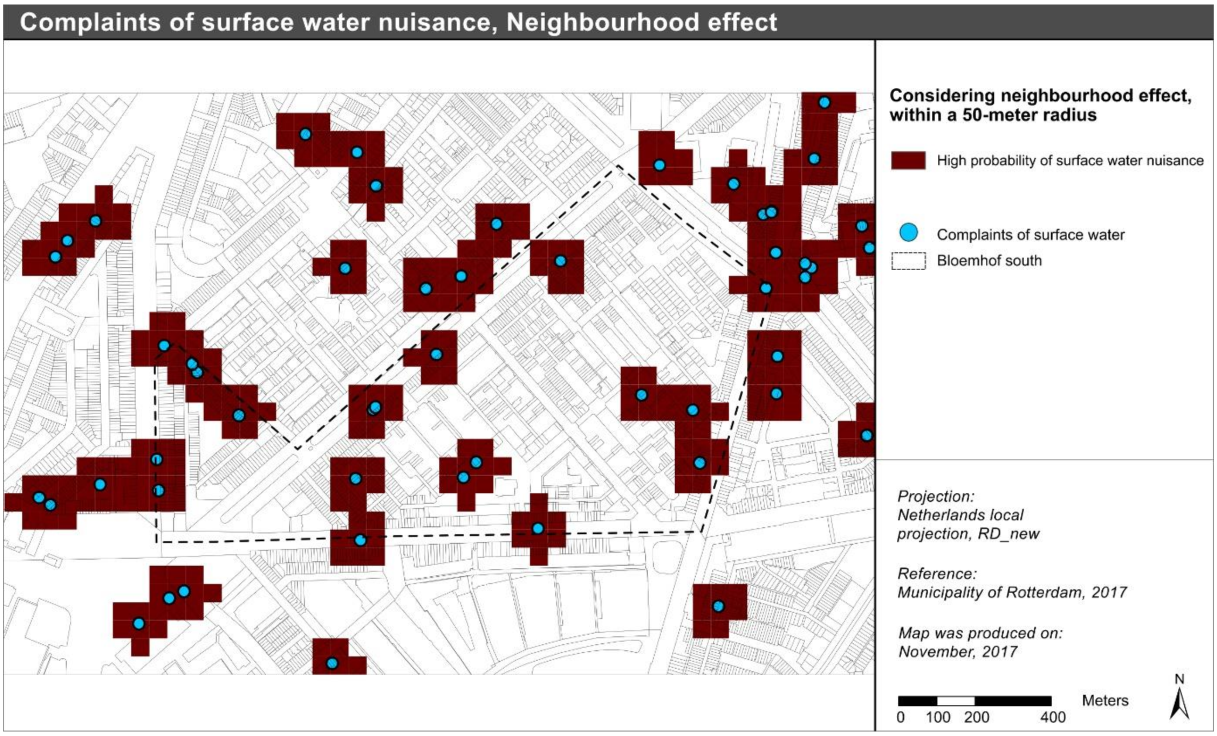
	Component	
	1	2
E1	.196	.795
E2	-.832	.147
E3	.002	.873
E4	.098	-.382
E5	.822	-.012
E6	.589	.114

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 4 iterations.

Annex 7. Risk of surface water flooding considering neighbourhood effect



Annex 8. Surface water complaints considering neighbourhood effect



Annex 9. Correlation between surface water flooding risk and real surface water complaints

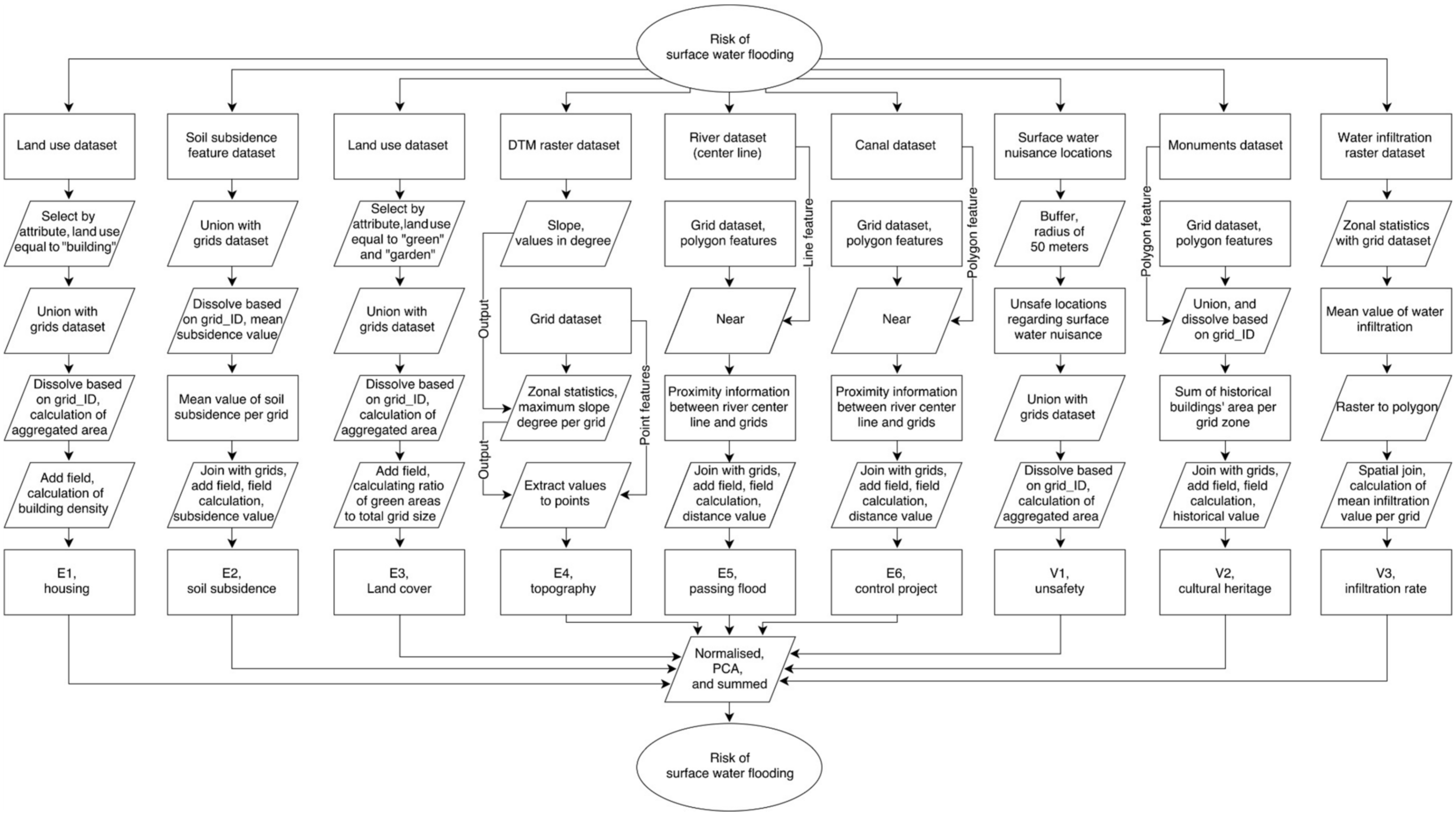
Correlation Matrix

		Risk	Complaint
Risk	Pearson Correlation	1	.453**
	Sig. (2-tailed)		.000
	N		1584
Complaint	Pearson Correlation		1
	Sig. (2-tailed)		
	N		

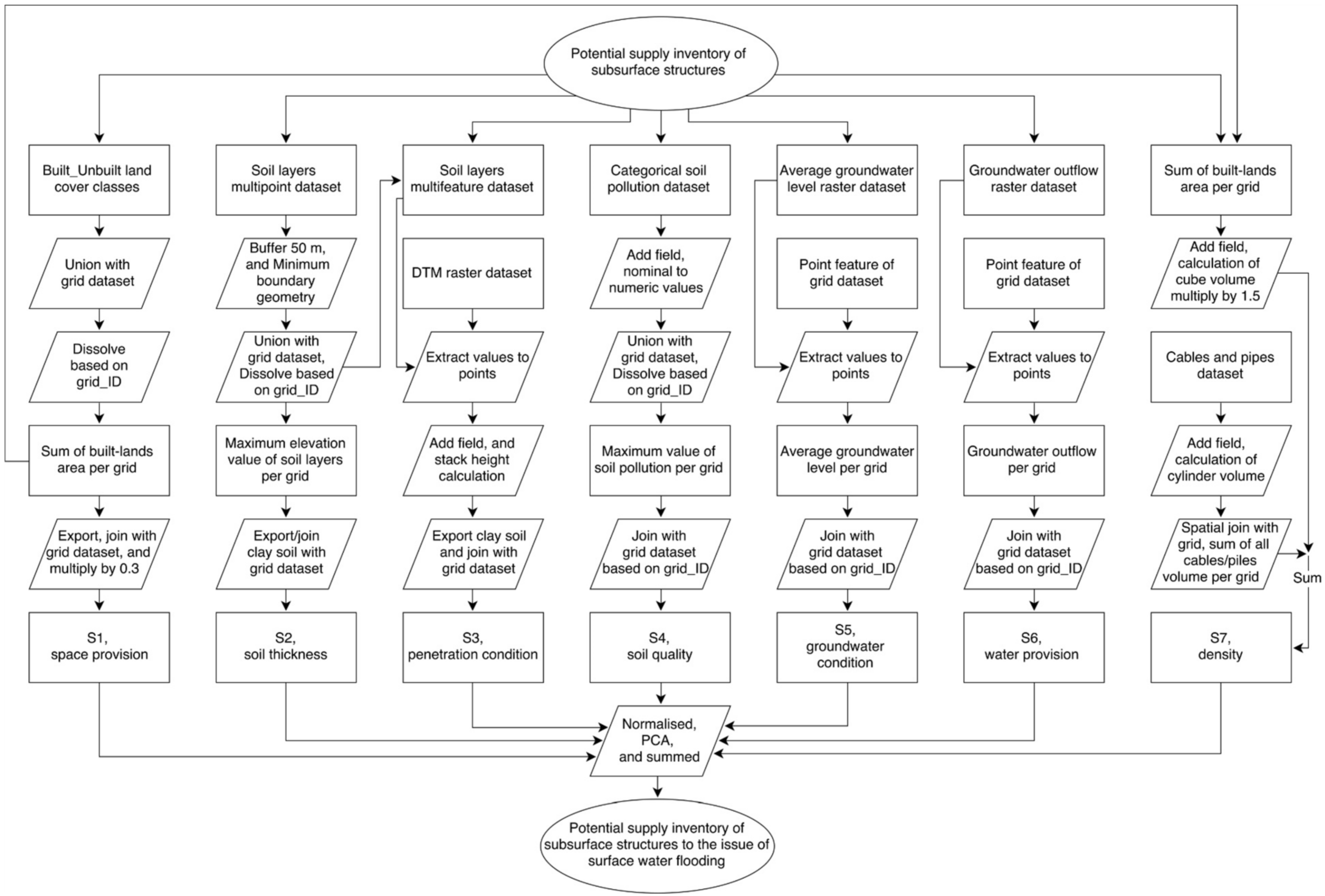
**. Correlation is significant at the 0.01 level (2-tailed).

Note: The values are calculated by considering neighbourhood effect (explained by section 4.2.2.)

Annex 10. Flowchart for risk of surface water flooding analysis



Annex 11. Flowchart for supply inventory analysis



Annex 12. Correlation between supply inventory indicators

Correlation Matrix[a]

		S1	S2	S3	S4	S5	S6	S7
S1	Pearson Correlation	1	.149**	-.022	-.002	-.032	.087**	-.683**
	Sig. (2-tailed)		.000	.389	.926	.205	.001	.000
	N		1584	1584	1584	1584	1584	1584
S2	Pearson Correlation		1	.309**	-.044	.024	-.134**	-.086**
	Sig. (2-tailed)			.000	.078	.338	.000	.001
	N			1584	1584	1584	1584	1584
S3	Pearson Correlation			1	.142**	-.367**	-.138**	.035
	Sig. (2-tailed)				.000	.000	.000	.168
	N				1584	1584	1584	1584
S4	Pearson Correlation				1	-.103**	-.424**	.039
	Sig. (2-tailed)					.000	.000	.121
	N					1584	1584	1584
S5	Pearson Correlation					1	-.008	.121**
	Sig. (2-tailed)						.753	.000
	N						1584	1584
S6	Pearson Correlation						1	-.131**
	Sig. (2-tailed)							.000
	N							1584
S7	Pearson Correlation							1
	Sig. (2-tailed)							
	N							

**. Correlation is significant at the 0.01 level (2-tailed).

a. Determinant = .289

Annex 13. KMO test for supply inventory indicators

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.490
Bartlett's Test of Sphericity	Approx. Chi-Square	1963.774
	df	21
	Sig.	.000

Annex 14. PCA components for supply inventory indicators

Total Variance Explained

	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings[a]
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	1.772	25.310	25.310	1.772	25.310	25.310	1.724
2	1.653	23.619	48.930	1.653	23.619	48.930	1.365
3	1.189	16.987	65.917	1.189	16.987	65.917	1.475
4	1.072	15.309	81.225	1.072	15.309	81.225	1.236
5	.541	7.732	88.957				
6	.468	6.679	95.636				
7	.305	4.364	100.000				

Extraction Method: Principal Component Analysis.

a. When components are correlated, sums of squared loadings cannot be added to obtain a total variance.

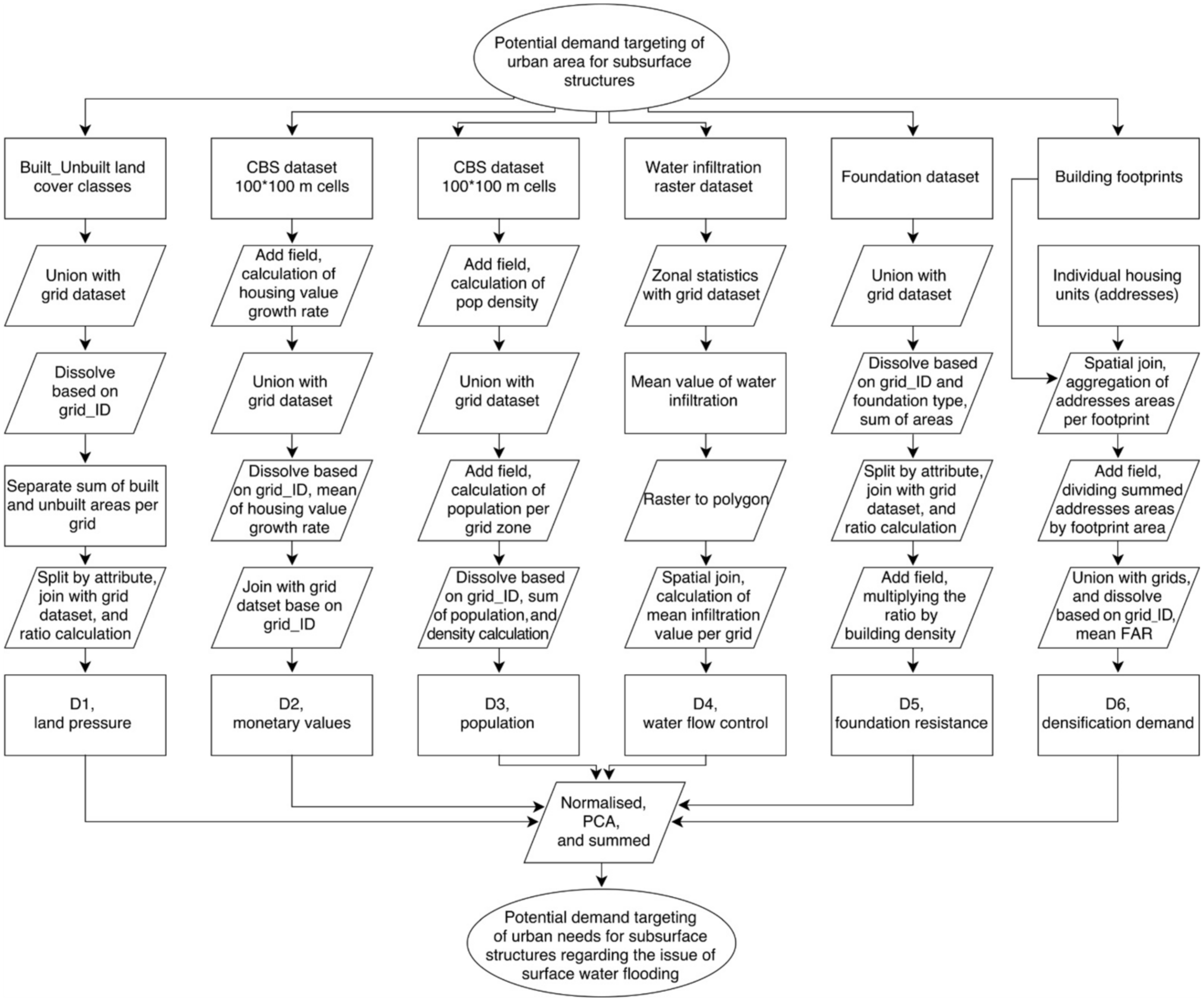
Annex 15. PCA pattern matrix for supply inventory indicators

Pattern Matrix[a]

	Component			
	1	2	3	4
S1	.915	-.047	-.036	.094
S2	.108	-.035	.018	.932
S3	-.109	.682	-.072	.472
S4	.075	.106	-.864	-.192
S5	-.071	-.909	-.024	.176
S6	.079	.114	.823	-.180
S7	-.911	-.058	-.030	.009

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.
a. Rotation converged in 9 iterations.

Annex 16. Flowchart for demand targeting analysis



Annex 17. Correlation between demand targeting indicators

Correlation Matrix[a]

		D1	D2	D3	D4	D5	D6
D1	Pearson Correlation	1	.090**	.071**	.020	.132**	.265**
	Sig. (2-tailed)		.000	.005	.427	.000	.000
	N		1584	1584	1584	1584	1584
D2	Pearson Correlation		1	.092**	-.061*	-.083**	-.012
	Sig. (2-tailed)			.000	.016	.001	.645
	N			1584	1584	1584	1584
D3	Pearson Correlation			1	-.032	.154**	.211**
	Sig. (2-tailed)				.203	.000	.000
	N				1584	1584	1584
D4	Pearson Correlation				1	.055*	.003
	Sig. (2-tailed)					.029	.902
	N					1584	1584
D5	Pearson Correlation					1	.482**
	Sig. (2-tailed)						.000
	N						1584
D6	Pearson Correlation						1
	Sig. (2-tailed)						
	N						

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

a. Determinant = .655

Annex 18. KMO test for demand targeting indicators

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.572
Bartlett's Test of Sphericity	Approx. Chi-Square	668.508
	df	15
	Sig.	.000

Annex 19. PCA components for demand targeting indicators

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings[a]
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total
1	1.713	28.550	28.550	1.713	28.550	28.550	1.709
2	1.138	18.964	47.515	1.138	18.964	47.515	1.138
3	.980	16.336	63.851				
4	.913	15.222	79.072				
5	.765	12.747	91.819				
6	.491	8.181	100.000				

Extraction Method: Principal Component Analysis.

a. When components are correlated, sums of squared loadings cannot be added to obtain a total variance.

Annex 20. PCA pattern matrix for demand targeting indicators

Pattern Matrix[a]

	Component	
	1	2
D1	.500	.190
D2	.027	.784
D3	.463	.317
D4	.047	-.512
D5	.751	-.342
D6	.830	-.133

Extraction Method: Principal Component Analysis.
Rotation Method: Oblimin with Kaiser Normalization.

a. Rotation converged in 3 iterations.

Annex 21. Rule file for an integrated 3D model of surface/subsurface structures

```
/**
 * File:    Surface_subsurface 3D model.cga
 * Created: 20 Nov 2017 16:04:21 GMT
 * Author:  maryam
 */

version "2017.1"

#######################################
# Textures
#######################################
satellitepicture = "maps/Terrain_Imagery2/texture.jpg"
Concretepipe = "ConcreteBrightHighContrast.jpg"


#######################################
# Attributes
#######################################
attr Building_Height=0    #getObjectAttr("Building_Height")
attr Function = ""        #getObjectAttr("Function"), for buildings
attr Risk=0               #connected to value of risk raster
attr Vulnerability=0      #connected to value of vulnerability raster
attr Exposure=0           #connected to value of exposure raster
attr opacityvalue=0.6
attr Soil_Depth = 0
#getObjectAttr("Soil_Depth_BasedOnCrownSpread"), for trees
attr Soil_Type = ""       #getObjectAttr("ONDERGRO_1"), for trees
attr Soil_Volume = 0      #getObjectAttr("Soil_Volume"), for trees
attr Trunk_Radius = 0     #getObjectAttr("Trunk_Radius"), for trees
attr STRAAL_KRO = 0       #getObjectAttr("STRAAL_KRO"), for trees
attr satellitePicture = "maps/Terrain_Imagery2/texture.jpg"
attr Radius = 0           #getObjectAttr("STRAAL_KRO"), for trees
attr sizeX   = 2616.001
attr sizeZ   = 1807.442
attr offsetX  = 92825.468
attr offsetZ  = -433381.935
attr Depth = 0            #getObjectAttr("Depth"), for groundwater
```

```
attr Average_Groundwater_Level=0 #getObjectAttr("Average_waterlevel")
attr Groundwater_LowLevel=0     #getObjectAttr("PERC_05")
attr Groundwater_HighLevel=0    #getObjectAttr("PERC_95")
attr Z = 0                #getObjectAttr("Z"), for soil layers
attr StackHeight=0        #getObjectAttr("StackHeight"), for soil layers
attr strat = 0            #getObjectAttr("strat"), for soil layers
attr Soil_Type = ""       #getObjectAttr("Soil_Type"), for soil layers
attr Pollution_Class_Value = 0
#getObjectAttr("MAX_Pollution_Class_Value"), for soil pollution
attr Subsidence = 0
#getObjectAttr("Subsidence"), for soil subsidence
attr Subsidence_Base_Visualisation = 0
#getObjectAttr("Subsidence_Base_Visualisation"), for soil subsidence
attr Fundtype_oud = "" #getObjectAttr("Fundtype_oud"), for piles
attr Intersect_PileAndGroundwater_Normalised = 0   #For piles'
# rottenness
attr Material = ""        #getObjectAttr("Materil"), for pipes
attr Radius = 0           #getObjectAttr("Radius"), for pipes
attr Risk_IDW_Float=0     #getObjectAttr("Risk_IDW_Float"), for Risk
attr Vision_ReverseNormalised = 0    #for (re)development vision
attr Vision_Supply_Demand = 0        #for (re)development vision
attr Supply_IDW_Normalised= 0        #for (re)development vision
attr Demand_IDW_Normalised = 0       #for (re)development vision



######################################
# Color function reference
######################################
Yellow = "#FFFF00"
LightYellow = "#FFFFE0"
Khaki = "#F0E68C"
Red = "#FF0000"
Orange = "#FFA500"
White = "#FFFFFF"
Grey = "#9c9c9c"
LightGrey = "#D3D3D3"
GreenYellow = "#ADFF2F"
Green = "#00FF00"
DarkGreen = "#228B22"
LightGreen = "#90EE90"
Brown = "#DEB887"
LightBrown = "#D2B48C"
DarkGoldenBrown = "#B8860B"
Blue = "#0000FF"
DarkBrown = "#800000"
SteelBlue = "#4682B4"
LightBlue = "#ADD8E6"


######################################
# Rules
######################################

@startRule
Buildings -->
# Building height: from BAG_3D
    extrude(world.y, Building_Height)
    report("Building height:", Building_Height)
    report("Vulnerability rate", Vulnerability)
```

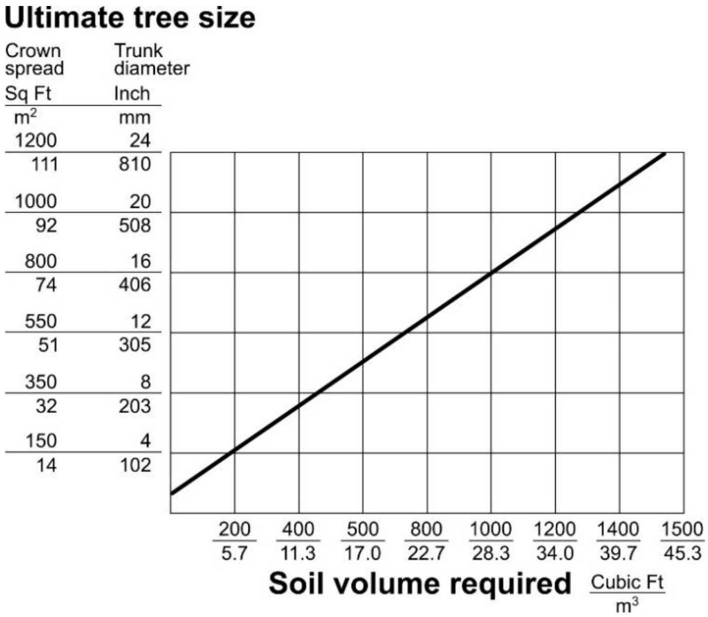
```
    report("Exposure rate", Exposure)
    report("Risk rate:", Risk)
    comp(f) { side : VulnerabilityRate | top : ExposureRate }

@Range (min=0 , max=1)
VulnerabilityRate -->
      color (colorRamp("greenToRed", Vulnerability))

ExposureRate -->
      color (colorRamp("greenToRed", Exposure))


# Trees
Trunk -->
      extrude(world.y, 2)     # Height of the trunks is an assumption
      color(DarkGreen)
      report("Trunk radius:", Trunk_Radius)

Crown -->
      primitiveSphere(16, 16, Radius)
      translate(rel, world, 0, 2, 0)
      color(DarkGreen)
      set(material.opacity, opacityvalue)
      report("Crown radius:", STRAAL_KRO)


# Canal
# File is named as "Canal__Water" for animation water movement
Canal -->
      set(material.name, "watermaterial__waterparams_2_5")


# Subsoil space use by trees
Subsoil_SpaceUse -->
      extrude(world.y,- Soil_Depth )
      report("Required soil volume:", Soil_Volume)
      report("Depth of required soil:", Soil_Depth)
      comp(f) { side : Soil | top : Soil  | bottom : Surface}

Soil -->
      case Soil_Type == "Klei" :
      color(Brown)
      case Soil_Type == "Zand" :
      color(LightBrown)
      case Soil_Type == "Veen" :
      color(DarkBrown)
      else :
      color(White)

Surface -->
      setupProjection(0,world.xz,sizeX, -sizeZ, offsetX, offsetZ)
      projectUV(0)
      texture(satellitePicture)


# Groundwater
Groundwater -->
      color(LightBlue)
      translate(rel, world, 0, Groundwater_LowLevel, 0)
      extrude(world.y, Depth)
```

```
        set(material.opacity, opacityvalue)
        report("Average groundwater level:", Average_Groundwater_Level)
        report("Water depth:", Depth)

Wells -->
# for visualisation, radius of well is considered as 0.5 meter as an
# assumption
        translate(rel, world, 0, Groundwater_LowLevel, 0)
        primitiveCylinder(6, 0.5, Depth)
        color(LightBlue)
        report("Highest groundwater level:", Groundwater_HighLevel)
        report("Lowest groundwater level:", Groundwater_LowLevel)

Tubes -->
# to make wells visible (since they are too small and few),
# tubes are generated to connect wells to the surface, and
# considered size is based on assumption
        color(Grey)
        primitiveCylinder(6, 0.2, Groundwater_LowLevel)


# Soil layers
SoilLayer -->
        translate(rel, world, 0, Z, 0)
        report("Soil layer height:", StackHeight)
        report("Soil code:", strat)
        extrude(world.y, StackHeight)
        comp(f) { all : SoilStrat }

SoilStrat -->
        case strat == 1000 : color(LightGrey)
        case strat == 1050 : color(Brown)
        case strat == 1100 : color(Brown)
        case strat == 4010 : color(Brown)
        case strat == 1070 : color(LightGreen)
        case strat == 2010 : color(LightGreen)
        case strat == 4000 : color(LightGreen)
        case strat == 1090 : color(DarkGoldenBrown)
        case strat == 1130 : color(DarkGoldenBrown)
        case strat == 5120 : color(Khaki)
        else :
        color(LightBlue)    #for strat = 6010, groundwater flow path


Anthropogenic -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(LightGrey)
        report("Soil layer height:", StackHeight_Edited)

FineSand -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(Brown)
        report("Soil layer height:", StackHeight_Edited)

Clay -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(LightGreen)
```

```
        report("Soil layer height:", StackHeight_Edited)

Peat -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(LightBrown)
        report("Soil layer height:", StackHeight_Edited)

Sand -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(LightYellow)

GroundwaterPath -->
        translate(rel, world, 0, Z, 0)
        extrude(world.y, StackHeight)
        color(LightBlue)
        report("Soil layer height:", StackHeight_Edited)


# Soil pollution and subsidence
@Range (min=0.25 , max=1)
Pollution -->
        color (colorRamp("yellowToRed", Pollution_Class_Value))
        report("Soil subsidence rate:", Subsidence)
        translate(rel, world, 0, Subsidence*10, 0)
        # Soil Subsidence value is used with *10 exaggeration-->
        extrude(world.y, Subsidence_Base_Visualisation)


# Pile, foundation
# Depth and geometry of piles are based on assumption.
foundation -->
        case Fundtype_oud == "Hout" :
        primitiveCylinder(6, 0.3, -3)
        translate(rel, world, 0, -1.5, 0)
        color(Brown)
        case Fundtype_oud == "Beton" :
        primitiveCylinder(6, 0.3, -3)
        translate(rel, world, 0, -1.5, 0)
        color(LightGrey)
        else :
        # Rest are steel foundations which are buildings without pile.
        primitiveCylinder(0, 0, 0)


Pile_cap -->
        extrude(world.y, -1.5)
        color(Grey)


# Pile, potential rottenness
PileRot -->
        case Intersect_PileAndGroundwater_Normalised == 999 :
        extrude(world.y, Building_Height)
        color(White)
        set(material.opacity,opacityvalue)
        else :
        extrude(world.y, Building_Height)
        color(colorRamp("brownToBlue",
```

```
      Intersect_PileAndGroundwater_Normalised))


# Infrastructures, pipes
@InMesh
# Infrastructures were imported as multipatch objects, generated by
# 3D buffer.
# Depth of pipes is based on assumption
Sewerage -->
      texture("ConcreteBrightHighContrast.jpg")
      translate(rel, world, 0, -3, 0)

Sewerage wells --> # Size of wells is based on assumption
      color(LightGrey)
      primitiveCylinder(16, 1.5, -5)

Gas -->
      color(DarkGreen)
      translate(rel, world, 0, -0.5, 0)

DrinkWater -->
      color(Blue)
      translate(rel, world, 0, -1.5, 0)

Electricity -->
      color(Red)
# Radius for electricity cables is considered based on assumption and
# about 0.05 meter


# Risk of surface water flooding
Risk -->
      report("Risk rate:", Risk_IDW_Float)
      comp(f) { all : Risk_Rate }

Risk_Rate -->
      case Risk_IDW_Float >= 0.373953092 :
      color(Red)
      case Risk_IDW_Float >= 0.241832734 :
      color(Orange)
      case Risk_IDW_Float >= 0.163122734 :
      color(Yellow)
      case Risk_IDW_Float >= 0.098468092 :
      color(LightGreen)
      else : color(Green)


# (Re)development vision
@Range (min=0 , max=1)
Vision -->
      report("Supply inventory rate:", Supply_IDW_Normalised)
      report("Demand targeting rate:", Demand_IDW_Normalised)
      report("(Re)development vision rate:", Vision_Supply_Demand)
      color (colorRamp("greenToRed", Vision_ReverseNormalised))
```

Annex 22. Graph for calculating the approximate volumes required to grow trees of various sizes



Source: Urban (2008)

Annex 23. Description of lithostratigraphic units

Code	Afkorting	Beschrijving
1000	AAOP	Antropogene afzettingen
1010	NIGR	Formatie van Nieuwkoop, Laagpakket van Griendtsveen
1045	NINB	Formatie van Nieuwkoop, Laag van Nij Beets
1020	NASC	Formatie van Naaldwijk, Laagpakket van Schoorl
1030	ONAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (gedeelte boven NAZA)
1040	NAZA	Formatie van Naaldwijk, Laagpakket van Zandvoort
1050	NAWA	Formatie van Naaldwijk, Laagpakket van Walcheren, gelegen onder Formatie van Naaldwijk, Laagpakket van Zandvoort
1060	BHEC	Formatie van Echteld (gedeelte buiten NIHO)
1070	OEC	Formatie van Echteld (gedeelte boven NIHO)
1080	NAWOBE	Formatie van Naaldwijk, Laagpakket van Wormer, Laag van Bergen
1090	NIHO	Formatie van Nieuwkoop, Hollandveen Laagpakket
1100	NAWO	Formatie van Naaldwijk, Laagpakket van Wormer
1110	NWNZ	Formatie van Naaldwijk, laagpakketten van Wormer en Zandvoort
1120	NAWOVE	Formatie van Naaldwijk, Laagpakket van Wormer, Laag van Velsen
1130	NIBA	Formatie van Nieuwkoop, Basisveen Laag
2000	NA	Formatie van Naaldwijk
2010	EC	Formatie van Echteld
2020	NI	Formatie van Nieuwkoop
2030	KK	Kreekrak Formatie
3000	BXKO	Formatie van Boxtel, Laagpakket van Kootwijk

Code	Afkorting	Beschrijving
3010	BXSI	Formatie van Boxtel, Laagpakket van Singraven
3020	BXWI	Formatie van Boxtel, Laagpakket van Wierden
3030	BXWISIKO	Formatie van Boxtel, laagpakketten van Wierden, Singraven en Kootwijk
3040	BXDE	Formatie van Boxtel, Laagpakket van Delwijnen
3050	BXSC	Formatie van Boxtel, Laagpakket van Schimmert
3060	BXLM	Formatie van Boxtel, Laagpakket van Liempde
3090	BXBS	Formatie van Boxtel, Laagpakket van Best
3100	BX	Formatie van Boxtel
4000	KRWY	Formatie van Kreftenheye, Laag van Wijchen
4010	KRBXDE	Formatie van Kreftenheye en Formatie van Boxtel, Laagpakket van Delwijnen
4020	KRZU	Formatie van Kreftenheye, Laagpakket van Zutphen
4030	KROE	Formatie van Kreftenheye, gelegen onder de Eem Formatie
4040	KRTW	Formatie van Kreftenheye, Laagpakket van Twello
4050	KR	Formatie van Kreftenheye
4060	BEWY	Formatie van Beegden, Laag van Wijchen
4070	BERO	Formatie van Beegden, Laag van Rosmalen
4080	BE	Formatie van Beegden
4090	KW	Formatie van Koewacht
4100	WB	Formatie van Woudenberg
4110	EE	Eem Formatie
4120	EEWB	Formatie van Woudenberg en Eem Formatie
5000	DR	Formatie van Drente
5010	DRGI	Formatie van Drente, Laagpakket van Gieten
5020	GE	Door landijs gestuwde afzettingen
5030	DN	Formatie van Drachten
5040	URTY	Formatie van Urk, Laagpakket van Tijnje
5050	PE	Formatie van Peelo
5060	UR	Formatie van Urk
5070	ST	Formatie van Sterksel
5080	AP	Formatie van Appelscha
5090	SY	Formatie van Stramproy
5100	PZ	Formatie van Peize
5110	WA	Formatie van Waalre
5120	PZWA	Formatie van Peize en Formatie van Waalre
5130	MS	Formatie van Maassluis
5140	KI	KiezeloÃ liet Formatie
5150	OO	Formatie van Oosterhout
5160	IE	Formatie van Inden
5170	VI	Formatie van Ville
5180	BR	Formatie van Breda
5190	RUBO	Rupel Formatie, Laagpakket van Boom

Code	Afkorting	Beschrijving
5200	RU	Rupel Formatie
5210	TOZEWA	Formatie van Tongeren, Laagpakket van Zelzate, Laag van Watervliet
5220	TOGO	Formatie van Tongeren, Laagpakket van Goudsberg
5230	TO	Formatie van Tongeren
5240	DOAS	Formatie van Dongen, Laagpakket van Asse
5250	DOIE	Formatie van Dongen, Laagpakket van Ieper
5260	DO	Formatie van Dongen
5270	LA	Formatie van Landen
5280	HT	Formatie van Heijenrath
5290	HO	Formatie van Holset
5300	MT	Formatie van Maastricht
5310	GU	Formatie van Gulpen
5320	VA	Formatie van Vaals
5330	AK	Formatie van Aken
6000	AEC	Formatie van Echteld (geulafzettingen generatie A)
6010	ANAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (geulafzettingen generatie A)
6020	ANAWO	Formatie van Naaldwijk, Laagpakket van Wormer (geulafzettingen generatie A)
6100	BEC	Formatie van Echteld (geulafzettingen generatie B)
6110	BNAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (geulafzettingen generatie B)
6120	BNAWO	Formatie van Naaldwijk, Laagpakket van Wormer (geulafzettingen generatie B)
6200	CEC	Formatie van Echteld (geulafzettingen generatie C)
6210	CNAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (geulafzettingen generatie C)
6220	CNAWO	Formatie van Naaldwijk, Laagpakket van Wormer (geulafzettingen generatie C)
6300	DEC	Formatie van Echteld (geulafzettingen generatie D)
6310	DNAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (geulafzettingen generatie D)
6320	DNAWO	Formatie van Naaldwijk, Laagpakket van Wormer (geulafzettingen generatie D)
6400	EEC	Formatie van Echteld (geulafzettingen generatie E)
6410	ENAWA	Formatie van Naaldwijk, Laagpakket van Walcheren (geulafzettingen generatie E)
6420	ENAWO	Formatie van Naaldwijk, Laagpakket van Wormer (geulafzettingen generatie E)
0	NN	Niet formeel ingedeelde afzettingen of onbekend

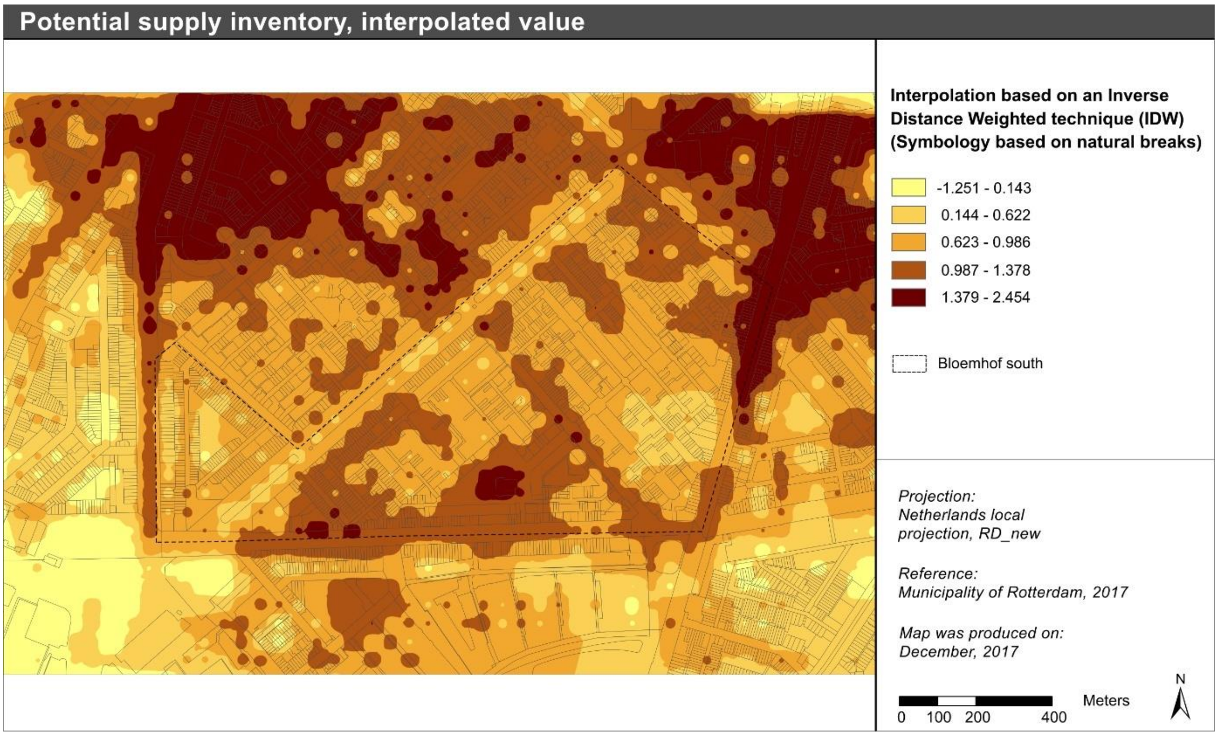
Source: ESRI Nederland (2017)

Annex 24. Specified colours for lithostratigraphic units

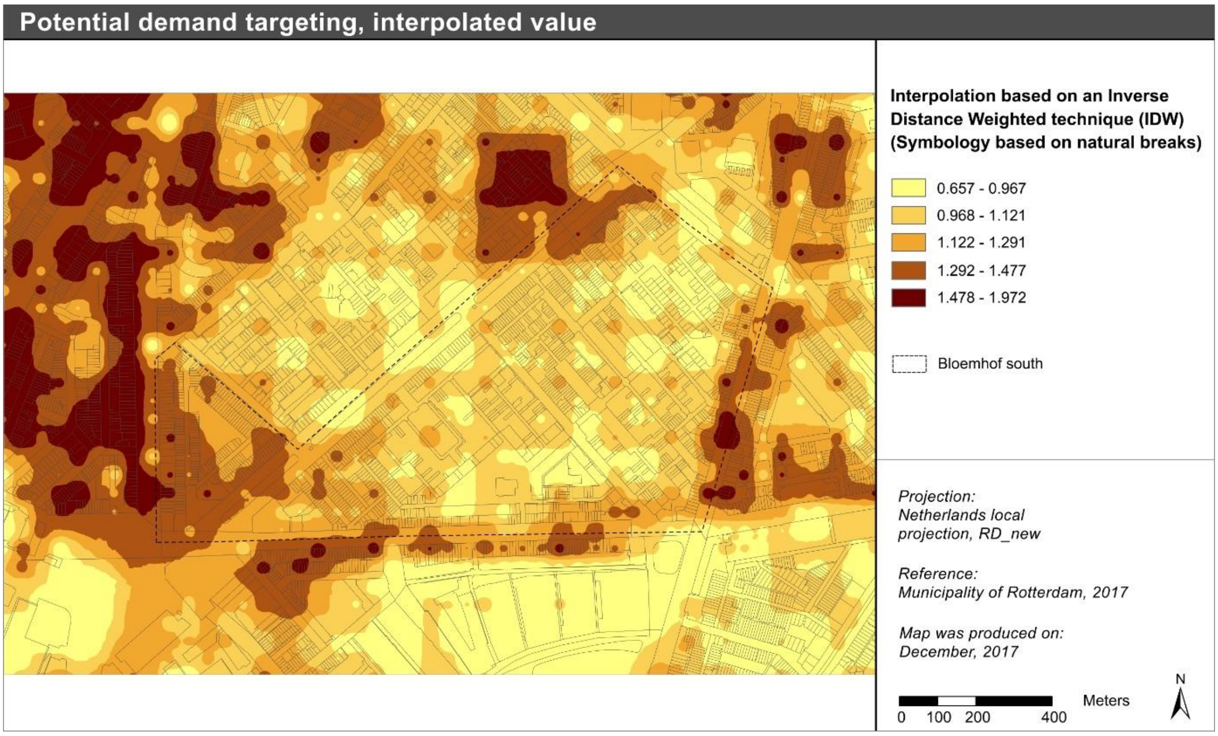
Laag	**Nr**	**Type**	**Legenda**	**Kleur**
Laag_01_aaop	1	AAOP	antropogeen	lichtgrijs
Laag_07_aec	7	AEC	Stroombaan	lichtblauw
Laag_06_anawa	6	ANAWA	Stroombaan	lichtblauw
Laag_09_bec	9	BEC	Stroombaan	lichtblauw
Laag_08_bnawa	8	BNAWA	Stroombaan	lichtblauw
Laag_33_bx	33	BX	fijn zand	lichtgeel
Laag_26_bxwisiko	26	BXWISIKO	zand	geel
Laag_16_dec	16	DEC	Stroombaan	lichtblauw
Laag_15_dnawo	15	DNAWO	Stroombaan	lichtblauw
Laag_20_ec	20	EC	klei siltig	lichtgroen
Laag_18_eec	18	EEC	Stroombaan	lichtblauw
Laag_39_kr	39	KR	zand	geel
Laag_34_krwy	34	KRWY	klei	groen
Laag_03_nasc	3	NASC	fijn zand	lichtgeel
Laag_10_nawa	10	NAWA	fijn zand	lichtgeel
Laag_19_nawo	19	NAWO	fijn zand	lichtgeel
Laag_05_naza	5	NAZA	grof zand	felgeel
Laag_22_niba	22	NIBA	Basis Veen	donkerbruin
Laag_13_niho	13	NIHO	Hollands veen	lichtbruin
Laag_11_oec	11	OEC	klei siltig	lichtgroen
Laag_59_pzwa	59	PZWA	zand	geel
Laag_54_st	54	ST	zand	geel
Laag_53_ur	53	UR	zand	geel

Source: provided data by the Municipality of Rotterdam

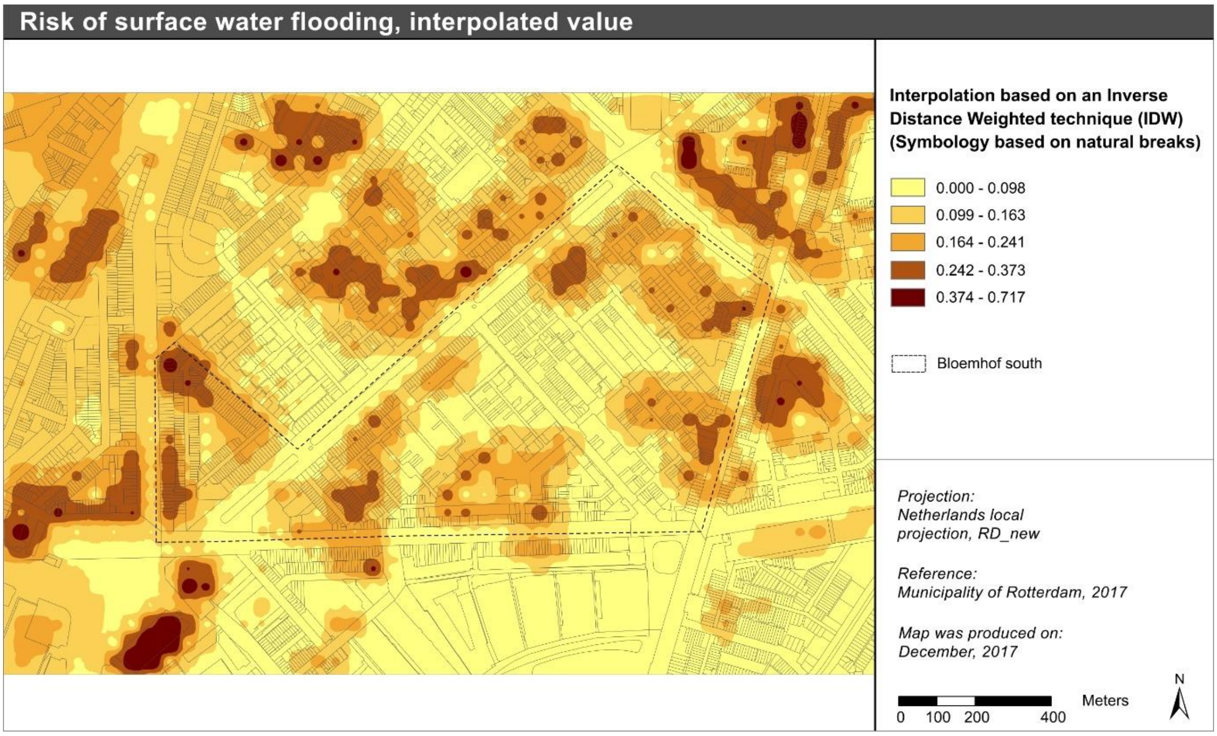
Annex 25. Interpolated potential supply inventory factor



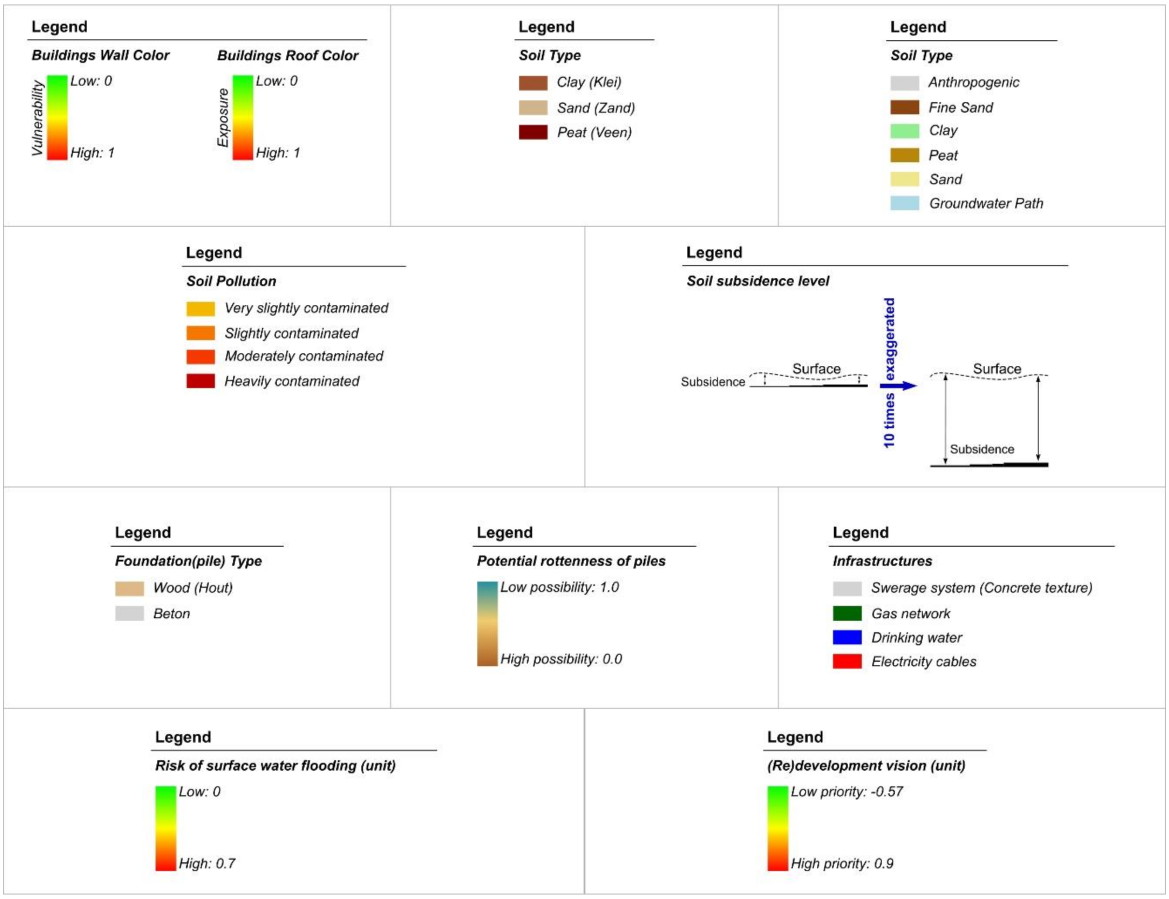
Annex 26. Interpolated potential demand targeting factor



Annex 27. Interpolated risk of surface water flooding factor



Annex 28. Legends of the 3D model objects



This research investigates the role of an integrated 3D model in dealing with issues of knowledge exchange and development situations (i.e., physical and social developments) in a particular setting. The setting was identified by the City of Rotterdam, where all these issues are actual and have come together. They are looking exactly now at what to do with this area and how to improve it.

Studied literature highlights gap of academic research and practice in terms of knowledge exchange among diverse professions in this subject. Interdisciplinary projects gather professionals from different subjects to communicate and make decisions. Urban planners and subsurface specialists are target groups in this research for multidisciplinary communications. In order to reach a consensus of opinions, their specialised information should be transformed to comprehensible contents for all and be effectively utilised.

The table below describes current state of this fact in academic research and practice in terms of issues related to knowledge exchange, data transformation, and information enrichment. Knowledge exchange refers to sharing knowledge between experts of diverse proficiencies. In addition, data transformation refers to converting specialised data to easy-to-understand information for non-expert people in that field. Moreover, information enrichment refers to enhancement of information utilisation approaches.

	Knowledge exchange		***Data transformation***	***Information enrichment***
Current state	Poor focus on data-sharing communications and their quality in terms of demand-driven collaborations.	Uncertainty and reliability of specialised data are less assessed, therefore made decisions might have some levels of uncertainty.	Subsurface-related knowledge is mostly produced in a specialised manner for planners' uses.	Supportive information for planners is presented in 2D features. In addition, mostly aboveground and underground structures are analysed and modelled separately.
Gap description	Isolated urban decision making, even within involved parties. Lack of bilateral awareness.	Lack of metadata management regarding detailed information about collection methods, date, and specialization of data providers.	Lack of proper methods and considerations in terms of data conversion to effective information.	Lack of an integrated data provision of underground structure to involve this valuable resource in (re)development planning.

This research aims to develop an integrated 3D model of subsurface/surface conditions and their interactions to support communication and knowledge exchange between urban planners and subsurface specialists. The sub-objectives are to:

1. Identify key surface and subsurface interactions;
2. Prepare a demand-driven set of surface/subsurface specialised data for urban planning insight;
3. Transform specialised data into comprehensible contents for urban planners and subsurface specialists;
4. Develop an integrated 3D model of surface/subsurface conditions;
5. Evaluate the usefulness of developed integrated 3D model.

The proposed 3D model was generated to enhance communications between planners and subsurface specialists using the Bloemhof neighbourhood as a case study.

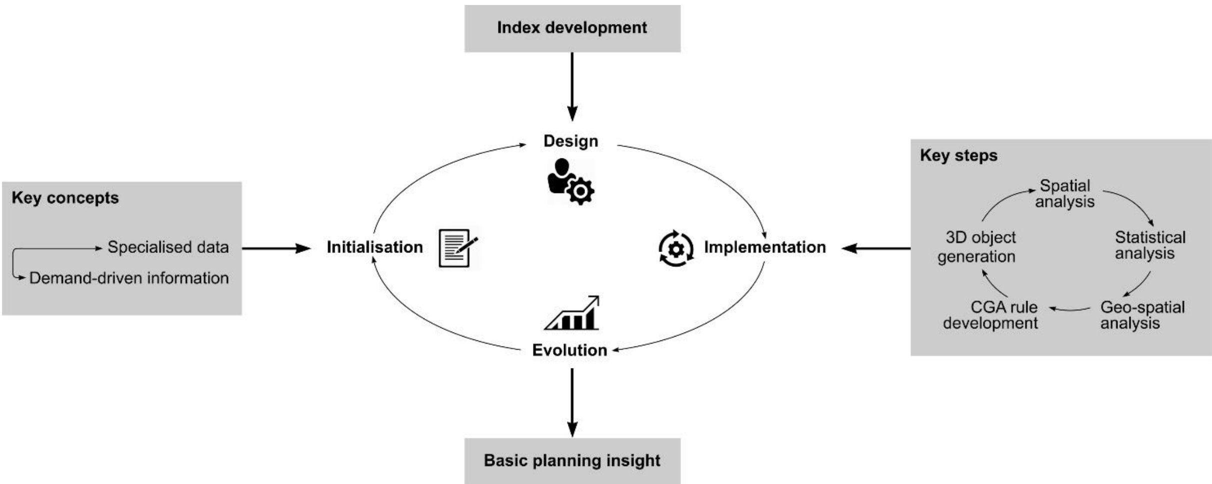
Following statements are needed to assess usefulness and effectiveness of the model. Statements are divided into three parts:

A. Introduction to the model
B. Key validation statements
C. General validation statements

A. Introduction to the model

Following figure illustrates conceptual development process of the model.

The process starts with inputs initialisation. The inputs are specialised data collected various sources regarding demand of planners and subsurface specialists. Input initialisation refers to convergence of data in terms of their unit, scale, projection, and format. After initialisation, data transformation is second step which develops indices for transformation of the initialised data to comprehensible/demand-driven information for users (urban planners and subsurface specialists). The indices contain indicators describing issue of the study area (i.e., surface water flooding). Implementation of the 3D model is the third step in which initialised data are transformed to comprehensible information and then visualised in 3D. Data transformation using developed indices implemented based on several analytical techniques. Then, model validation and appraisal of model usefulness describes evolution step, the fourth step of 3D model generation.



B. Key validation statements

This part contains statements regarding the model in terms of effectiveness of data provision, properness of objects visualisation, and ease of utilisation.

Data provision:

1. The model effectively provides required information for subsurface specialists.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

2. The model effectively provides required information for urban planners.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

3. Specialised data are properly transformed for urban planners to make (re)development decisions.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

4. level of detail of the model is sufficient for the vision phase of (re)development planning.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to data provision.

Visualisation:

5. The created model is an accurate geometric representation of the surface and subsurface objects.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

6. Assigned colours are appropriate to related information.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

Ease of utilisation:

7. CityEngine Web viewer facilitates exploitation of the model (rather application-based visualisation).

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to this statement.

8. Assigned colours to and geometry design of objects made model easy to be used and understandable.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

9. It is easy to interact with the model in terms of zooming, panning, etc.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

C. General validation statements

This part contains statements regarding usefulness, effectiveness, and evolution possibilities of the model.

Applicability:

10. The integrated 3D model is a significant improvement compared to the existing voxel model.

    [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

11. The integrated 3D model of surface and subsurface structures is usable in practice.

    [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

12. The integrated 3D model of surface and subsurface structures is useful in practice?

    [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

13. The generated model appears to be adaptable to different subjects and case areas?

    [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to validation.

Suggestions:

14. Please list and explain any deficiencies you have observed in the model.

15. Please list and explain the major benefits you have observed in the model.

16. Please provide any other suggestions on ways in which the model could be further developed and improved.

Annex 30. Responses to validation questions

Questionnaire responses, Project manager

Data provision:

1. The model effectively provides required information for subsurface specialists.

   [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

2. The model effectively provides required information for urban planners.

   [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

3. Specialised data are properly transformed for urban planners to make (re)development decisions.

   [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

4. level of detail of the model is sufficient for the vision phase of (re)development planning.

   [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to data provision.

I can't answer these questions. I am projectleader…The urban planners/subsurfase specialist have to answer this questions.

Visualisation:

5. The created model is an accurate geometric representation of the surface and subsurface objects.

   [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

6. Assigned colours are appropriate to related information.

   [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

Ease of utilisation:

7. CityEngine Web viewer facilitates exploitation of the model (rather application-based visualisation).

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [x] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to this statement.

I can't open the model.

8. Assigned colours to and geometry design of objects made model easy to be used and understandable.

   [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

9. It is easy to interact with the model in terms of zooming, panning, etc.

   [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

I can't test it because I can't open the model. Probably to big to open.

Applicability:

10. The integrated 3D model is a significant improvement compared to the existing voxel model.

    [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

11. The integrated 3D model of surface and subsurface structures is usable in practice.

    [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

12. The integrated 3D model of surface and subsurface structures is useful in practice?

    [ ] Strongly agree [ ] Agree [x] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

13. The generated model appears to be adaptable to different subjects and case areas?

    [ ] Strongly agree [x] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to validation.

I don't know the voxel model.

Suggestions:

14. Please list and explain any deficiencies you have observed in the model.

15. Please list and explain the major benefits you have observed in the model.

16. Please provide any other suggestions on ways in which the model could be further developed and improved.

I think it is important that is available at any computer. That means probably the model need to be smaller….

Questionnaire responses, Subsurface specialist

Data provision:

1. The model effectively provides required information for subsurface specialists.

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

2. The model effectively provides required information for urban planners.

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

3. Specialised data are properly transformed for urban planners to make (re)development decisions.

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

4. level of detail of the model is sufficient for the vision phase of (re)development planning.

   [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to data provision.

a. We have had many sessions (over the past 12 years) with combined project teams of urban planners and subsurface specialists. Success of these meetings always depends upon the willingness (and the capability) of the specialists to get out of their silo's and to adapt a "holistic" approach and to feel responsible not only for their part of the input but for the success of the project as a hole. Unfortunately not many specialists (from both sides (urban planners as well as subsurface specialists)) have that ability (and/or willingness). It is a cultural issue and all has to do with the sectoral way how we are educated and still educate our professionals.

b. Such a cultural issue it is not an issue that can be easily and quickly fixed. Occasionally I wonder myself about the lack of progress that we made in Rotterdam over all these years. However, having worked over the pat 4 year in the European COST SUB-URBAN project, which aim was to bring urban planners and subsurface specialists together, we were able to directly compare the situation in Rotterdam to the situation in 25 other cities in Europe. Only then I realised that we in Rotterdam were, together with Glasgow and Oslo, far ahead of the rest in finding ways of bringing various disciplines in urban development together. One of the conclusions of COST SUB-URBAN was that a 3D integrated above/below ground model was absolutely necessary in order to make progress. And additionally it was concluded that various cities were busy with developing such an integrated model (Odense, Helsinki, Vienna, Rotterdam) but all only qualified as "best efforts", not as showcase examples of "good practice". Also from a technical point of view there are many complexities to be solved, not only in the way of combining urban planning and subsurface topics but also in the field of combining various subsurface topics (for instance the differences in scale between geological composition and structure of the subsurface and the use of the subsurface (sewers, infrastructure groundwater, energy).

c. Above mentioned cultural and technical complexities combined indicate that coming up with the right 3D/4D integrated model that will satisfy all disciplines involved will involve a huge combined effort of various organisations in various countries during the forthcoming *years*.

d. Last year I asked our French internship student Audrey to discuss with urban planners and to translate their demands to our 3D modeler Jeroen and vice versa. (in my concept our subsurface specialists had enough interaction with Jeroen). Unfortunately Audrey had to spend all her time on the interaction between subsurface specialists and Jeroen. (my concept was way too optimistic). It meant that at the end of her internship we had made enormous progress with our 3D model, but mainly in the subsurface area. I was and am very proud of what Audrey has produced (together with Jeroen of course) and I have shown her video to all our COST SUB-URBAN partners.

e. Maryam has taken the model a giant leap forward both in terms of integrating the subsurface with the above ground topics as in terms of technology (she has done a giga modelling exercise parallel to Jeroen's modelling) as in terms of defining, and modelling quantified parameters. Impressive, and also performed in a very short time. (So I will proudly circulate Maryam's model to the COST SUB-URBAN community.

f. Indeed an enormous step on our road towards… but I also realise that it will take a few years before we can produce results that will make our target audience (urban planners and subsurface specialists happy. (but as explained above that also is a matter of educating our audience)

Visualisation:

5. The created model is an accurate geometric representation of the surface and subsurface objects.

[X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

6. Assigned colours are appropriate to related information.

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

   Please provide any comments or suggestions related to visualisation.

Ease of utilisation:

7. CityEngine Web viewer facilitates exploitation of the model (rather application-based visualisation).

   [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to this statement.

8. Assigned colours to and geometry design of objects made model easy to be used and understandable.

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

9. It is easy to interact with the model in terms of zooming, panning, etc.

   [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

I can answer these questions from my perspctive, but better ask the real audience of the model, the project urban planners and subsurface specialists (but select only the ones who have a helicopter view)

Applicability:

10. The integrated 3D model is a significant improvement compared to the existing voxel model.

    [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

11. The integrated 3D model of surface and subsurface structures is usable in practice.

    [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

    By finetuning the model to focussing on specific topics it can already be used in practice. As we discussed before it is better not to show to many topics at the same time to urban plannners: first show the 3D model to urban planners and demonstrate how the model solves one of their issues. This way you seduce them to ask for more, they familiarise themselves with your model and you can introduce a new topic.

12. The integrated 3D model of surface and subsurface structures is useful in practice?

    [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

    Very useful to the urban planner with a "helicopterview" see my comments on first page. Unfortunately there are not to many of them. So if you would ask an urban planner right now you probabaly get a less positive answer.

13. The generated model appears to be adaptable to different subjects and case areas?

    [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to validation.

Absolutely,

Ignace

Suggestions:

14. Please list and explain any deficiencies you have observed in the model.

15. Please list and explain the major benefits you have observed in the model.

16. Please provide any other suggestions on ways in which the model could be further developed and improved.

Questionnaire responses, Cartographer

Data provision:

1. The model effectively provides required information for subsurface specialists.

   [ ] Strongly agree [ ] Agree [×] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

   All specialist have a tendency to have their own sets of conditions for their needs, a one size fits all model usually won't work for them

2. The model effectively provides required information for urban planners.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [×] No response

   I don't dare to answer this one because I'm still looking for this answer myself

3. Specialised data are properly transformed for urban planners to make (re)development decisions.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [×] No response

   I don't dare to answer this one to, I wish I knew how planner think

4. level of detail of the model is sufficient for the vision phase of (re)development planning.

   [ ] Strongly agree [ ] Agree [×] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

   My personal opinion is that the model is to detailed, but it does look very inviting to use. But my lack of knowledge about the planning fase does not help me to judge its usefulness in this phase

Please provide any comments or suggestions related to data provision.

Visualisation:

5. The created model is an accurate geometric representation of the surface and subsurface objects.
   [ ] Strongly agree [×] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
   I still don't completely agree how you converted the Geotop model to 10x10 voxels, besides that the model looks really accurate

6. Assigned colours are appropriate to related information.
   [ ] Strongly agree [ ] Agree [×] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
   Colours are emotion, what works for one person does not work for another. For now it works, but it will probably become really complicated as we expand the information. And if/when this method becomes more accepted in the field the will probably form a committee to decide the final colours.

Please provide any comments or suggestions related to visualisation.

Ease of utilisation:

7. CityEngine Web viewer facilitates exploitation of the model (rather application-based visualisation).
   [ ] Strongly agree [×] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
   As far as I found this is the best way of putting out a model like this, there might come other methods in the future but for now it's the only thing available that does what I want it to do

Please provide any comments or suggestions related to this statement.

8. Assigned colours to and geometry design of objects made model easy to be used and understandable.
   [ ] Strongly agree [ ] Agree [×] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
   I was asked to demo another map the other day, it had loads of layers in it, some did not have any meta data or description, and a lot of abbreviations were used. One of my colleagues then suggested, can't you make a story map that gives an explanation per layer, I love that idea!

9. It is easy to interact with the model in terms of zooming, panning, etc.
   [ ] Strongly agree [×] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
   But… I think we need to make smaller models, less is more I think…

Please provide any comments or suggestions related to visualisation.

Applicability:

10. The integrated 3D model is a significant improvement compared to the existing voxel model.
    [ ] Strongly agree [ ] Agree [×] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
    Almost all the data I gave you is mostly in my brain, I'm planning on studding you methodology really well to see how I can use your mind to improve on my thoughts

11. The integrated 3D model of surface and subsurface structures is usable in practice.
    [ ] Strongly agree [×] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response
    I think the methodology is useful, but I think that one viewer that answers al questions is not the best solution. Different viewers for different question would be my approach

12. The integrated 3D model of surface and subsurface structures is useful in practice?

[ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [×] No response

This is more a question for the people who are gone use it, builders always think that what they build is useful, but the user decides ;)

13. The generated model appears to be adaptable to different subjects and case areas?

[ ] Strongly agree [×] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

New ideas are being generated in my mind as I write these answers ;)

Please provide any comments or suggestions related to validation.

Suggestions:

14. Please list and explain any deficiencies you have observed in the model.

Difference in detail between different datasets needs to be respected, just like paper maps we ned to think in different scale levels (stories)

15. Please list and explain the major benefits you have observed in the model.

There never has been a sub-surface model this integrated before, that alone will peak interest with certain people.

16. Please provide any other suggestions on ways in which the model could be further developed and improved.

Already working on it ;)

Questionnaire responses, Urban planner

Data provision:

1. The model effectively provides required information for subsurface specialists.

[ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Doubt because they will refer to their own models that work better but not in an integrated way

2. The model effectively provides required information for urban planners.

[ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

3. Specialised data are properly transformed for urban planners to make (re)development decisions.

[ ] Strongly agree [ ] Agree [X] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

needs to be tested

not on all topics and you can not access independently.

4. level of detail of the model is sufficient for the vision phase of (re)development planning.

[ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to data provision.

even though it is now one topic

Visualisation:

5. The created model is an accurate geometric representation of the surface and subsurface objects.

   [ ] Strongly agree [ ] Agree [X] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

6. Assigned colours are appropriate to related information.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [X] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

pollution is now red, this is usually buildings in spatial planning and design, some colours should be adopted from their language

Ease of utilisation:

7. CityEngine Web viewer facilitates exploitation of the model (rather application-based visualisation). ?

   [ ] Strongly agree [X] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to this statement.

it needs good internet!

8. Assigned colours to and geometry design of objects made model easy to be used and understandable.

   [ ] Strongly agree [ ] Agree [ ] Neither agree nor disagree [X] Disagree [ ] Strongly disagree [ ] No response

9. It is easy to interact with the model in terms of zooming, panning, etc.

   [ ] Strongly agree [ ] Agree [X] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to visualisation.

the drawing can be finetuned

Applicability:

10. The integrated 3D model is a significant improvement compared to the existing voxel model.

    [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

11. The integrated 3D model of surface and subsurface structures is usable in practice. needs testing!

    [ ] Strongly agree [ ] Agree [X] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

12. The integrated 3D model of surface and subsurface structures is useful in practice?

    [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

13. The generated model appears to be adaptable to different subjects and case areas?

    [X] Strongly agree [ ] Agree [ ] Neither agree nor disagree [ ] Disagree [ ] Strongly disagree [ ] No response

Please provide any comments or suggestions related to validation.

would be nice to see 2D output like sections

Suggestions:

14. Please list and explain any deficiencies you have observed in the model.

On my wifi it worked not so wel and putting layers on and off was hard.

15. Please list and explain the major benefits you have observed in the model.

looking around and combining topics, making sections would be interesting

16. Please provide any other suggestions on ways in which the model could be further developed and improved.

- the decisions made for the different components should be accessable