Determining drought-induced subsidence in urban areas

An in-practice analysis of drought impacts on subsidence in two Dutch soft-soil cities

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by

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Front cover image:
Raising the surface level in Vogelweide, Diemen - February 2021

Summary

Drought and subsidence are two out of several water-related urban climate adaptation challenges many cities in the Netherlands currently face. Drought is expected to increase in frequency and extent due to climate change. Therefore, drought is likely to further pressurize (subsiding) urban areas in the coming decades. Although the impact of drought on soft soils and hence subsidence is described in academic literature, in-practice analyzes are limited. Given the expectation of increased drought impacts, as well as the current urge for new housing developments to combat housing scarcity, this research focuses on in-practice drought impacts on subsidence in two soft-soil urban areas in the Netherlands.

This research's objective is to gain insight into drought-induced subsidence in soft-soil urban areas in the Netherlands, in order to better understand drought impacts on subsidence rates in future housing developments on comparable soils. With a better understanding more appropriate site preparation strategies can be applied. The objective is endeavoured by an **in-practice analysis** of two study areas: a 90s neighbourhood in Diemen and a recently finished urban area in Kampen. Firstly, variations in relative surface levels, observed by InSAR (2015-2019), are compared for dry and wet periods. Afterwards, this subsidence data is separated based upon local characteristics (soil structure, pavement type, vegetation percentage and vicinity of surface water) to analyze their influence on drought-induced subsidence. Lastly, an expert questionnaire is conducted on suggestions for both mitigation and adaptation strategies.

Subsidence is not a linear process in time: surface level movements vary due to the soil's wetting and drying. The extent of soil compaction in dry periods is found to increase with intenser droughts. The extent of soil swell in wet periods is approximately similar for varying wetness extents. This research found that the severe drought of 2018 thereby caused a soil compaction to such extent it could not be balanced with subsequent winter swell, and hence resulted in approximately **1 to 1.5 millimeter of drought-induced subsidence**. Drought-induced subsidence is thus a net result of the (change in) seasonal surface level fluctuation. This net result is assumed to be consequence of extensive groundwater level drops, although the exact share of processes and subsidence mechanisms could not be estimated. Moreover, surface level movements are found to be prone to a lag and difference in duration (hysteresis) in comparison to the start and duration of dry and wet periods.

Various **local characteristics** are found to influence drought-induced subsidence. In general more compressible soils show slightly larger surface level movement between dry and wet periods. The (sand) cover thickness is found to be influential on which subsidence mechanisms are triggered during a drought: a cover thickness resulting in groundwater levels to drop to present clay/ peat layers causes shrinkage and/ or peat oxidation additional to clinch. Unpaved surfaces are found to fluctuate more extensively than paved surfaces, but this does not necessarily result in more irreversible subsidence. Furthermore, abundant vegetation might result in extra irreversible subsidence due to its extensive water usage in dense urban areas. Lastly, in the analyzed soft-soil areas the surface waters seem to influence groundwater levels and hence surface level movements only on short distance.

Suggestions on feasible enhancing site preparation strategies are given based upon research results and experts' opinions. The suggested mitigation strategies consist of two approaches in order to hamper the variations in effective stresses and hence minimize the seasonal surface level fluctuation. The first approach focuses on preventing extensive groundwater level variations: increasing storage and infiltration of water, reversed drainage, building crawl-space free and choosing vegetation types based on their water usage. Additionally, it is suggested to apply a sufficient cover thickness (at raises) if soft soil layers are near the surface. This prevents that future extensive groundwater drops within these layers, and thereby limits (seasonal) shrinkage and/ or peat oxidation. The second approach focuses on reducing the top soil's weight, via lightweight materials or self-carrying constructions.

Adapting to drought-induced subsidence starts with measuring/ monitoring surface level movements in order to analyze spatial and temporal trends. Additionally, drought is to be considered to greater extent in subsidence modelling in order to improve subsidence estimations. This can be done by applying variable or lower groundwater levels in estimations of the (change in) effective stresses, at calculations of consolidation or creep. Lastly, urban utility management should focus on long-term costs via e.g. Life Cycle Analysis, and on overlapping maintenance cycles of surface level raising and e.g. sewer pipe replacements.

The most important **conclusion** derived on urban drought-induced subsidence is that despite individual drought impact on subsidence is limited to 1 to 1.5 millimeters, its seasonal occurrence continuously affects surface levels. Moreover, due to climate change drought is expected to increasingly impact surface levels in Dutch soft-soil urban areas in the coming decades. The suggested strategies mainly hamper variations in soil stresses, via fluctuating groundwater levels, and hence drought impacts on soft soils. These strategies help to limit future soil movements and hence result in more climate adaptable soft-soil urban areas.

The focus of this research is on qualitative analyses of in-practice data such that significant processes have been disclosed, rather than statistically verifying the results. Consequently, the research initiates **further specific studies** on statistical verification of drought-induced subsidence, and moreover topics on its mechanisms; its spatial and temporal variation; its measurement and modelling; the influences of local characteristics hereupon; and the effectiveness of the suggested enhanced site preparation strategies.

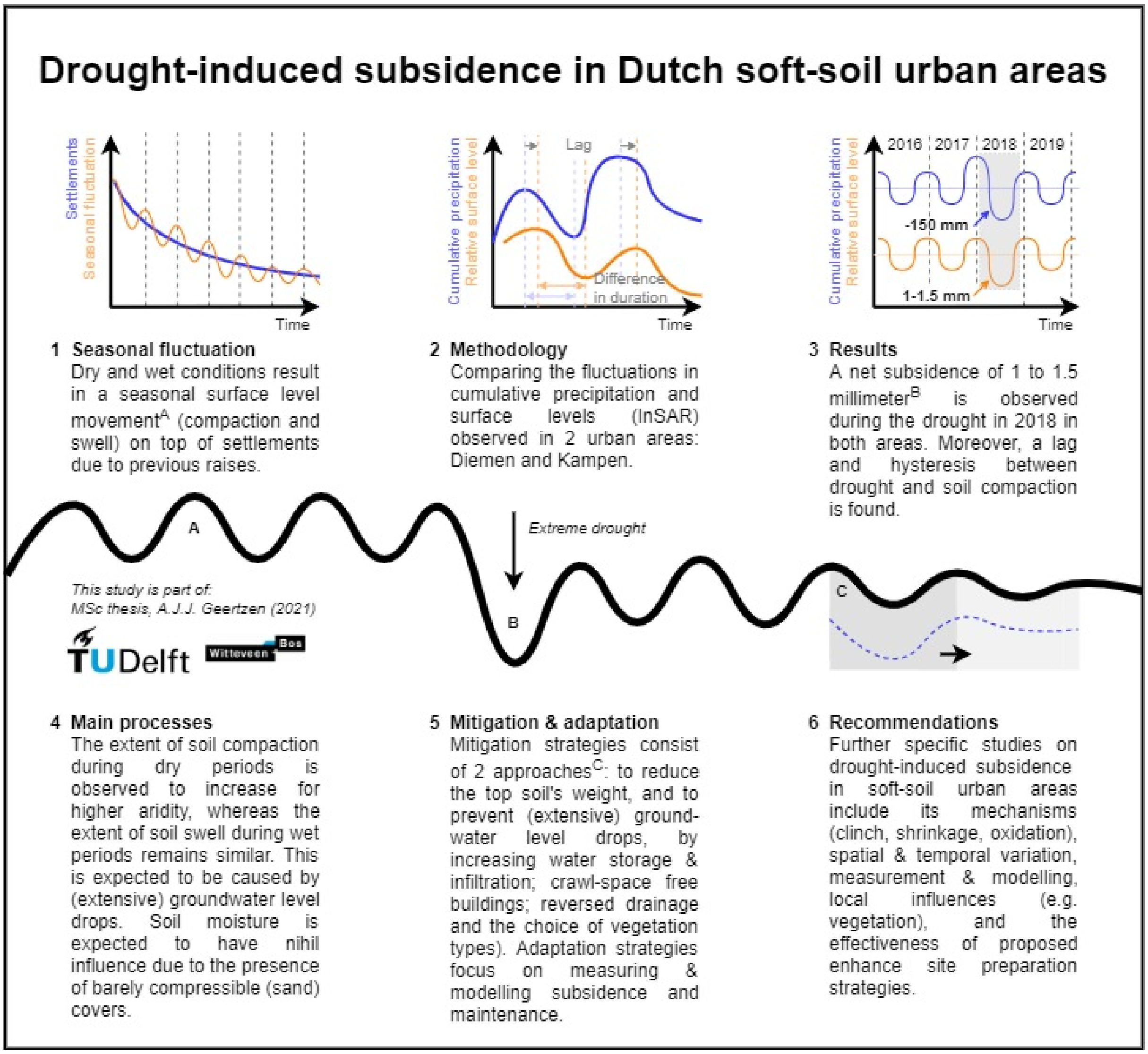


Figure 1: *Graphical summary.*

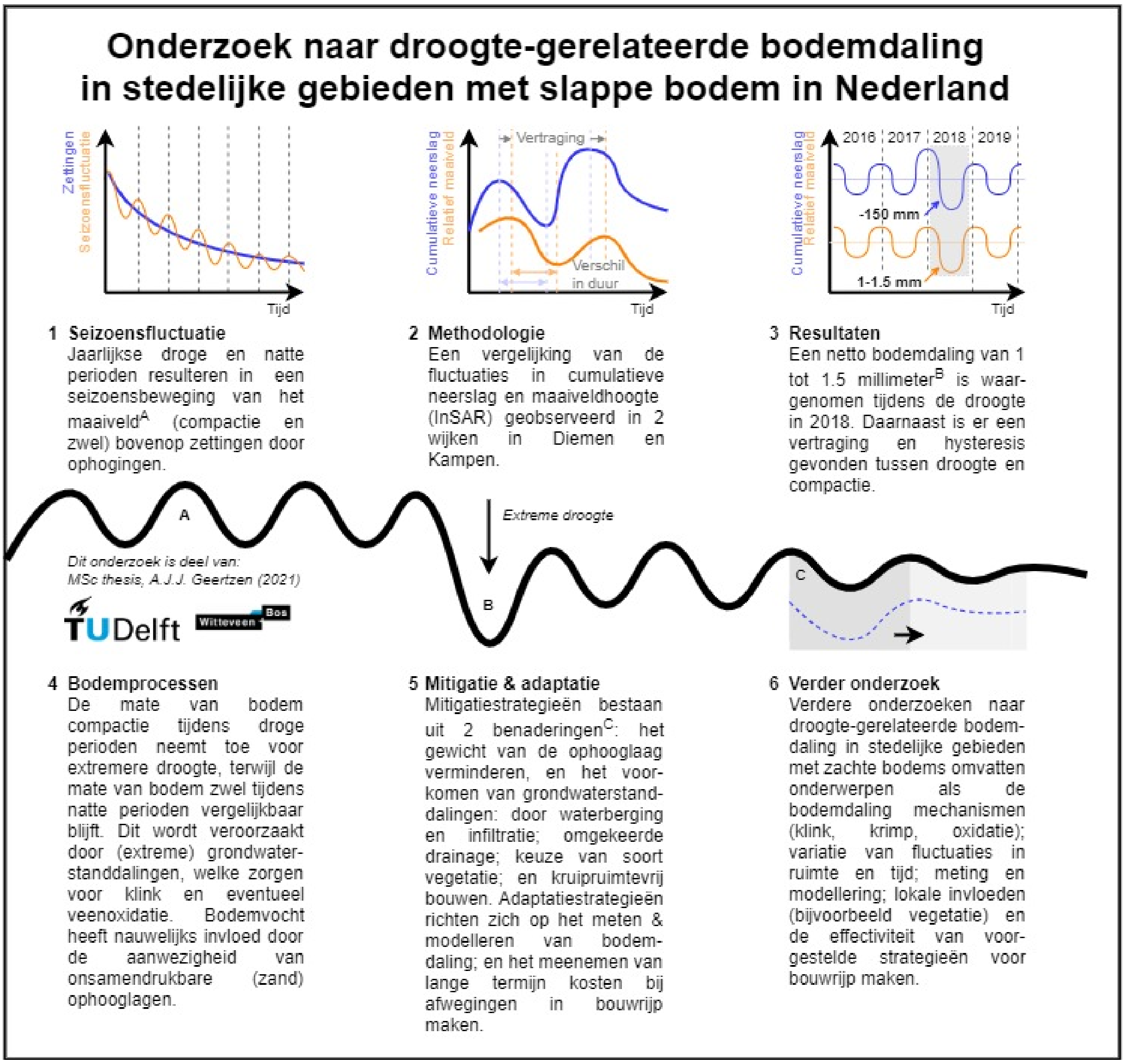


Figure 2: *Graphical summary in Dutch.*

Preface

Working together integrally on climate adaptive urban areas

Dear reader,

Most of us live in cities without realizing these urban areas are very complex, dense and dynamic systems. Not only for its inhabitants with various cultures and personalities, but also due to its infrastructure above ground, in subsurface and deeper soil. It is complex due to forever ongoing urbanization; water, energy & waste flows; traffic and telecommunication; hydrological- and soil processes; biodiversity and life. Are urban areas not fascinating?

Despite these charming words urban areas worldwide are increasingly stressed by climate change pressurizing their water systems (and more!). This report comprises a thesis study for obtaining my Master's degree in Watermanagement (TU Delft, NL) as intern of Witteveen+Bos. The study focuses on the wilderness of infrastructures, hydrological- and soil processes covering two main climate adaptation theme's: drought and subsidence. Before you start reading my work and findings I would like to express my sincere gratitude to numerous collaborators and supporters.

Firstly I would like to thank the consultancy company Witteveen+Bos in its whole for providing me a chance as intern to develop myself within working atmospheres. Specifically I would like to mention the group 'Stedelijke Klimaatadaptatie' in where positive and motivational colleagues gave me tips but mostly a warm feeling within the company. Especially regarding my company supervisor Jaap and even to greater extent daily supervisor Ilse. Ilse, you are an approachable person and you committed an enormous amount of time, energy and enthusiasm to help me. I am greatly thankful to have you as daily supervisor, especially in the Corona pandemic issuing less contact between students themselves and professors.

Secondly I would like to show my appreciation to my TU Delft graduation committee. To Olivier I would like to say it's a pity no (special) beers could be drunk during our collaboration, but I will bring some beers when university opens again. I want to thank Femke for her openness, you gave constructive feedback and were very willingly to discuss difficult topics together. Lastly, particularly, I would to thank Frans for his time, accurate advice but sociable and easy meetings. It is an honor to graduate in urban water management having you as head of the committee and I am glad you were enthusiastic to help me.

I do not want to forget a large group of supporters. Firstly and mainly my family and relatives, who have always supported me to thrive for the best but moreover to do what seems fun and enjoyable. I would like to thank all friends and roommates in Delft who willingly or unwillingly listened to my complains and shared both cheering and cheerless moments. For you all, I hope some day I will stop talking so much!

Some wise words to conclude. Climate adaptation is an enormous transition of (urban) areas towards resilient and live-able places for its inhabitants, flora and fauna. This study only contributes modestly to these great future urban challenges. However, by working together as experts with citizens and nature, step by step urban challenges will be conquered. Cheers!

Sander (A.J.J.) Geertzen
Delft, June 2021

Contents

Glossary

This glossary provides for many phrases the description in form of (formal) definitions, as stated in: [1] the Dutch Hydrological Glossary (Moors et al., 2002); [2] the book *Grondmechanica* (Verruijt, 2010); [3] the publication *Deltafact: Bodemdaling* (Van Asselen et al., 2019); or [4] the report *Beter bouw- en woonrijp maken* (Biron, 2004). Other references are given within the description themselves.

General

Phrase	Description
Cone penetration test	Method to observe a soil's characteristics by measuring the resistance of a pin (cone) pushed into the soil (P. Robertson & Cabal (Robertson), 2014).
Drought-induced subsidence	The net irreversible subsidence of the soil as consequence of drought.
Legger	Legal document (could contain a map) of Dutch water authorities consisting of rules and dimensions regarding water bodies and -system.
Local characteristic	A characteristic within an urban area possibly influencing surrounding soil processes. *Defined in the research to be either soil structure, pavement type, vegetation percentage, or vicinity of surface water.*
Vegetation	Collection of plants growing in a certain place. *In this research vegetation is defined as plants (<2.5m height) and trees (>2.5m height). No further distinguishment is made between their types and sizes.*

Methodology

Phrase	Description
Box plot	An informative graph showing the distribution of a variable for certain categories, or a second variable. *In this research different percentiles (0/100; 5/95; 25/75; 50) can be seen within the box plot.*
Difference in duration	The difference in time span (duration) of two variables.
Lag	The difference between the start of two events (delay), mostly in days.
Median plot	A plot showing the median behaviour through time (chronological development) of a variable.
Simple moving average	A method which takes the average of some observations/ values to be representative. *This research uses a centered simple moving average, which has an equal amount of observations at both sides (before and after) of the representative value to calculate the average over.*
Time series plot	A plot showing the simultaneous development (time series) of various variables in order to interpret qualitatively their interdependence.
Voronoi method	A method (spatial analysis) which divides an area into zones, based upon few locations, such that all segments within these zones are closest to their accompanying locations (Gold et al., 1997).

Drought

Phrase	Description
Cumulative precipitation surplus	The difference in (daily or e.g. hourly) precipitation and potential (reference crop) or actual evaporation fluxes added up for a certain duration (period) [1]. Positive when precipitation outnumbers actual evaporation. *This research calculates the cumulative precipitation surplus using actual evaporation, estimated via the Urban Water balance Model (UWBM).*
Cumulative precipitation deficit	Same-like cumulative precipitation surplus, but positive when actual evaporation outnumbers precipitation [1].
Drought (urban)	A period in which one or more water components (e.g. soil moisture) has insufficient water (in comparison to a reference) resulting in a disruption of its related functions (e.g. wilting of plants) (Machairas, 2020).
Evaporation	Process of vaporization of a liquid into the gas phase at a surface (e.g. wet pavement or soil surface) [1]. *Transpiration is included in this research within the usage of the phrase evaporation (evapotranspiration).*
Evaporation, actual	The calculated/ modelled/ measured evaporation occurring [1]. *In this research the actual evaporation is modelled by the Urban Water balance Model (UWBM).*
Evaporation, potential	The theoretical (extent of) evaporation occurring if sufficient water is available [1].
Transpiration	Process of water movement through a plant in order to supply nutrients and water needed for photosynthesis (at its leaves), resulting in evaporation of water from the unsaturated zone [1].

Soils

Phrase	Description
Capillary rise	Induced movement of water above the phreatic line through surface tensions in (small) pore spaces [1].
Compressibility	The ability of a material to have change in deformation when a pressure is laid upon [2].
Compression (granule)	The change in volume of a granule, without a change in shape [2].
Distortion (granule)	The change in shape of a granule, without a change in volume [2].
Groundwater, level	Level where the groundwater has a pressure height equal to zero [1]. Is the same as the phreatic line, but might be higher when capillary rise is present.
Groundwater, regime	The total movement of the (lowest and highest) groundwater level for a certain reference period within the soil.
Permeability	The ease of water to flow through a medium (soil) [1]. Generally expressed in meters per day for soils.
Phreatic line	Elevation within a soil in where where the pore water pressure is equal to atmospheric conditions [1]. The groundwater level is equal to this level in case no capillary rise is present.
Root zone	The soil zone in where the roots of vegetation is present [1]. Might be in the order of centimeters or decimeters.

Phrase	Description
Soil	Combination of materials (clay, peat, sand) generally situated in the outer layer of the earth. Consists of materials in general not older than the Pleistocene. Is bounded at the bottom by hard rock or solid sand layers and has hence a depth of (tens of) meters.
Soil, hysteresis	The phenomenon that the soil retention curve differs at wetting or drying conditions of a soil. At wetting conditions the suction pressure is lower than at drying conditions, for a similar water content [1].
Soil, soft	A soil consisting of (layers with) compressible materials (peat, clay).
Soil structure	The profile of a soil. Might consists of several layers of differing materials having a high spatial variability.
Soil, moisture content	The amount of water present in the unsaturated zone [1]. Might be expressed as ratio of volume, or in millimeters.
Stress, effective	The stress (internal forces) in a soil concentrated at the contact points of the granule structure [2].
Stress, total	The total internal forces that granules or particles (in a soil) exert on each other [2] due to (external) load. Is an addition of water & effective stress.
Stress, water	The stress (internal forces) in a soil carried by a pressure in water (particles) [2].
Strain	The measure of deformation of particles (granules) through a force [2].

Subsidence

Phrase	Description
Auto-compaction	The compaction of soil layers due to mass of young sediments [3].
Autonomous subsidence	A general name for natural subsidence & variable (drought-related) subsidence (shrinkage, clinch, degradation) (Te Groen, 2016).
Clinch	Subsidence (consolidation and creep) due to lowering of the groundwater level [3].
Compaction	A collective name for several causes and mechanisms (mainly consolidation and creep) [3].
Compression (subsidence)	Same-like consolidation, but not specifically referred to a process in time or to aquifers [3].
Consolidation	The slow process of decrease of a poor-permeable soil's volume by pressing water out, due to change (increase) in effective stresses (see section soils) [2].
Creep	The process of granule structure reorganization. Happens simultaneously with consolidation, but is not directly induced by effective stresses and therefore also occurs after the hydro-dynamic period [3].
Degradation (of organic materials)	The process of decay of organic material due to direct exposure to oxygen in the unsaturated zone or to chemical oxidators in the saturated zone [3].
Hydro-dynamic period	The time span of the process of pressing out water from poor-permeable layers due to change in stresses (consolidation) [2].
Isostasy	The change in surface level elevation due to the movement of different plates of the earth's crust [3].
Maturation	A collective name for soil-forming (consolidation, creep, degradation) [3]. Can be used as soil classification.
Natural subsidence	The change in surface level elevation due to natural processes which cannot be diminished or stopped [3].
Oxidation (of organic materials)	See also degradation (of organic materials).

Phrase	Description
Relative surface level movement	The movement of the surface level with respect to the average subsidence rate. This is mainly a (seasonal) sinusoidal behaviour.
Residual settlement	A general name for all subsidence occurring after hydro-dynamic period.
Settlement	Consolidation and creep due to addition of an artificial load [3].
Shrinkage	In- & decrease of volume of unsaturated zone due to change in suction pressure [3].
Subsidence	The process of a decreasing surface level with respect to a reference, e.g. NAP [3].
Subsidence mechanism	The distinct process of change in soil structure which causes variations in a soils volume and hence variations in surface level elevation.
Swell	The process of expansion of a soil's volume. *In this research a swell does not essentially cause a net rise of surface levels. It might also be a swell with respect to the average subsidence rate and hence a (temporary) decrease of this rate.*
Tectonic movements	The change in surface level elevation due to contact of tectonic plates in the lithosphere which move in different directions [3].

Site preparation strategies

Phrase	Description
6M approach	An approach of 6 steps on emerging from land subsidence lock-in: the cycle of subsidence, groundwater nuisance, groundwater level reduction, and subsequently more subsidence (Erkens & Stouthamer, 2020).
Accessibility (site)	The ability for construction workers to access (greenfield) areas in order to work/ construct [4].
Adaptation (strategy)	A type of strategy focusing on reducing consequences of processes like drought-induced subsidence.
Bearing capacity	The ability of the soil to carry heavy equipment and infrastructure [4].
Building (construction) phase	The phase after the preparation phase of a construction site in which the large infrastructures like buildings are build [4].
Cover (sand/soil)	A (well permeable) layer of sand, mixture or other materials laid upon soft soils to increase the freeboard and/or bearing capacity.
Drainage system	The system of drainage pipes & provisions, sewer and surface waters to cope hydrological processes [4].
Drainage depth	The designed minimum depth of the groundwater level in center of two surface waters or drainage pipes [4]. Is mainly determined by default depths of (subsurface) infrastructure to keep them dry and unfrozen.
Excavation method	A method of raising soils only at parts of the site where this is needed (infrastructure) [4].
Freeboard	The distance between surface levels and surface water levels [4].

Phrase	Description
Greenfield area	An untouched (not constructed) area which needs preparation in order to be constructed upon.
Groundwater nuisance	Such groundwater levels it causes damage or other consequences (unwanted water in crawl-spaces) (Van de Ven, 2016). Mainly refers to too high groundwater levels.
Integral fill method	A similar thickness in raise of the entire site [4].
Mitigation (strategy)	A type of strategy focused on minimizing severity of processes such as drought impacts on subsidence.
Partial fill method	A complete raise of site (integral fill), with exception to parks and water bodies [4].
Preparation phase	The phase of urban development of several activities to improve the soil conditions of a site (accessibility, bearing capacity) to construct buildings and infrastructure but also for later (living) phases [4].
Raise (sand, soil, other)	The increase of surface level by adding material on top of the current soil [4]. This material might be sand, mixed materials or light-weight materials, or constructions.
Ready-to-live phase	The last phase of urban development before the living phase [4]. Main activities are adding the final pavement and greenery, cleaning the site, and adding provisions like benches, streetlights, and playgrounds.
Reverse drainage	A drainage system where (surface) water can be supplied into the soil in dry periods via the drainage pipes.
Site preparation (strategy)	The combination of (chosen parameters for) the considered methods during the preparation phase of construction sites.
Vertical drainage	A system of vertical pipes applied at e.g. soil raises in order to shorten the hydro-dynamic period [4].

Abbreviations

Abbreviation	Phrase	Description
CPT	Cone penetration test	See also glossary, general section.
EPS	Expanded polystyrene	A rigid closed-cell foam made of polystyrene (synthetic aromatic hydrocarbon polymer).
GIS	Geographic information system	A computer-based system to overlay, interpret, analyse and present spatial data (Gold et al., 1997).
IFCO	Intensief Forceren Consolidatie Ondergrond	A site preparation method used to decrease the hydrodynamic period. It makes use of deep horizontal drainage pipes placed in equally deep sand trenches.
KNMI	Koninklijk Nederlands Meteorologisch Instituut	The Dutch national weather forecasting service, including climate changes and seismic activities.
InSAR	Interferometric Synthetic Aperture Radar	A technique which generates radar images made by a 'scanner' attached to a satellite (Sataloff et al., n.d.).
LiDAR	Light Detection And Ranging	A technique which computes the time between laser pulses send from a scanner attached to a rod or e.g. a drone and the interception of reflectors, and transfers this to a height (Van Asselen et al., 2019).
NAP	Normaal Amsterdams Peil	A standardized vertical datum (reference surface elevation) used in large parts of West-Europe [1].
PDOK	Publieke Dienstverlening Op de Kaart	A Dutch open geoportal to find and access geographic spatial information (GIS layers) (PDOK, n.d.).
SMA	Simple moving average	See also glossary, methodology section.
UWBM	Urban Water balance Model	A lumped conceptual model constructed by the Dutch institute Deltares regarding water flows and resources in urban areas.

List of figures and tables

Required soil raise
Parijsch, Culemborg
February 2021

1

Introduction

1.1. Urban (water) challenges in the Netherlands

The Netherlands faces a variety of challenges regarding urban water management in coming decades. Urban water systems in the Netherlands endure and inadequate quality of surface waters, a lack of biodiversity in surface waters, encounter both a surplus of water due to extreme precipitation events and a deficit of water as consequence of dry periods, bear heat stress with rising temperatures, and are subject to subsidence (Hoogvliet et al., 2012).

1.1.1. Drought in urban areas

One of the main urban water challenges concerns (urban) droughts. Drought impacts in urban areas have not been studied thoroughly (Zhang et al., 2019). Despite drought can be assessed with numerous indicators (Weijers, 2020), a general definition of drought is hard to determine due to its many involved factors (complex urban (water) infrastructure systems) and varying affected stakeholders (Lloyd-Hughes, 2014). The multiple-interpretive definition of drought thereby leads to ineffective researches regarding the subject (Yevjevich, 1967). Urban drought is however generally characterized by evaporation via vegetation and a lack of infiltration (Brolsma et al., 2012). Extensive evaporation leads to a decrease of soil moisture content, groundwater- and surface water levels (Van Asselen et al., 2019). Dry periods thereby induce damage risks in urban areas. Urban drought damage includes: 1. rotting wooden pile foundations; 2. heat stress; 3. damage at vegetation; 4. problems regarding water quality; and 5. heterogeneous subsidence (Brolsma et al., 2012).

The extent of damage as consequence of drought differs per local situation due to soil heterogeneity and water system complexity (Brolsma et al., 2012) (Alves et al., 2020). Effects of drought do not emerge abruptly (Wilhite & Vanyarkho, 2000), resulting in a possible underestimation of the consequences (Machairas, 2020). Moreover, drought damage seems in greater extent consequence of design of the urban water/ infrastructure system (Brolsma et al., 2012). Regarding the changing climate, an urge arises to mitigate the urban design and water system to reduce impacts of drought.

During and after the last severe drought in the Netherlands, in 2018, drought-induced damage at various types of urban infrastructure was observed in (soft-soil) cities (Hekman et al., 2019). Although the damage is hardly quantifiable, the number of notifications regarding cracks in buildings or crooked buildings increased strikingly compared to prior years, suggesting the severe urban drought had impact on buildings. Moreover, rotting wooden pile foundations, less vegetation growth, cracks in infrastructure (asphalt), and loose or uneven street tiles were mentioned more during and after the drought in 2018 than in prior years. It is hard to fully accredit the observed damage to the drought of 2018, since it is not known if prior drought or other factors (partly) induced the damage (van Haastregt, 2019). Also, the damage might not been observed or occurred yet.

1.1.2. Subsidence in urban areas

Subsidence, like drought, is referred to as urban (water) challenge in the Netherlands. Many areas in the Netherlands subside due to soft soils (Kwakernaak, 2015). Rural areas in the Netherlands subside mainly due to artificial lowering groundwater levels for crop cultivation and dry grassland for livestock (Van den Born et al., 2016). Dutch soft-soil urban areas subside due to large loads on top of the soil and subsurface such as (sand) raises and infrastructure or buildings on footings or slab, in combination with low groundwater levels. Subsidence might lead to negative consequences, such as damage to infrastructure, crooked houses, higher maintenance costs for municipalities, land owners and real estate owners, and more. Subsidence also affects urban areas on long-term, via for example higher flooding risks (Vleugels, 2019) - especially regarding sea level rising (Van Asselen et al., 2019).

Subsidence is estimated, by calculations or models, over larger zone(s) at the preparation of construction sites, based upon one or more representative soil structures derived by e.g. cone penetration tests. These estimations are consequently, due to small-scale soil heterogeneity, subject to spatial uncertainties and errors. The errors in subsidence modelling result in higher costs for maintenance of infrastructures (Waltham, 2015). It is therefore necessary to better understand subsidence processes during and after site preparation. Subsidence is affected by the groundwater level and soil moisture content (Verruijt, 2010) and thus complex urban (water) systems also affect soil processes spatially and temporally. Since drought influences these water contents via evapotranspiration, it might thereby intensify subsidence rates (Erkens & Kooi, 2018) and hence increase damage risks to urban infrastructure. Current (international) studies regarding drought-impacts on subsidence focus mainly on consequences of (increased) groundwater extractions. Likewise, cost estimations of drought-induced subsidence in studies are mainly focused on agricultural production losses (Machairas, 2020). Given that drought impacts groundwater levels and soil moisture content, and these water components are present in soft-soil urban areas, it might thus be valuable to study drought impacts on subsidence rates and its consequences in soft-soil urban areas. However, only limited studies have been performed on the in-practice extent of drought (evapotranspiration) impacts on subsidence and its consequences in soft-soil urban areas.

1.1.3. Scarcity of houses

Next to urban water challenges, the Netherlands faces yet another challenge: a scarcity of houses for its inhabitants (Groenemeijer et al., 2020). Acceleration of new housing developments is required to combat the scarcity in coming years (De Jong et al., 2019). What hampers the housing development is that most solid soils, with high bearing capacity, in the western part of the Netherlands are scarce since there is already built upon (Tromp, 2008). Therefore, new housing areas are to be positioned on softer soils, which tend to subside more after loading. Nonetheless, the intention is to design these new urban development areas to be climate adaptive. This challenges constructors to understand and estimate subsidence of new housing areas more accurately in order to minimize damage and hence maintenance costs of infrastructure in later phases.

Covenant Zuid-Holland is a recent example in the Netherlands of urban climate adaptation intention (Provincie Zuid-Holland, 2019). Municipalities, water authorities, (construction) companies, financiers, project developers and other parties have signed the covenant's objectives to have climate adaptation measures implemented in current and new housing areas. In general these climate adaptation goals consist of six themes: subsidence, drought, heat stress, biodiversity, pluvial- and fluvial flooding. The covenant is open to join by all stakeholders in the Netherlands. This shows the nationwide ambition to integrate these climate themes, including subsidence and drought, in future urban design.

1.2. Knowledge gaps

This research focuses on subsidence and drought processes in Dutch soft-soil urban areas, considering these processes increasingly affect urban infrastructures and might result, due to climate change, in (greater) consequences the coming decades. The in-practice relation between drought and subsidence in soft-soil urban areas is yet to be further clarified since focus of (international) studies is mostly on subsidence consequences of groundwater extractions. Studies on urban drought-induced subsidence might enable integration of solutions on its causes and consequences as part of urban climate adaptation. Subsidence is a worldwide problem, for example soils in Indonesian cities subside up to 17 centimeters per year due to groundwater extractions (Andreas et al., 2017). This research however focuses on Dutch soft-soil cities since in-practice knowledge hereupon lacks. Knowledge gaps on urban drought-induced subsidence still exist despite large contributions of institutions and researchers. The following knowledge gaps are endeavored to be answered in this research:

- In-practice knowledge of the extent of drought impact on subsidence rates in urban areas via measure-

ments (Brolsma et al., 2012) (STOWA, 2014).
- The portion of various subsidence processes in urban areas (shrinkage, oxidation) compared to settlements via soil raising (Van Asselen et al., 2019).
- The influence of climate change on urban drought vulnerability (Machairas, 2020) and hence subsidence rates.

1.3. Research objective

The in-practice impact of drought on subsidence is not fully clarified yet. This research therefore aims to contribute to in-practice knowledge of drought impacts on subsidence rates in urban areas. Furthermore, the research's clarifications should be translated into solutions to minimize (consequences of) urban drought-induced subsidence considering the current urge of developing new housing areas in the Netherlands. Application of the research' findings into practical guidelines is therefore an additional ambition. The research objective is expressed as follows:

Gaining insight into **drought-induced subsidence** in soft-soil urban areas in the Netherlands, and applying the gained knowledge to enhance **site preparation strategies**, in order to better **predict and limit the impact and consequences of drought on subsidence rates** in future new housing developments on soft soils as found in the Netherlands.

The research objective will be achieved by answering following research question and sub-questions:

How can effects of drought be considered in site preparation strategies in order to minimize drought-induced subsidence in Dutch soft-soil urban areas?

1. To what extent does drought influence subsidence rates in the analyzed Dutch soft-soil urban areas?
2. To what extent do local characteristics affect these drought influences on subsidence rates?
3. What improvements in site preparation strategies can be made in order to minimize drought-induced subsidence in Dutch soft-soil urban areas?

The research is partitioned into three stages based on the research sub-questions. Firstly, the general impact of drought on subsidence will be analyzed in several Dutch soft-soil urban areas. Afterwards, analyses are specified on local characteristics to determine their influence on drought-induced subsidence. Lastly, recommendations are given on enhanced site preparation strategies, both mitigation and adaptation, in order to minimize drought-induced subsidence and its consequences.

1.4. Reading guide

In this report the research methodology and findings are presented. Firstly, Chapter 2 covers the theoretical framework required for understanding and interpreting the methodology and analyses. The Chapter therefore discusses soil processes such as subsidence, and moreover drought and site preparation strategies.

Afterwards, the step-by-step methodology and required data for the analyses are explained in Chapter 3. The methodology consists of several phases in order to structure the research and hence make it understandable and reproducible. The gathered data for analyses of study areas Diemen and Kampen are shortly discussed in Chapter 4.

Subsidence and meteorology time series are analyzed in Chapter 5 to answer research questions 1 and 2. Chapter 6 covers suggestions on enhancing site preparation strategies based upon the research results and an expert questionnaire in order to minimize drought-induced subsidence, answering research question 3. Both mitigation and adaptation strategies will be covered.

In Chapter 7 the research results, methodology, and limitations are discussed. Finally, in Chapter 8 research conclusions are drawn by answering the research sub-questions stated in this Chapter. The conclusions are followed up by recommendations on further research.

Site preparation activities

Parijsch, Culemborg

February 2021

2

Soil processes, drought and site preparation strategies

This chapter provides background information in order to understand soil and atmospheric processes required to interpret research results. Soils, drought, subsidence and site preparation strategies are covered. This chapter ends with an overview of recent studies on drought-induced subsidence.

2.1. Soils

In order to understand subsidence processes and drought impacts on (sub-)soils, it is essential to firstly comprehend the soil composition, balance and movements (Verruijt, 2010). This section briefly covers soil type classification, soil properties, and cone penetration tests to determine a soil's structure.

2.1.1. Classification of soil types

Soils mainly consist of (organic) materials, water, and gasses (air). In order to describe soil structures it is common use to make a classification of present materials. The regular classification is based on granule sizes of present materials. An overview of this classification reprocessed from Verruijt (2010) is given in Table 2.1. As shown, clay particles have a very small size compared to sand or gravel. Peat consists of organic materials with a varying size and therefore mainly the composition of this organic material determines properties of the soil type. The granule size affects various soil properties.

Table 2.1: *Soil type classification based on granule sizes.* Reprocessed from Verruijt (2010).

Soil type classification	**Min. size**	**Max. size**
Clay	<	0.002 mm
Silt	0.002 mm	0.063 mm
Sand	0.063 mm	2 mm
Gravel	2 mm	63 mm
Stone	63 mm	>
Peat	-	-

2.1.2. Soil properties

Numerous soil properties determine its behaviour. In order to determine the effect of drought on soils it is essential to understand property differences for various soil types, briefly explained below. Equations and more extensive explanation of these properties are given in Appendix H.

The soil porosity represents the 'pore' space available for water and gasses. Therefore porosity (partly) depends on the granule size: larger granule sizes result in more pores between these granules and therefore a higher porosity. The ratio of water between pores, saturation degree, is described by dividing the present water volume by pore volume. Next, in order to estimate the total weight of a volume of soil the aforementioned porosity, saturation degree and moreover averaged density of present particles is needed. Gasses or air may be neglected in weight determination due to their (very) low density. The unit weight describes the soil's weight per unit of volume. Sand has a high unit weight compared to peat which unit weight is very close to water. The unit weight of clay may vary between these of sand and peat.

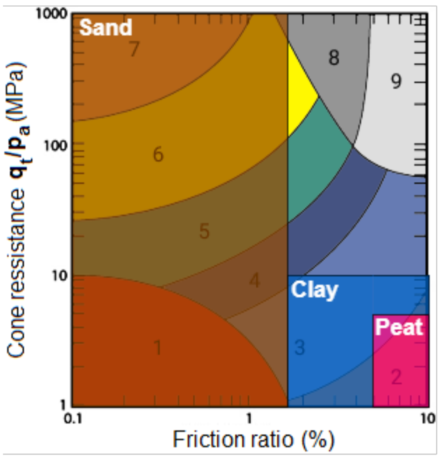
Soil permeability represents the ease of water to flow through the soil. It is affected by the soil geometry (granule size and shape, stacking of granules, and porosity) as well as properties of the flowing fluid, for example its viscosity (Verruijt, 2010). The permeability of sandy soils is large compared to silt or clay soils (up to a factor 1000 difference). Therefore, in general sand soils are considered well-permeable (aquifer), whereas clay soils are referred to as poor-permeable (aquitard). The compressibility of soil types refers to their ease to be compressed due to an increased stress (pressure). Compression coefficients of sand are very high: sand is hardly compressible. Compression coefficients of clay respectively peat are lower.

Soils are called saturated in case pores consist only of water. Otherwise they are referred to as unsaturated. In general only the soil's upper space (approximately subsurface) consists of both water and air. The water content in this zone generally depends on infiltration of water into the ground, percolation, evapo(transpi)ration, and resulting capillary rise (Brolsma & Vergroesen, 2020). The saturated and unsaturated zones are divided by the so-called phreatic line, where water pressure is equal to atmospheric pressure (Verruijt, 2010). The groundwater level is equal to the phreatic line if no capillary rise is present. Otherwise it might be positioned slightly higher.

The soil's weight and present external loading (for example infrastructure or sand covers) is carried by present water and by contact points in the granule structure. The resulting (water and effective) stresses can be intervened by changing the soil's water content (groundwater level (including seepage) and/ or saturation degree) or by changing (external) loads.

2.1.3. Cone penetration tests

Soils differ spatially in structure and composition: they are heterogeneous, even on small scale (within meters). Dutch soils however are generally made up of a structure of horizontal layers of different soil types. This typical layer structure existed due to a frequency of depositions of organic material, clay and sand in past millions of years. Cone penetration tests (CPT) are the standardized way in the Netherlands (and worldwide) to estimate the overall layer structure at a location.



(a) *Simplification of soil classification.* Reprocessed from Robertson & Cabal (2014).

Zone	*Soil Behavior Type*
1	*Sensitive, fine grained*
2	*Organic soils - clay*
3	*Clay – silty clay to clay*
4	*Silt mixtures – clayey silt to silty clay*
5	*Sand mixtures – silty sand to sandy silt*
6	*Sands – clean sand to silty sand*
7	*Gravelly sand to dense sand*
8	*Very stiff sand to clayey sand**
9	*Very stiff fine grained**

** Heavily overconsolidated or cemented*

(b) *Soil Behaviour Types.* Acquired from Robertson & Cabal (2014).

Figure 2.1: *Simplification of Robertson & Cabal's (2014) classification of soil types based on cone penetration test results.* Reprocessed from Robertson (2014).

A CPT is a way of obtaining measurements by drilling into soils. This drill consists of a series of rods with a cone attached to the end (P. K. Robertson, 2009). Continuous measurements are made from forces through resistances at the cone and drill's side during soil penetration. The classification of soil types can be determined from these forces. A simplification of Robertson & Cabal's (2014) soil type classification, Figure 2.1b, is used in this research to distinguish sand, clay and peat soils, as shown in Figure 2.1a. The exact resulting table of forces and soil types is given in Appendix A. The measured thickness, soil type and compressibility of layers is used in order to calculate or model future soil behaviour.

2.2. Urban drought

This section firstly covers the definition and characterization of urban drought. Afterwards drought impacts on soils is discussed. Lastly, influences of a changing climate on drought is briefly noted.

2.2.1. Definition of urban drought

The definition of urban drought is hard to determine due to its many involved factors (for example complex urban (water) infrastructure systems) and varying affected stakeholders (Lloyd-Hughes, 2014). Machairas (2020) however defined a general definition for urban droughts. Urban droughts occur in case one or more present *water components* in urban areas have *insufficient water* resulting in a *disruption of its related function(s)*. Several terminologies in this definition are to be specified in order to estimate the conditions for urban droughts.

Water components

In general drought can be classified into four categories consisting of different hydrological processes and/ or water components (Mishra & Singh, 2010): meteorological (precipitation deficit), hydrological (deficiency of (sub-) surface water resources), agricultural (soil moisture depletion/ wilting of crops), and socio-economic (fresh water supply shortage). KNMI (Royal Netherlands Meteorological Institute) defines drought in the Netherlands by both cumulative potential precipitation deficit (meteorological) for a certain area and discharge of the Rhine river (hydrological) as an estimate of nationwide shortage of fresh water (Beersma & Buishand, 2002). Machairas (2020) however specified urban drought in terms of the following present water components:

- *Soil Moisture Urban Drought*
  Insufficiency of **soil moisture** content within urban boundaries.
- *Groundwater Urban Drought*
  Insufficiency of **groundwater** level within urban boundaries.
- *Open Water Urban Drought*
  Insufficiency of **surface water** (canals, ponds, wetlands) level and/ or -quality within urban boundaries.
- *Water Supply Urban Drought*
  Insufficiency of **external reservoir- and/ or groundwater level**, or surface water quality reduction, where city receives water from.

These components are interconnected and might vary simultaneously or subsequently (Helder-Feijen & Van der Toorn, 2020). This research focuses quantitatively on precipitation and evaporation data (precipitation deficit/ surplus) since this data is available for last decades via KNMI databases. Soil moisture content, groundwater- and surface water levels within urban areas are analyzed qualitatively since the first is to be modelled (its almost not measured in urban areas) and limited data is available for the latter two variables.

Water insufficiency

The insufficiency of water in the aforementioned components depends on their water content in normal conditions (long-term, e.g. 30 year average (Machairas, 2020)) and degree of water deficit occurring. For example, a groundwater level drop does not directly induce a drought since it might be relatively small compared to the average fluctuation of last years or decades and hence does not essentially disrupt related functions. A threshold is thus to be defined.

The degree of water insufficiency for given categories depends on hydrological variables: precipitation, evaporation & transpiration, soil moisture content, groundwater levels, and surface water levels (Machairas, 2020). It is required to determine temporal changes in these hydrological variables in order to estimate if such conditions occur that it results in drought and hence disrupts functions.

Disruption of related function(s)

The extent of disruption of related function(s) regards to societal, economical, or/ and environmental losses due to the water insufficiency (Machairas, 2020). This might be for example loss of human life (due to heat), biodiversity (due to lesser water quality) or irreversible loss of surface level elevation (subsidence). This research focuses on the functions of the water components in soft-soil urban areas which are related to (irreversible) variations in surface levels (subsidence). In Section 2.3 the functions will be explained in more detail.

The extent or appearance of urban drought differs per region/city since water availability thresholds (what conditions determine a water deficit?) vary on their present water systems. It is hence useful to study distinct urban areas to interpret differences of drought extents. In this research the therm 'drought' refers to *dry conditions*, mainly via precipitation deficits. The focus of this research is to determine the extent of dry conditions (change in the hydrological variables) resulting in irreversible subsidence.

2.2.2. Drought characteristics

Four characteristics describe the extent of drought: deficit, duration, frequency and spatial extent (Machairas, 2020). Analysis of these characteristics can be applied on all four drought categories to determine if such water insufficiency occurs that related functions are disrupted. These characteristics have strong interrelationships (copulas), which are not covered in this research.

Deficit

The cumulative potential precipitation deficit of an area (KNMI) over a time interval (seasonal) is calculated by subtracting the daily precipitation flux [mm] from daily potential evaporation flux [mm] and accumulating the outcome for total days in a determined time interval. Drought starts when daily evaporation outnumbers precipitation and ends in case cumulative precipitation deficits turn negative (surplus). The cumulative potential precipitation deficit throughout summer half-years is given for record year (1976), median, and last severe drought (2018) in Figure 2.2. KNMI computes precipitation deficits for large areas based on meteorological data from weather stations across the Netherlands.

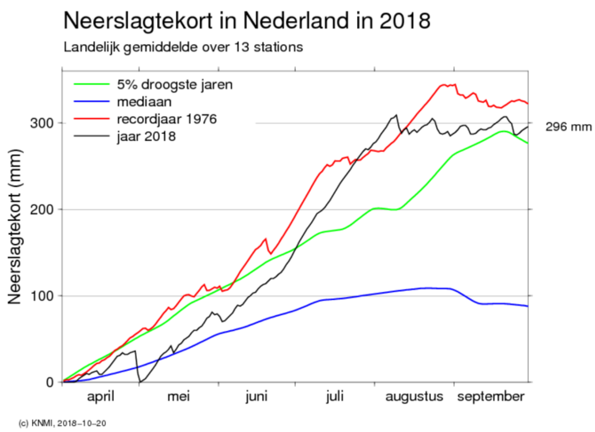


Figure 2.2: *Cumulative potential precipitation deficit in the Netherlands for various years.* Acquired from (Koninklijk Nederlands Meteorologisch Instituut, n.d.-b).

Duration

The duration of drought might be several months or longer (Mishra & Singh, 2010). In the Netherlands KNMI evaluates drought during summer half year (April to October) since evaporation is extensive mainly in this period. Although the months October and November are not included in computed summer half year period, effects of (severe) precipitation deficits can still be present. It is therefore important to take into account the variability of duration of drought in its evaluation.

Frequency

The general frequency of drought in The Netherlands is yearly due to seasonality (yearly precipitation deficits). However, the frequency of extreme droughts such as shown in Figure 2.2 is lower: the 2018 drought has a (current) return period of 30 years (Kramer et al., 2019).

Spatial extent
The spatial extent of drought differs within urban areas based on local characteristics as explained in Section 2.2.1. These local influences are explained in next section. Furthermore, on larger scale drought differs between urban areas based upon difference in precipitation and potential evaporation intensities.

2.2.3. Drought impacts on soils

At evapo(transpi)ration intensities distinction is made between paved and unpaved (vegetated) surfaces (Van de Ven, 2016). The rapid heat supply from the warm pavement plays an important role in evaporation processes (Van de Ven, 2016). However, only if water is available on nearly completely paved areas, example given during and after precipitation events due to wetting and ponding, the pavement's temperature causes considerable evaporation. Otherwise, evaporation is very limited. The evaporation process at unpaved surfaces consists of two components: evaporation from the surface itself and transpiration via plants. The transpiration intensity depends on the roots' depths and water uptake. Transpiration is the most intense evaporation component in comparison to evaporation from (paved) surfaces.

KNMI computes precipitation deficits by potential evaporation based on temperature, humidity, radiation, and wind. Actual evaporation is however not an endless process due to limited water availability (on surfaces and) in subsurface. The change in soil moisture content and groundwater level as consequence of meteorologic processes is complex to estimate due to the present (surface) water system and soil heterogeneity. The Urban Water balance Model from Deltares (Brolsma & Vergroesen, 2020) is a recent example of a model which computes (simplified) soil moisture content and groundwater variations by drought. The energy required to stimulate capillary rise and thus decrease of groundwater level (and same-like percolation) is simplified in the Urban Water balance Model to be influenced by difference between equilibrium and actual soil moisture content (Brolsma & Vergroesen, 2020). The model however does not include example given hysteresis between soil moisture content and suction pressure: at drying conditions soils contain more moisture than at wetting conditions for same suction pressures (Staple, 1961).

Drought influences on soil moisture content and groundwater level thus depend on surface material type or present plants, soil structure, and (surface) water system present. These local characteristics are taken into account in Chapter 3.

2.2.4. Future drought

Part of the research objective is to contribute to knowledge concerning drought-induced subsidence in order to minimize it at future housing developments. In order to understand the extent of subsidence in these future developments, it is also necessary to understand changes in future drought. KNMI predictions are covered briefly to estimate these changes.

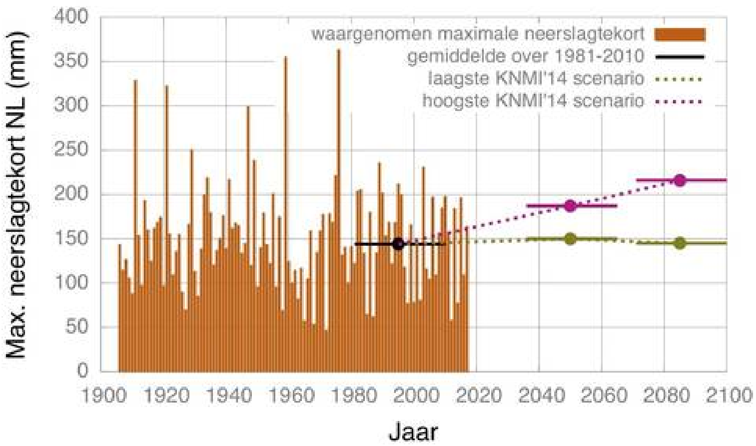


Figure 2.3: *KNMI predictions regarding the 30-year average of cumulative precipitation deficits until 2085.* Acquired from (Linden & Selten, 2018).

KNMI has estimated different climate scenarios for the time span of 2050 and 2085 based on climate change predictions of the Intergovernmental Panel on Climate Change (IPCC) (Klein Tank et al., 2015). Changes in temperature, precipitation, radiation, humidity, evaporation and cumulative precipitation deficit are predicted per season. All four scenarios based on variations in global air flows & temperature predict at least equal or even longer and more intense future droughts, as also shown in Figure 2.3. It is likely from KNMI calculations that future frequency of for example 2018 drought (Figure 2.2) increases to once per 10 years (Klein Tank et al., 2015). This rule of thumb is therefore used in further references in this research regarding future (extreme) drought.

2.3. Subsidence

Subsidence is the process of a decreasing surface level with respect to a reference level, e.g. Normaal Amsterdams Peil (NAP) (Erkens & Kooi, 2018). Causes of subsidence can be distinguished into natural (geological) processes and consequences of human activities (Van Asselen et al., 2019). Natural processes proceed for thousands or millions of years, while subsidence due to human activities is mainly from last centuries. Furthermore, natural subsidence varies only over large areas, whereas other subsidence processes might occur very local (Stouthamer & Van Asselen, 2015) (kilometers vs (deci-)meters respectively). Lowering of surface levels due to soil excavations as well as subsidence due to extraction of gasses in deep soil layers will not be covered in this research.

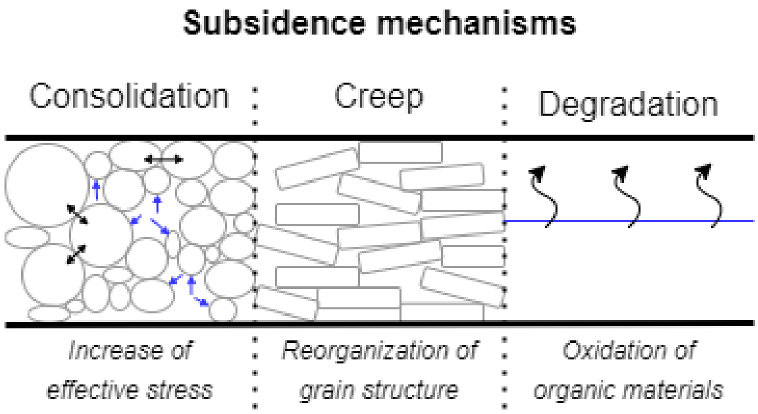


Figure 2.4: *Overview of various mechanisms of subsidence, excluding natural mechanisms.*

It is important to notice that subsidence as consequence of human activities is additional to everlasting (and only slowly changing) natural processes. The (combination of) various subsidence mechanisms have different nomenclature in literature. It is therefore important to clarify numerous subsidence terms. The individual underlying mechanisms structuring this research's theoretical framework are -excluding natural mechanisms- displayed in Figure 2.4. Other terms which are used in literature are stated in Table 2.2.

Natural causes of subsidence will be shortly covered first, followed by the three mechanisms. Methods to determine and calculate the extent of subsidence are afterwards clarified, as well as consequences of subsidence in urban areas.

Table 2.2: *Nomenclature for subsidence types and their underlying mechanisms.* Excluding natural subsidence mechanisms. Information abbreviated from STOWA (2020).

Subsidence type	**Underlying mechanisms**	**Description**
Compaction	Consolidation Creep	A collective name for undermentioned causes and mechanisms.
Settlement	Consolidation Creep	Consolidation and creep due to addition of an artificial load.
Clinch	Consolidation Creep	Consolidation and creep due to lowering of the groundwater level.
Shrinkage	Consolidation Creep	In- & decrease of volume of unsaturated zone due to change in suction pressure.
Compression	Consolidation Creep	Same-like consolidation, but not specifically referred to a process in time or to aquifers.
Maturation	Consolidation Creep Degradation	A collective name for soil-forming, can be used as soil classification.
Residual Settlement	Consolidation Creep Degradation	A general name for all subsidence occurring after hydrodynamic period (mainly thus in living phases of areas).
Autonomous subsidence	*Natural* *Consolidation & Creep* Degradation	A general name for natural subsidence & variable (drought-related) subsidence (shrinkage, clinch, degradation)

2.3.1. Natural causes of subsidence

Natural subsidence is not induced by human activities and cannot be diminished or stopped. To determine future surface level movements therefore natural subsidence should be accounted for. The underlying mechanisms of natural subsidence are isostasy, tectonic movements, and auto-compaction (Kooi et al., 1998). The spatial extent of natural causes in the Netherlands is illustrated in Figure 2.5.

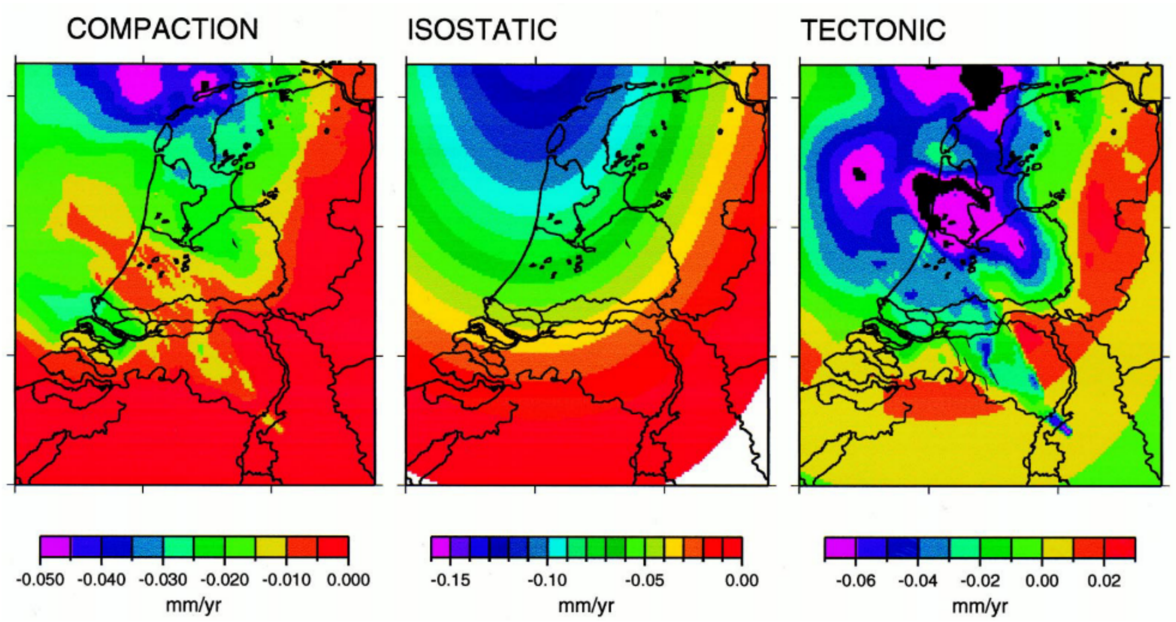


Figure 2.5: *Overview of extent of various types of natural subsidence in the Netherlands: auto-compaction, isostasy, and tectonic movements.* Acquired from Kooi et al. (1998).

Auto-compaction

Auto-compaction, also called natural compaction, is compaction of shallow layers (up to 300 meters) due to mass of young sediments. Auto-compaction mainly increases towards coastal areas in the Netherlands.

Isostasy
Isostasy describes movement of different plates of the earth's crust, which float on magma (Asthenosphere) and are subject to changes in masses, for example glaciers. Due to the North Sea fill after last glacial period and the melting of ice sheets in Scandinavia isostasy soil movements are present in the Netherlands.

Tectonic movements
Tectonic movements are caused by forces acting between tectonic plates in the lithosphere due to the different directions plates are moving. The contact between multiple plates cause the earth's surface to move in a vertical direction.

2.3.2. Consolidation and creep

Consolidation and creep are in general the main processes in soft-soil urban areas which cause deformations. These mechanisms are discussed below. Moreover the terminology clinch and shrinkage is explained shortly.

Consolidation
Consolidation is a slow process where, due to increasing effective stress, water is pressed out of present poor-permeable layers (Verruijt, 2010). The soil's weight and external loads such as infrastructures are partly carried by contact points between granules - and partly by the present groundwater. The granules transfer a normal (pressure) force and, if these forces are large enough, a shear force via these contact points to one another. An increase of effective stress causes both a deformation of granules and changes in granule skeleton (stacking of granules). The degree of this deformation is influenced by the extent of compression and distortion of granules (Verruijt, 2010), illustrated in Figure 2.6.

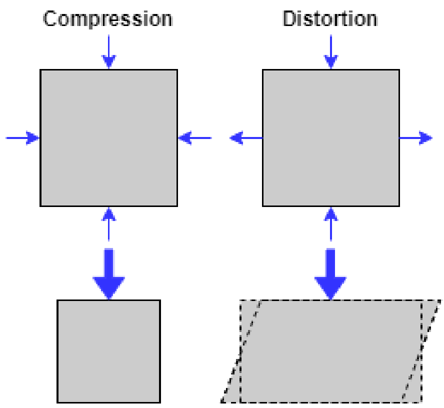


Figure 2.6: *Compression and distortion of granules illustrated.* Reprocessed from Verruijt (2010).

Compression refers to the decrease of volume of a granule without a change of its shape. This is solely possible if the forces acting on the granule are equal in all directions. The lower volume causes mainly an increase of contact points between granules. It does not necessarily generate a change in shear forces and thus nor changes in granule skeleton. The increase of contact points however indicates an increase of soil stiffness. This causes soils to be more stiff at increasing depth.

Distortion refers to the change of granule shape without a volume change. Granules deform due to an uneven increase in loads causing an unequal increase of shear stresses at contact points. In general distortion causes larger soil deformations than compression. A continuing distortion may however lead to weaker soils (Verruijt, 2010). The consequential change in granule skeleton is an irreversible process. The original granule structure cannot fully restore to its original state in case effective stresses decrease back to their original state. Soils therefore react stiffer after its first loading and unloading.

If additional load is placed on a soil the slow process of pressing water out of pores in aquitards causes an immediate increase of water stress (Cirkel, 1985). The pressed out water flows to aquifers or drains surrounding these poor-permeable layers. The time of this process, also called hydro-dynamic period, (equation in Appendix H) depends on the speed of outflowing water and hence on the soil's permeability (Van Asselen et al., 2019). The water pressure will thus slowly decrease back to its original state due to the mentioned outflow. The additional placed load will now gradually be carried more by the granule skeleton: in the end a new balance should be reached. The soil deformation does however not stop after the water stress is reduced to its original state.

Creep
Creep is the process of granule structure reorganization. It is additional to the consolidation process and therefore the two processes are mostly considered together in explanations of subsidence mechanisms. The exact process of creep is not understood yet. Next to a reorganization of the granule stacking, the main physical process explaining creep is that during consolidation phase water is pressed out of macropores, whereas during creep phase water is expelled from micropores causing a further decrease of volume (Ten Bosch, 2020). Creep is not directly induced by effective stresses and therefore it also occurs after the hydro-dynamic period.

Terzaghi described the compression of a soil logarithmically, however since consolidation and creep are related to time it can be best described by the equation of Koppejan, who combined Terzaghi's law and findings of Keverling-Buisman (Van de Ven, 2016):

$$\Delta z = Z\left(\frac{1}{C_p} + \frac{1}{C_s} log\frac{t}{t_0}\right) ln\frac{\sigma'_2}{\sigma'_1} \tag{2.1}$$

Where:

Δz	Compression of layer [m]
Z	Thickness of compressed layer [m]
C_p	Primary compression constant [-]
C_s	Secondary compression constant [-]
t_0	Unit of time [d]
t	Loading time [d]
σ'_1	Original effective stress [kN m^{-2}]
σ'_2	Effective stress after increase of load [kN m^{-2}]

In general, sand is barely compressible. Peat may cause large deformations due to its large compressibility. Peat layers however do not swell in case of an unloading. Clay contrary does swell in case of unloading. This compressibility and ability to swell (elastic behaviour) is important to take into account when looking at periodic changes in a soil's stresses.

Clinch
As stated in Table 2.2, clinch is referred to as the process of increasing effective stresses due to decreasing groundwater level. This drop might be caused by either an artificial lowering of the surrounding surface water levels, or due to seepage, (extensive) drainage, evaporation or water uptake by roots. It should be elaborated that a lower groundwater level indicates both an increase in effective stress due to decrease of water pressure and a decrease of effective stress due to decrease of weight (less water). The first process however has a larger influence and therefore dominates for soil compression.

Shrinkage
The periodical compaction and swell of unsaturated soil due to an increase and decrease of suction pressure is called shrinkage (Van Asselen et al., 2019). Shrinkage mainly causes cracks near the surface due to a shortage of weight (Chen & Lu, 2018). Deeper in the soil, these cracks are pressed together due to the weight of overlaying soil. Shrinkage in deeper soil layers therefore causes mainly subsidence. The three stages of shrinkage describing the extent of soil volume change as result of water volume change are clarified in Appendix H. The volume decrease in clay soils is almost equal to volume decrease of water. More water might be evaporated at peat soils due to the high water content, causing a large volume reduction than at clay soils.

2.3.3. Degradation of organic material
Peat originated through the saturated accumulation of humus in past thousands years (Erkens et al., 2016). It consists for 23 to 100% of organic materials, mainly carbon elements and nutrients (Van den Akker et al., 2007). The saturated condition is of importance for peat: decrease in saturation degree -oxidation- starts a process of decay of organic material (Van Asselen et al., 2019). This process is possible due to direct exposure

of organic material to oxygen in the unsaturated zone, or to lesser extent due to chemical oxidators in saturated peat layers.

The decay of organic material causes a change in volume and structure of peat soils and therefore compaction. Moreover it induces an emission of greenhouse gasses (Erkens et al., 2016), as well as eutrophication of surrounding surface waters. Amongst other factors the soil moisture content, available oxidators and chemical elements, temperature, and pH influence the oxidation rate. Oxidation of peat is generally irreversible: in theory degradation of organic material due to oxidation stops only if no organic material or oxygen is present anymore. Oxidation therefore causes no swell. Theoretically however, could peat layers swell due to such an extensive increase of hydraulic head that underlying light peat layers are fully unloaded (Van den Akker et al., 2007).

2.3.4. Interaction of subsidence mechanisms

Subsidence mechanisms are described separately or combined with (empirical) equations, example given consolidation and creep in saturated zones (Koppejan, 1948) or degradation of organic material (Van den Akker et al., 2007). It is important to note that various subsidence processes might occur simultaneously and influence each other (Ten Bosch, 2020). In unsaturated zones loss of organic material results in a loss of soil's water retention capacity and thus more extensive shrinkage. Contrary, extensive shrinkage causes cracks in soils resulting in penetrating air and thus oxidation of present organic material. Furthermore, degradation of organic materials is sometimes incorporated in creep estimations which might affect the components' extents (Ten Bosch, 2020). Oxidation nonetheless effects compression and consolidation parameters by decrease of permeability (Zain, 2019). Shrinkage however is independent of soil compaction (Peng et al., 2012). It is clear that distinction of separate subsidence mechanisms and hence their extent is complex.

2.3.5. Measuring and modelling of subsidence

Subsidence might be a very slow process of only a few millimeters per year. Therefore effects of subsidence can only be noticed by inspecting surface levels for a longer time span, say a few months, years, or even decades. Moreover, the height of surface levels should be measured multiple times per year (Van Asselen et al., 2019) in order to observe seasonal trends such as drought. Subsidence can either be measured via field measurements or remote sensing, discussed below. Afterwards subsidence modelling is covered briefly.

Field measurements

Various field measurement techniques exist to assess subsidence. Most common is to compare measurements from surface level elevations by a transit or theodolite with a solid reference level, for example a rod positioned in a deeper stable sand layer (Van Asselen et al., 2019). Other field measurement techniques compute changes in elevation of various soil layers or depths by comparing variations in height of plates or anchors. For example an extensometer consisting of a rod positioned in a stable sand layer together with anchors in different layers.

Newer techniques process images by making use of remotely collecting differences in emission and reflection of radiation. Distinction is made between LiDAR and InSAR. LiDAR (Light Detection and Ranging) computes the time between laser pulses send from a scanner attached to a rod or example given a drone, and the interception of reflections, and transfers this to a height. The accuracy of LiDAR from flying scanners is in order of centimeters, while scanners attached to solid rods is in order of millimeters.

InSAR

InSAR (Interferometric Synthetic Aperture Radar) is a technique which generates radar images made by a 'scanner' attached to a satellite. Advantage of this technique in comparison to LiDAR is the coverage of large areas of precise measurements (accuracy with a magnitude of millimeters).

InSAR instruments create images, while orbiting the earth, of the amplitude and phase of radar signals sent and reflected from the earth's surface (Sataloff et al., n.d.). These images can be processed to calculate particularly the difference in phases of two (subsequent) images, which is used to estimate a change in the earth's surface level, as shown in Figure 2.7. After processing the InSAR images, there is thus no estimation of absolute surface level elevation, but rather relative displacements of the surfaces (locations) in time. The technique does not always function at smooth surfaces (water) due to a mirror bouncing effect of the signal, nor with rapidly changing objects such as vegetation (unless the signal penetrates the vegetation and measures the bare soil).

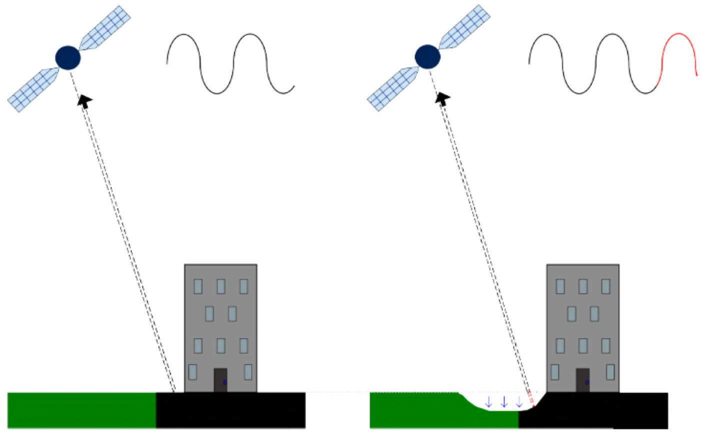


Figure 2.7: *Phase difference of two measurements due to land subsidence.* Acquired from Sataloff et al. (n.d.).

Several factors influence the measurement accuracy of InSAR. The satellite resolution determines the scanned grid cells size and thus amount of measurements. Also the precision and accuracy of radar signals and thus individual measurements depend on the satellite type. Moreover corrections of raw radar data are made for varying atmospheric conditions affecting the radar signals: temperature, pressure and humidity. The accuracy of these corrections depends on the scale (size) of analyzed areas over which atmospheric conditions are estimated through interpolation. Although these atmospheric conditions influence the individual surface level measurements if they are not exactly corrected for, they are not the leading factor for temporal changes in surface levels (Sataloff et al., n.d.). The exact influence is however not known. An overview of the InSAR information is found in Appendix B.

Subsidence modelling

Soil processes are modelled in urban areas in order to predict future subsidence due to artificial changes in loads or present water systems. Various modelling software programs are developed, ranging in scale from regional (example given province) to specific construction areas. In general these models cover the mechanisms consolidation and creep, as consequence of artificial loading and/ or (large) changes in hydraulic heads (clinch). Most models nowadays use the 'Isotache model' instead of the method of Koppejan for these calculations since it improves on the influence of temporal changes in stresses on subsidence (Van Asselen et al., 2019).

Degradation of organic materials (peat oxidation) is however excluded from most models, mainly since the focus is on artificial changes (load, hydraulic head) instead of e.g. seasonal fluxes in groundwater levels. Moreover, most models focus on undeep soil layers (Holocene) and hence exclude natural subsidence mechanisms. The compaction of deeper layers (up to 1000 meter) is merely taken into account for in models on regional scale (Van Asselen et al., 2019). Lastly, no model yet explicitly includes shrinkage in its calculations, probably due to the complexity of processes in the unsaturated zone (Van Asselen et al., 2019).

D-Settlement, a software program developed by Deltares (Deltares, n.d.), is an example of a model usable to predict (the bandwidth of) settlement during urban design stages. Several factors are taken into account at subsidence modelling in D-Settlement: soil structures via CPTs as well as compression coefficients from either in-situ testing or standardized tables, in combination with a representative average groundwater table. In practice mainly the CPT with most compressible soil structure is taken as simplified representative for the overall soil structure of (sub-)areas. This might lead to misinterpretation of local subsidence rates. Variants of site preparation strategies can be tested in the model (Deltares, n.d.) in order to determine a fit strategy which fits a residual settlement demand set by the responsible municipality (Section 2.4.2).

2.3.6. Consequences of urban subsidence

In general the extent of consequences of urban subsidence depends on infrastructure's exposure, susceptibility, adaptability, resilience and recovery capacity (Van De Ven et al., 2011). Subsidence in urban areas may have large consequences. In case subsidence is homogeneous in space, caused by deep extractions of groundwater or gasses covering a large area, it results in changes in water resources (example given change in seepage) and accordingly water management systems require adjustments. Consequences are more direct and local in case surface levels in urban areas subside heterogeneous. The consequences can be divided in direct and indirect types (Waltham, 2015). Direct consequences result in immediate damages while indirect consequences may induce larger long-term risks and hence damages.

Damage to buildings, foundations, and infrastructure is considered as direct consequence of subsidence. Uneven subsidence due to heterogeneity and complexity of urban soils leads to damage at roads, sewerage-, gas-, and water pipes (Hoogvliet et al., 2012). On top, uneven subsidence of buildings damages their structure or causes uneven connections of buildings with private areas, gardens, or streets. Extensive maintenance is needed in order to maintain the area livability, increasing the costs for municipalities, land owners and real estate owners. Maintenance costs of buildings and infrastructure in the Netherlands as consequence of subsidence is estimated to be 250 euro per person per year (Erkens, 2015).

Indirect consequences of subsidence are for example an increase in flood risks due to a larger or smaller difference between surface waters and surface levels (Vleugels, 2019). Furthermore, the water management system of urban areas might be disrupted: gradients of canals and drains change, pumping capacity is to be increased, seepage rates change, or salt water intrusion intensifies (Waltham, 2015).

2.4. Preparation of construction sites

Effective measures have to be taken in case new housing developments are planned in greenfield areas with a compressible soil in order to prepare the soil for construction of houses and infrastructure. The development of new urban areas can be divided into three phases: preparation, building, and ready-to-live (Biron, 2004). The preparation phase consists mainly of activities in order to have the construction site be accessible by foot or machine and create such bearing capacity to carry loads, example given building materials, infrastructure or houses. Improper soil structure improvements during preparation phase are considerable contributor (50%) to numerous complications during later phases (Van de Ven et al., 2007). Soft soils, mainly peat and clay, need significant improvement of their structure to satisfy the (future) conditions of accessibility and bearing capacity. The terminology 'site preparation strategy' (Dutch: bouwrijp maken) is defined in this research as the combination of (chosen parameters for) the considered methods during the preparation phase of construction sites. This section thus focuses on methods in this phase, but also on raise sequences during the living phase, to control land subsidence.

2.4.1. Soil conditions as input for site preparation strategies

Several considerations are taken during site preparation. The chosen strategy depends mainly on present subsurface and soil conditions (Biron, 2004). Table 2.3 shows an indication of soil condition aspects for distinct soil types, based on Biron (2004). The aspects accessibility & bearing capacity and water holding capacity are not covered in Section 2.1.2 yet and therefore discussed below.

Table 2.3: *Indication of soil condition aspects for various soil types.* Reprocessed from Biron (2004).

	Sand	**Fine sand**	**Clay**	**Peat**
Accessibility & bearing capacity	large	medium - large	small - medium	very small
Compressibility	small	small	medium	very large
Water holding capacity	small	large	large	large
Permeability	large	medium	small - large	small

Accessibility & bearing capacity
Greenfield areas need to be accessible by construction workers and their equipment during construction phase. Heavy equipment used during construction also need a sufficient bearing capacity in order not to 'sink' into soft soils. Same applies for buildings and infrastructures, even after preparation and ready-to-live phase, though/ hence these constructions are carried by (shallow) foundations, footings or slabs. The bearing capacity of a site depends on granules distribution, soil's volume weight, subsurface moisture content and suction pressure (Biron, 2004). Soil structure improvement is needed in case greenfield areas lack sufficient bearing capacity to be accessible or to build upon, which is mainly practiced by sand raises. Sandy soils or well drained clay and peat soils raised (with sand) satisfy the bearing capacity requirements.

Water holding capacity
The water holding capacity describes the ability of the soil to hold water. This is mainly of importance for water uptake by plant roots and prevention of water logging. Sand has a very low retention capacity and therefore few specific species grow on this soil type. The final coverage of sandy layers with soils capable of retention of water falls out of the preparation phase scope and is included in the ready-to-live phase (Biron, 2004).

2.4.2. Soil raising methods
Since mainly locations for constructions like infrastructure or buildings need an increase of bearing capacity it raises the question if entire areas should be raised or only exclusively locations of infrastructure. Various methods can be applied in case a site is to be raised:

- *Integral fill method*
  A complete raise of site. No distinction is made in sand layer thickness for different functions.
- *Excavation method*
  A raise of parts of site where needed (infrastructure). Gardens, embankments and parks might be raised with other (mixed) soil types. The sand layer thickness depends on required bearing load of specific functions.
- *Partial fill method*
  A complete raise of site, with exception to parks and water bodies.
- *Alternatives*
  Different alternatives exist in order to minimize or avoid subsidence (Egyed et al., 2006). Examples are filling with light materials such as EPS, vulcanized granules (Bims or Flugsand), lava stones, foam concrete). Alternatively self-carrying constructions might be used, such as constructions on rods, Modieslabs, Watershells, or constructions on footings.

The suited method is chosen by trade-off between urban- & water management plan, soil characteristics, costs and organisational procedures (Van de Ven, 2016). In the Netherlands, municipalities set a requirement for the residual subsidence after the preparation phase. The requirement, which has mostly a magnitude of 10, 20, or 30 centimeters in 30 years, guarantees the municipality an indication of subsidence and hence a certain degree and planning of maintenance and costs. Constructor companies design land raises in such a way that it satisfies the given requirement. Several aspects should be considered in the calculation to satisfy the demand, which are explained below.

2.4.3. Required freeboard and drainage depth
Two most important criteria disputable during the preparation phase are the drainage depth and the required freeboard (Biron, 2004), shown in Figure 2.8.

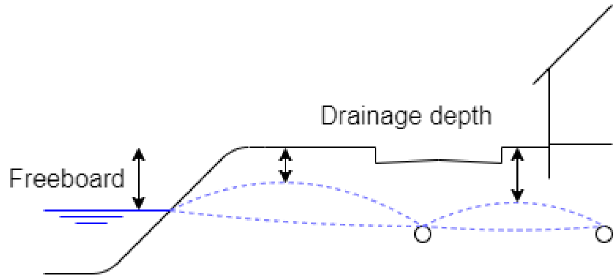


Figure 2.8: *Overview of freeboard and drainage depth.*

The freeboard is described as distance between surface level and surface water level. The freeboard is determined by the maximum acceptable water level increase and gradient between paved urban area and edges of the surface waters for runoff. The freeboard moreover influences the depth of groundwater levels surrounding the surface waters.

The drainage depth is defined as design (minimum) depth of the groundwater level in center of two surface waters or drainage pipes. A minimum drainage depth is needed in order to construct and maintain infrastructures and to keep them unfrozen in cold periods. The extent of bulge of this groundwater level is influenced by inflow (infiltration) and outflow (drainage) of water in the subsurface or soil, and moreover the distance of surface waters or drainage pipes, characteristics of drainage pipes (example given diameter), and soil permeability (Appendix H). The required drainage depth depends on (sub-) surface functions above the bulge and drainage pipes. In general distinction of required drainage depths is made for crawl spaces, cables & (sewerage) pipes, streets, and vegetated areas.

Disconnection techniques
Disconnection techniques are used to decrease the paved area connected to (combined) sewer system and therefore reduce the load of rainwater in these systems (Biron, 2004). Various disconnection techniques exist. Examples are creating storage or infiltration facilities, for example porous pavement, infiltration beds, -basins or -trenches, and wadis. A three-step-strategy is introduced in the year 2000 in the Netherlands in order to prevent rainwater nuisance in wet periods and drought in dry periods: retain, store (or infiltrate), and discharge rainwater (Reinders, 2000). These techniques thus infiltrate more water in surrounding soils and hence help to reduce groundwater level drops in dry periods.

2.4.4. Thickness and material of cover layer

Sites need raising in case the bearing capacity or freeboard of a site is to be increased. Soft soils start to subside as consequence of soil raising. Therefore a larger thickness of cover is needed in order to satisfy a net-raise, as shown in Figure 2.9. The required soil (sand) volume is calculated using a soil balance (Appendix H). For the excavation method excavated soil for ditches and sewer trenches is used to raise the surface level, accomplishing a minimal soil transport. At the integral method the bulging of groundwater, controlled by drain distance, determines the soil (sand) layer thickness. A financial optimisation between costs of drainage structure and soil (sand) can be made to optimize the fill layer's thickness.

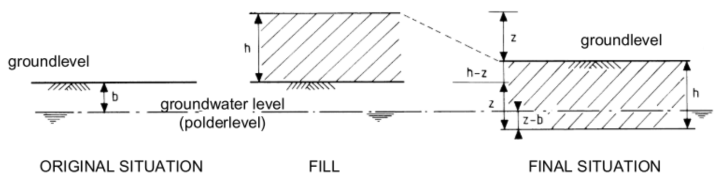


Figure 2.9: *Overview of estimating the net raise.* Acquired from Van de Ven (2016).

As explained in Section 2.4.2 various alternatives exist for raising soils. These alternatives mainly reduce the top soil's weight in order to reduce additional subsidence (settlements) as consequence of the raise. These methods are not further covered.

2.4.5. Acceleration of the consolidation process

Raising and subsequent subsidence takes time until an acceptable residual subsidence is expected. This duration can financially be optimised according to three factors: interest loss of invested capital, interest loss of acquisition costs of the area, and maintenance costs after the raise (Van de Ven, 2016). The first two factors increase with a longer filling time, while maintenance costs decrease due to less subsidence after raising. Consolidation is however generally accelerated in-practice to cohere to construction schedules which are tight due to large demands for housing.

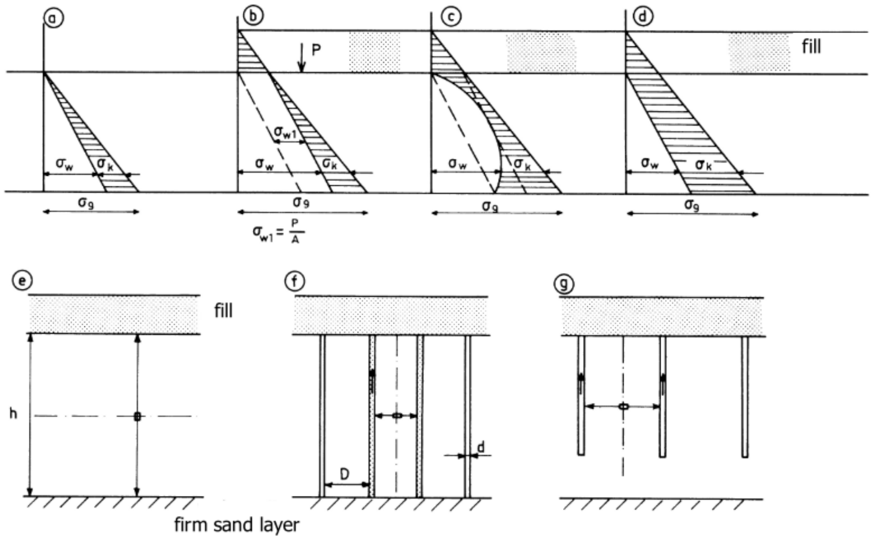


Figure 2.10: *Sand raise and vertical drainage concepts.* Acquired from Van de Ven (2016).

Figure 2.10 illustrates present stresses prior to soil raise (a), increase of water pressure in aquitards as result of soil raise (b), and decrease of water pressure through time to its original condition (c & d). Acceleration can be achieved by means of temporarily extra increase of sand layer thickness resulting in a larger over-pressure of water and hence a quicker discharge and compaction. Moreover, the distance groundwater has to cover to be discharged out of soft layers (Figure 2.10, e) is shortened if vertical drainage is installed (f) resulting in larger discharge and hence quicker compaction. This drainage should remain above the underlying aquifer (g) if its hydraulic head rises above the surface level. Other methods to accelerate subsidence are for example IFCO (conceptualized by companies), where deep horizontal drainage pipes are placed in equally deep sand trenches to accelerate groundwater flows.

2.5. Recent studies on drought-induced subsidence

So far this chapter provided a theoretical overview of soil processes, drought, and site preparation strategies. This section ends the theoretical framework by providing a brief review of (recent) studies on the impact of drought on subsidence rates.

Various publications are found which cover general impacts of drought on soil movements, however an exact extent of subsidence rates is mostly not mentioned. General subsidence mechanisms, including influences of drought via clinch, shrinkage and peat oxidation, are covered by for example Van Asselen et al. (2020) and explicitly by Van den Akker et al. (2007). Drought impact on (heterogeneous) subsidence and its consequences in urban areas is greatly covered by Brolsma et al. (2012). An estimation of the consequential costs of urban drought on subsiding soils is also estimated (Hoogvliet et al., 2012).

Groundwater level drops affecting surface level movements are regarded to as cause by STOWA (n.d.) in their publication Deltafact: Drought and heat in cites. Machairas (2020) did not include subsidence as indicator for soil moisture drought, but solely groundwater drought. Raising groundwater levels reduces subsidence considerably (Broughton & Canada, 1984). The study of De Lange et al. (2009) however is an example which indicates both soil dehydration via evaporation and transpiration (soil moisture depletion) and hence groundwater level drops as generator of subsidence. De Lange et al. (2009) also include drainage and (horizontal) seepage as other causes of groundwater level drops and hence heterogeneous subsidence.

Few publications include an estimation of the extent of drought impact on subsidence rates. Erkens & Kooi (2018) mention degradation of organic material, clinch and shrinkage to be important subsidence processes, however in urban areas settlements as consequence of loads induce subsidence to much greater extent. A memorandum about subsidence in the Dutch city of Gouda describes a drought impact of several millimeters extra subsidence in 2018 (Van De Ven et al., 2017). Furthermore, one prior in-practice study is preformed for the municipality of Den Haag (Tolk, 2020) in where the 2018 drought is analyzed by comparing satellite images with the reference period 2010-2020. An estimated extra irreversible subsidence of 1 to 2 millimeter in drought-risk areas is found. The hypothesis regarding extent of drought-induced subsidence for this research therefore is:

Soft-soil (with present clay and/ or peat layers) urban areas in the Netherlands are prone to irreversible surface level subsidence of 1 to 2 millimeter as consequence of extreme (groundwater and/ or soil moisture) drought in summer 2018.

Kwakernaak (2015) describes decreasing groundwater levels as subsidence stimulant not only in the Netherlands but also abroad (Jakarta). Most international publications regarding drought and subsidence focus mainly on groundwater extractions as result of higher water demands during drought, examples given in California, USA (Faunt et al., 2016) (Miller et al., 2020) and Tehran, Iran (Pirouzi & Eslami, 2017). Moreover, subsidence is delayed to groundwater level fluctuations (extent yet unknown) due to elasticity and creep in both aquitards and aquifers in China (Xue et al., 2005). Drought causes both vertical and horizontal soil movements due to varying groundwater levels (Kalimantan, Indonesia), however vertical displacements have larger amplitudes than the horizontal component, which is relatively small (Heliani et al., 2020). Therefore, this research focuses only on vertical movements of surface levels due to drought.

Also regarding the soil characteristics literature can be found on estimations of their influence. In general, geology and land use influence damage levels of drought-induced subsidence (Corti et al., 2011), although they only researched damage on nationwide scale in France. More compressible soils are expected to subside more due to drought (Van De Ven et al., 2017). Pavement types are already covered in this chapter: fully paved areas only evaporate if water is present (ponding). Therefore unpaved areas are expected to result in more extreme surface level movement due to a higher infiltration capacity and transpiration through present vegetation giving larger soil moisture content and groundwater level fluctuations. This vegetation is therefore expected to have a negative influence via these water components: vegetated areas result in larger (irreversible) subsidence (de Lange et al., 2009) (Hommes, 2017). Lastly, based on theory, surface water is expected to have influence on groundwater levels (and hence subsidence rates) only on short distance (Brolsma et al., 2012).

Subsurface infrastructure

Parijsch, Culemborg

February 2021

3
Methodology

Current literature covers large parts of the relationships between drought and soil movements, as described in Chapter 2. The exact in-practice influence however is not yet fully examined. The relations between subsidence, drought and local characteristics: pavement type, soil structure, vegetation, surface water, and current missing links as derivation of the research questions are shown in Figure 3.1. This chapter covers the consecutive research activities required.

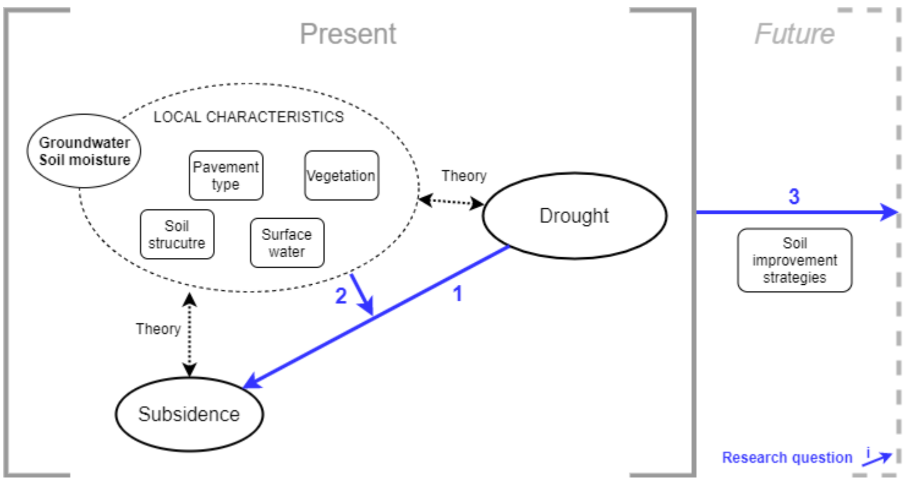


Figure 3.1: *Relation between drought, subsidence and local characteristics including associated research questions.* The blue arrows correspond to the research (sub-)questions defined in Chapter **??**.

3.1. Research methodology concept

The research is conducted descriptively by analyzing data at specific locations to find correlations between drought and subsidence. First the relationship between drought and soil processes is analyzed qualitatively by comparing time series graphs of subsidence, cumulative precipitation surplus, soil moisture content and groundwater level. Afterwards the impact of drought on subsidence is analyzed quantitatively by relating surface level movements in time intervals to its accompanying precipitation surplus. The objective in this analysis is to either accept or reject the hypothesis proposed in Section 2.5.

The data used in the quantitative analysis moreover is separated upon spatial zones within the study area based on present local characteristics shown in Figure 3.1. Afterwards the results of same analyses but of a second study area are compared to the first analyses results, in order to verify the hypothesis testing and outcomes. Suggestions on enhancing site preparation strategies are given in Chapter 6 in order to further improve urban (water) systems and hence minimize (drought-induced) subsidence.

3.2. Research framework

A research framework is set up in order to interpret the required order of activities. The research framework, shown in Figure 3.2, is divided into four phases: processing of acquired data, analysis of data, comparison of results with a case study (verification), and translation of results to in-practice mitigation strategies. The phases and activities are explained in following sections.

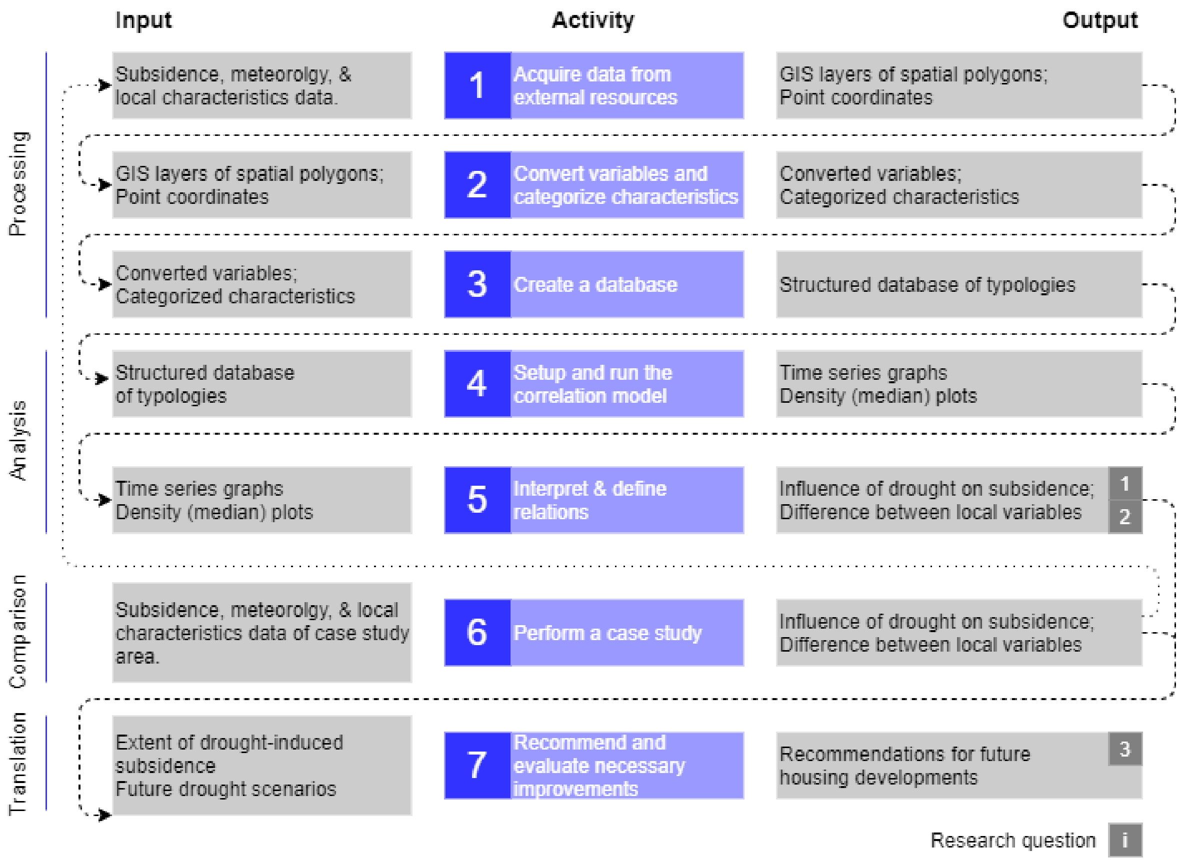


Figure 3.2: *Research framework.*

3.3. Data processing

The goal of the data processing phase is to convert the acquired external data, shown as parameters in Figure 3.1, into convenient data to be analyzed. The phase consists of three activities: data acquisition, data categorization and conversion, and database creation.

3.3.1. Acquisition of data from external resources

Data of subsidence (relative surface levels), meteorology (cumulative precipitation surplus), groundwater levels, and local characteristics is gathered from external sources. Soil moisture content data is not acquired but rather calculated via the Urban Water balance Model of Deltares based on various variables (acquired from KNMI) . Table 3.1 shows the acquired data and corresponding type, source, and kind of layer structure. The overlap in time of temporal varying data is of high importance to analyze their interdependence: if time series do not overlap no comparison of the processes can be made. The specific locations and acquired data are included in Chapter 4.

Table 3.1: *Acquisition of data from external resources.* [1] Cumulative precipitation surplus data consists of time series of precipitation, temperature, wind speed, relative humidity, and net radiation. [2] Consultancy or other companies often gather information regarding urban areas to advice municipalities or other public instances and hence possess this information. [3] Legal document (could contain a map) of Dutch water authorities consisting of rules and dimensions regarding water bodies and -system.

Data	**Type**	**Source**	**Layer structure**
(Relative) Surface levels	Time series	Bodemdalingskaart.nl	Locations
Cumulative precipitation surplus [1]	Time series	KNMI weather stations	Locations
Groundwater level	Time series	Municipality / Water board / Companies [2]	Locations
moisture content	Time series	Urban Water balance Model & KNMI weather stations	Areas
Soil structure	Cone penetration test results	Dinoloket / Companies [2]	Locations
Pavement type	TOP10NL map	PDOK	Areas
Vegetation	Percentage maps of trees and bushes	Atlas leefomgeving	Areas
Surface water	Legger [3]	Water board	Areas

3.3.2. Conversion and categorization of data

The acquired data is to be transformed into useful information before it can be analyzed. This section firstly explains the conversion of time series of subsidence (relative surface levels), meteorology (cumulative precipitation surplus), groundwater and soil moisture. The conversion consists of taking raw data and modify it (calculate, accumulate, group, average, medialise, etc.) to usable and comparable data. Afterwards the categorization of local characteristics is discussed. A categorization is needed in order to be able to differentiate analyses to specific locations and to reduce the amount of analyses to be conducted. The categorization of these local characteristics results in two data typologies (Stevens, 1946): nominal data, which is a determination of equality: a division of data into classes or numbers; or ordinal data, which is a determination of greater or less: a division of data based on medians or percentiles. A detailed overview of conversion steps of subsidence and cumulative precipitation surplus and groundwater is found in Appendix C and of soil moisture in Appendix D.

Subsidence

The change in surface level over time intervals (periods) is to be known in order to determine the impact of dry/ drought periods on subsidence rates. Subsidence data consists of time series of relative changes in surface level for many locations in an area, as observed by a satellite. As explained in Table 3.1 subsidence data is acquired from bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020), an initiative of Nederlands Centrum voor Geodesie en Geo-Informatica in collaboration with several other Dutch companies, universities and institutes. One of these companies, SkyGeo, processes and visualises the gathered raw satellite radar images (InSAR, Section 2.3.5) by means of corrections (Appendix B) to a nationwide map of relative changes in surface levels. The time series acquired need several conversion steps (Figure 3.3) in order to reduce the noise and next to distinguish the change of surface levels over the determined time intervals.

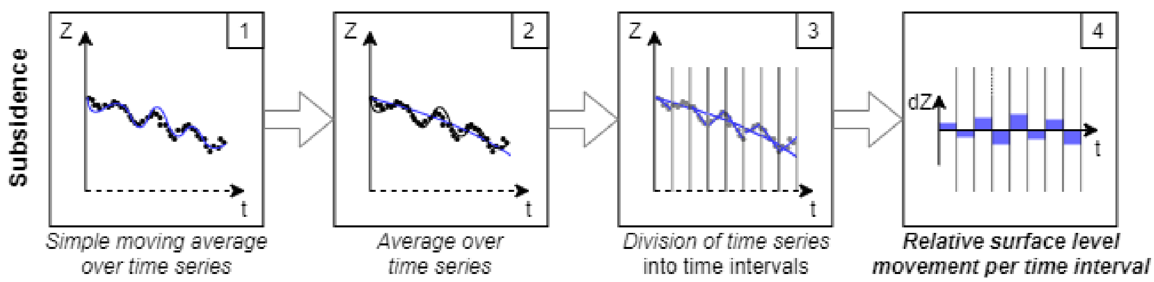


Figure 3.3: *Conversion of subsidence time series to relative surface level movements per time interval.*

1) In order to remove possibly existing noise of surface level data firstly a centered simple moving average (SMA) is constructed over the time series. Chosen is to have the SMA centered to not induce a lag/ delay within surface level data. The SMA is optimized by minimizing the mean absolute differences between SMA calculations and surface level observations for a range of moving average window sizes, as explained in Appendix C. **2)** As explained in Section 2.3 subsidence in induced by multiple factors and therefore the average subsidence is not essentially directly related to droughts. The average subsidence is computed to be thereafter outweighed of the analysis. **3)** A division of time series in intervals is based on the SMA graph's peaks and valleys in order to differentiate the subsidence data for dry and wet seasons. **4)** The relative surface level movement is calculated for every time interval to be the surface level change difference between average subsidence and SMA:

$$Z_{var} = \overline{\Delta Z} - \Delta Z_{SMA} \tag{3.1}$$

Where:

Z_{var}	Relative surface level movement in a time interval [mm]
$\overline{\Delta Z}$	Change over average surface level in a time interval [mm]
ΔZ_{SMA}	Change in simple moving average (SMA) in a time interval [mm]

The observations located on buildings (roofs) are excluded from the analyses, since this research's focus is on drought impacts on surface levels (streets), whereas buildings in Dutch soft-soil urban areas behave differently because these constructions mainly have deep foundations to the solid (Pleistocene) sand layers. The distinction of observations being on roofs or other surfaces is explained at the paragraph below concerning the categorization of pavement types. The exclusion of the observations on buildings is however done after the creation of the database (see Section 3.4) in order to preserve these observations for possible later analyses which include (solely) buildings.

Cumulative precipitation surplus

This research focuses qualitatively on groundwater and soil moisture (drought), and quantitatively on precipitation and evaporation, as explained in Section 2.2. KNMI defines a drought by, amongst other, cumulative potential precipitation deficits of areas. To be able to interpret the extent of drought or wetness of a period first few adjustments at this calculation method are required. An overview is given in Table 3.2, followed by a more detailed description.

Table 3.2: *Differences between calculation steps of KNMI and this research.* The Urban Water balance Model is a product of Dutch company Deltares (Brolsma & Vergroesen, 2020).

KNMI calculation	Research calculation
Usage of potential evaporation data via Makkink method	Usage of actual evaporation data via Urban Water balance Model
Cumulative precipitation deficit	Cumulative precipitation surplus
Fixed time intervals of summer & winter half years	Time intervals based on precipitation surplus

The main difference with KNMI calculations is usage of actual evaporation instead of potential evaporation. The actual evaporation improves process estimations since it is more specified to local context. This modification via Urban Water balance Model (Brolsma & Vergroesen, 2020) is given in Appendix D. Furthermore, the terminology *cumulative precipitation surplus* is used instead of *cumulative precipitation deficit* since this research focuses on both dry and wet periods (the differences). Lastly, fixed time intervals of KNMI do not exactly overlap drought time intervals (Section 2.2) and therefore time intervals based on peaks and valleys (maximum and minimum values) of cumulative precipitation surplus are used to account for the variability of drought duration throughout years.

The Urban Water balance Model requires open water evaporation and potential reference crop evapotranspiration data in order to calculate actual evaporation. This can then be used together with precipitation data to calculate cumulative precipitation surplus. Open water evaporation is calculated via Penman (Schuurmans & Droogers, 2010) by acquired temperature, relative humidity, net radiation, and wind speed time series from an open database of weather stations data of KNMI (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a). Potential reference crop evapotranspiration is estimated to be approximately 0.8982· Penman Evaporation

(Brolsma & Vergroesen, 2020). Precipitation data is directly acquired from aforementioned KNMI database.

The conversion of meteorologic data to cumulative precipitation surplus is shown in Figure 3.4. **1)** Firstly atmospheric data is modified in the Urban Water balance Model (Appendix D) to actual evaporation. **2)** The actual evaporation data is subtracted from precipitation data and cumulated resulting in cumulative precipitation surplus. **3)** The time series graph is divided into biannual seasons (dry/ wet time intervals) based on yearly peak (start of drought) and valley (end of drought) of cumulative precipitation surplus. No further separation of drought in shorter time intervals (and thus smaller extent) is considered since subsidence is a slow process having only changes in longer time spans (months), as explained in Section 2.3. **4)** The difference in cumulative precipitation surplus per time interval (between start and end) is calculated in order to estimate the extent of drought or wetness of time intervals.

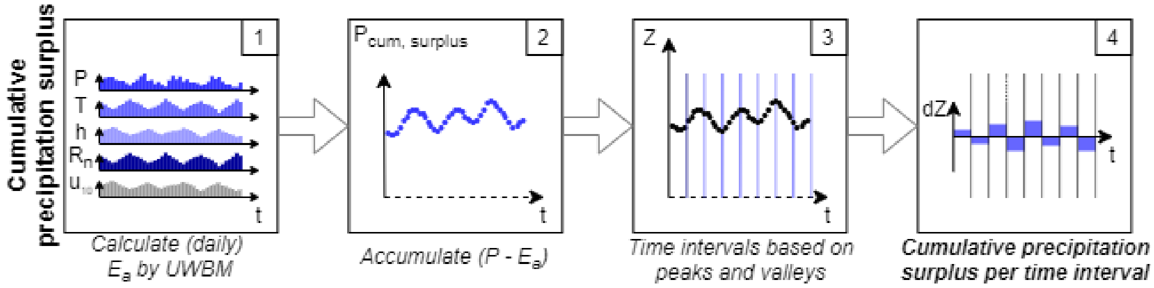


Figure 3.4: *Conversion of raw precipitation & variables for open water evaporation data (temperature T, relative humidity h, net radiation Rn, wind speed at 10 meters height u10) via Urban Water balance Model (Brolsma & Vergroesen, 2020) (UWBM) to cumulative precipitation surplus data.*

Groundwater regime

Groundwater levels are measured in urban areas by wells. The groundwater data is collected via municipalities, water authorities or companies (Table 3.1) and consists of time series of groundwater levels with respect to NAP. The depths of groundwater therefore could be determined by knowing the surface levels elevation w.r.t. NAP. If multiple groundwater wells are situated in an area (and surroundings) resulting in same-like groundwater levels a regime is constructed to display an approximated range of present groundwater levels. The use of multiple groundwater time series increases the trustworthiness of groundwater variations in the region. This groundwater regime thus consists of the minimum and maximum values of groundwater measurements and calculated median groundwater level from these groundwater measurements in surrounding area (Appendix C).

Soil moisture

Soil moisture time series are not directly acquired from external resources, but rather calculated by Deltares' Urban Water balance Model (Brolsma & Vergroesen, 2020) as explained in Appendix D. This model calculates change in soil moisture content per day to be infiltrated precipitation minus evapotranspiration and percolation. The evaporation rate is limited by the potential (open water) evaporation, while the infiltration is limited by the infiltration capacity of open paved areas (closed-paved areas do not infiltrate in the model). The resulting soil moisture content data is not further modified afterwards.

Soil structure

Cone penetration tests, commissioned by municipalities, are executed by geo-technical companies from which the results are used to estimate the general soil structure of an area. As explained in Section 2.1.1 soil types are classified based upon present granule sizes. Figure 3.5 shows the steps required to estimate the compressibility of soils based on the soil type classification from cone penetration tests results (Section 2.1.3). A detailed overview of cone penetration tests and the categorization into compressibility is found in Appendix A.

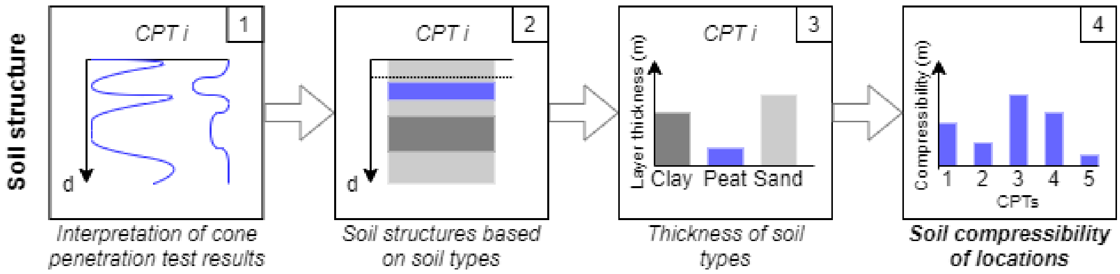


Figure 3.5: *Categorization of soil compressibility based on the soil structure derived from cone penetration test results.*

1) Firstly CPT results are digitized and the boundaries of obtained CPT variables for classification of soil types (Appendix A) is determined. **2)** Next, a general soil structure is constructed by categorizing classified soil types into sand, clay or peat. **3)** The total thickness of each soil type is calculated. **4)** Lastly, data is categorized ordinal for each CPT based on 20/80 percentiles of combined thicknesses of sand, clay and peat resulting in either a low, medium, or high compressibility. The rule of thumb derived from Te Groen (2016) is used as estimation for compressibility from combined thicknesses:

$$C = 0.5 \cdot \Delta P + 0.2 \cdot \Delta C \quad (+0 \cdot \Delta S) \tag{3.2}$$

Where:

C	Compressibility of soils [m]
ΔP	Thickness of peat layer [m]
ΔC	Thickness of clay layer [m]
ΔS	Thickness of sand layer [m]

Pavement type

If at locations no constructions like buildings or surface water are present the surface can either be paved or unpaved. The pavement type determines the infiltration capacity and evaporation intensity and hence the variation in groundwater level and soil moisture content, as explained in Section 2.2.3. The infiltration capacity and soil evaporation intensity are almost equal to zero for closed-paved soils. This affects the soil's moisture content and groundwater level. The acquired maps of the study areas from PDOK (open access database) (PDOK, n.d.) are processed in GIS and categorized nominal to be either unknown (gardens), buildings (roofs), unpaved (bare soil, grass/vegetation); open-paved (for example cobblestones); or closed-paved (for example asphalt). The distinction of the pavement type corresponding to a single surface level observation location is done by the GIS Geo-processing-tool 'Clip'.

InSAR signals barely function for vegetated and thus (most) unpaved areas, as explained in Section 2.3.5. However, this surface type is included in the analysis since observation locations are located on unpaved terrain in both areas. The radar signals resulting in these observations might be reflected by a small rod or a stone present in the unpaved terrain, or the signal pierces the present vegetation and is reflected by the soil surface itself. The usage of this data is, despite the uncertainty, the best possible option to analyze the influence of pavement types (since other data types in the observed area and time span lack, and moreover might be less comparable to the InSAR data). The uncertainty is taken into account in the analysis of the data.

Vegetation

Unpaved areas have either a bare soil surface or vegetation. The local characteristic vegetation is defined in this research to be either bushes or trees, and hence no grass (which is mainly considered in the pavement type analysis). Among others the type and size of vegetation determines their water use (Kjelgren et al., 2016). A vegetation map, acquired open access from Atlas Leefomgeving, is created as combination of acquired bushes and trees percentage maps. The rule of thumb used by Atlas Leefomgeving for differentiation between bushes and trees is the height of 2.5 meter. There is no differentiation made based on types of vegetation. The acquired maps have a raster structure of 10x10 meter wherein for each cell the percentage of area of bushes respectively trees is given. The percentage of vegetation per cell is estimated by adding the percentages of bushes and trees. Categorization is made ordinal at 10/50 percentiles (instead of for example 20/80, since not many cells consist of high vegetation percentages due to the urban infrastructure) resulting in a low, medium or high vegetated area.

Surface water

Surface waters influence groundwater levels in their surrounding area, shown in Figure 3.6 and explained in Section 2.4.3. The estimated extent of the length of this influence zone depends on precipitation or evaporation intensities and moreover the soil's permeability and present freeboard (Perrochet & Musy, 1992) as shown in equation 3.3. Such values are chosen to estimate the maximal possible influence zone length to include all possible influenced subsidence observation points.

$$L = H\sqrt{\frac{K}{N}} \tag{3.3}$$

Where:

- L Length of influence zone of surface water [m] as assessed by Perrochet & Musy (1992)
- H Freeboard [m]
- K Soil permeability [m $\cdot d^{-1}$]
- N Precipitation or evaporation [m $\cdot d^{-1}$]

The location and water level of surface waters is acquired from a so-called *Legger*, a legal document (might contain a map) of Dutch water authorities with information consisting of rules and dimensions regarding water bodies and -system. The areas are categorized nominal by differentiation on being either within or outside surface water influence zones.

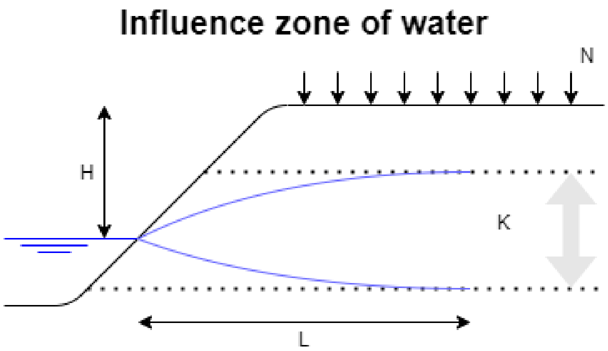


Figure 3.6: *Simplification of the estimation of influence zone distance L.*

3.3.3. Creation of a database

A database is created after the conversion and categorization of parameters. Two steps prior to the creation of the database are however required: a spatial and temporal transformation. A detailed overview of the temporal transformation is found in Appendix C.

Spatial transformation

Table 3.1 shows parameters have either a location or area structure. The locations where distinct data is observed might not exactly overlap each other. The created database however should satisfy corresponding information for subsidence data observation locations to compare these. Cumulative precipitation surplus and groundwater data cover the entire area and thus do not require a spatial transformation. Moreover, soil moisture data is modelled via the Urban Water Balance and hence also does not need a spatial transformation. Soil structure (CPT) data however requires the transformation since it differs within the area and multiple CPTs can be acquired per area. Therefore its CPT location structure is transformed to an area structure to overlap subsidence data locations.

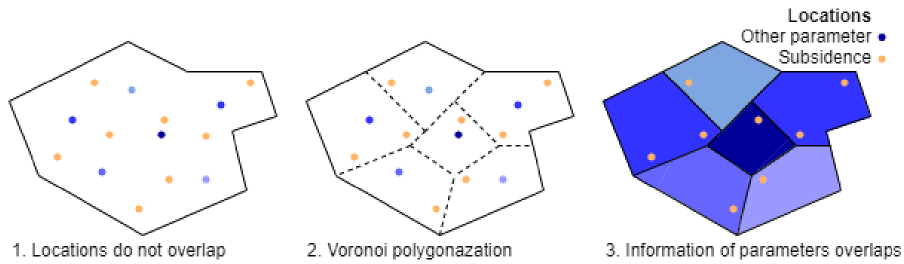


Figure 3.7: *Transformation of a location structure to an area structure.*

This transformation is done through the Voronoi method using GIS, conceptualized in Figure 3.7. This method divides areas into such zones that all segments within these zones are closest to their accompanying locations (Gold et al., 1997). The Voronoi method is only a rough estimation of the soil structure due to the heterogeneity of the soils on small scale. Other methods, for example to have the representative areas based on a certain maximum distance from the CPTs (resulting in circles) as is done for surface waters, would however exclude many subsidence observations without guarantee of improving the precision. Moreover it is chosen to not include a weight for the trustworthiness of compressibility calculations at subsidence observation locations based on the distance between observation location and its corresponding CPT, mainly also due to the small-scale heterogeneity of soils. After polygonization by Voronoi method the data can be extracted and compared for specified subsidence coordinates.

Temporal transformation

Subsidence data and cumulative precipitation surplus data are divided into time intervals based on their peaks and valleys (Section 3.3.2). The start and duration of the time intervals may differ, referred to as *lag* and *difference in duration* as shown in Figure 3.8. Lags are calculated by difference (in days) between peaks of cumulative precipitation surplus (start of dry season) and peaks of surface levels (start of intensified subsidence: compaction). Although lags cannot be negative, the model can calculate lags to be negative in case the model 'chooses' a wrong peak, due to the noisy data, of the relative surface level, as shown in Figure 3.9. Difference in duration of the time intervals is calculated by comparing the time spans (in days) of the decreasing cumulative precipitation surplus (drought period) and decreasing surface levels (compaction period), in order to verify hysteresis of soil wetting and drying (Section 2.3.2). A positive difference in duration indicates a longer time span of intensified subsidence (compaction) than drought. Surface levels continue to subside for longer time after a drought ended. This also means the subsequent swell has a shorter time span. A negative difference in duration indicates that a soil swell takes, relative to the drought duration, longer than a soil compaction.

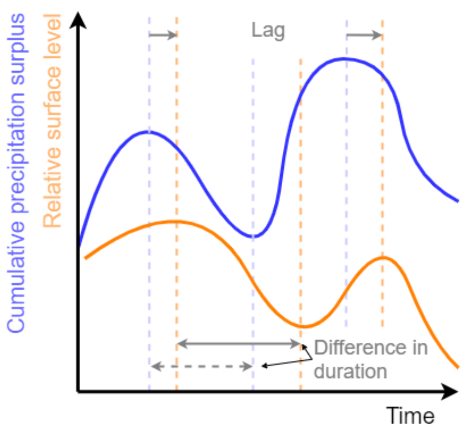


Figure 3.8: *Lag and difference in duration between cumulative precipitation surplus and relative surface level movement.*

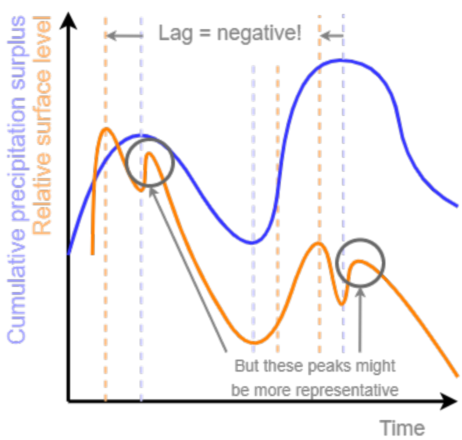


Figure 3.9: *Possible calculation of negative lag as result of model inaccuracies.*

Database structure

The resulting database structure is given in Figure 3.10. Each subsidence location *i* coheres with a certain variation in subsidence and cumulative precipitation surplus during time interval *j*. Furthermore, subsidence locations are linked to a compressibility, pavement type, percentage of vegetation, and possibility to be influenced by surface water. The area's representative soil moisture content and groundwater level are not included into the database since their time series are solely analyzed qualitatively.

Study location	Relative surface level movement	Cum. prec. surplus	Compress-ibility	Pavement type	Vegetation percentage	Surface water influence
A	i_1, j_1	i_1, j_1	i_1	i_1	i_1	i_1
A	i_1, j_2	i_1, j_2	i_1	i_1	i_1	i_1
⋮	⋮	⋮	⋮	⋮	⋮	⋮
A	i_1, j_n	i_1, j_n	i_1	i_1	i_1	i_1
A	i_2, j_1	i_2, j_1	i_2	i_2	i_2	i_2
⋮	⋮	⋮	⋮	⋮	⋮	⋮
A	i_m, j_n	i_m, j_n	i_m	i_m	i_m	i_m
B	i_1, j_1	i_1, j_1	i_1	i_1	i_1	i_1
⋮	⋮	⋮	⋮	⋮	⋮	⋮
B	i_m, j_n	i_m, j_n	i_m	i_m	i_m	i_m

Locations (latitude, longitude): i

Time intervals (-): j

Figure 3.10: *Database structure.*

3.4. Data analysis

Since the database is constructed, a comparison model can be setup. The observations situated at buildings (roofs) are however excluded prior to producing the various graphs for the analyses. This is done by for example deleting all rows in the database in Figure 3.10 having 'building' at the column 'Pavement type', and subsequently saving the database with a different name. It is chosen not to separate observation points being on buildings based on their estimated point and DEM heights (given by SkyGeo), since these points have a similar/ larger imprecision as the spatial differentiation used now.

As explained in Section 3.1 the research analysis consists of both a qualitative and quantitative part, resulting in three types of informative graphs shown in Figure 3.11: time series-, box- and median plots. These three graphs can be constructed by typologies in the database combined with groundwater and soil moisture time series. All three plots are used in a general analysis of the entire study area. Specific analyses of local characteristics however are solely done by interpreting specified median plots in order to determine differences in surface level movement between typologies of these local characteristics.

Figure 3.11: *Three types of plots analyzed: time series, box, and median plots.*

Time series plot
First a qualitative analysis is conducted by combining time series of subsidence, cumulative precipitation surplus, groundwater level and soil moisture content into one time series plot. The parameters' interdependence can be analyzed qualitatively due to this simultaneous plotting. Subsidence time series are adjusted to their *average lag* (Appendix C) between cumulative precipitation surplus peaks and subsidence peaks for each location. Furthermore, since subsidence data is measured *relatively* the reference surface level at t=0 is set equally to zero for all time series. Considering the possible large amount of subsidence observation locations and thus large amount of time series of relative surface levels a few different plots of these relative surface levels are made:

- The median of all simple moving averages of observed surface levels.
- The 5/95 and 25/75 percentiles of all simple moving averages of observed surface levels.
- A range of all observed surface levels (simple moving averages), bounded by the minimal and maximal surface levels (0/100 percentiles).

Box plot
Next a quantitative analysis is conducted by mapping out cumulative precipitation surplus versus relative surface level movements by means of a box (& whisker) plot. Objective is to interpret the extent and distribution of relative surface level movements in dry and wet periods. The box plots include the same percentiles of relative surface levels as given in the time series. The representation of percentiles in the plot is given in Figure 3.11. Drought is indicated in the box plot by a negative precipitation surplus. Moreover, a negative relative surface level movement represents intenser subsidence (compaction). Hence, a positive relative surface level movement represents a decrease in subsidence rate (swell). The first and last time intervals of the time series are removed from the analysis since these are bounded by the start and end of the time series rather than peaks or valleys of simple moving average graphs resulting in incomplete time intervals.

Median plot
Lastly an analysis is conducted by plotting the development of the median relative surface level movements together in certain time intervals with accompanying cumulative precipitation surplus in chronological order. This median plot illustrates the relationship between both parameters, but also the interdependence of surface level movements throughout time. Objective is to interpret if certain droughts resulted in (irreversible) extra subsidence and to what estimated extent. Both 25/75 and 5/95 percentiles are displayed in the median plot by vertical lines, a kind of simplification of box plots. Similar to the box plot, the first and last time intervals are removed from the analysis in this plot.

3.5. Comparison of results with a second study

After analysis of the first study area the results will be compared to a second descriptive (case) study. Purpose is to verify the hypothesis testing and additional results and hence interpret the reliability and uncertainties of results. To conduct the second descriptive (case) study the same activities as taken at the first study are to be taken: acquisition of data, conversion and categorization of data, creation of a database, setup and run the correlation model and analyze the results, and afterwards compare this to the prior study. The results of the second study are to lesser extent analyzed themselves but rather used as comparison. The comparison of the results of the two study areas is conducted qualitatively.

3.6. Translation of new insights to enhanced site preparation strategies

This research's analyses covered in Section 3.4 create an estimation of drought impacts on subsidence rates. Part of this study's objective however is to translate these gained insights to suggestions on improving site preparation strategies.

As explained in Chapter 2 the theoretical impact of drought on soil processes and hence subsidence rates depends on, among others, water availability and thus present water system in urban areas. Moreover various local characteristics might influence the extent of drought-induced subsidence. Site preparation strategies affect or are affected by soil conditions, water system and urban layout, as covered in Section 2.4. Therefore, it might be possible to minimize drought or drought impacts on subsidence by enhancing site preparation strategies.

In order to suggest constructively on enhancing site preparation strategies the research results are shared with (urban water/ site preparation) experts. These experts might interpret the severeness of drought impacts on subsidence rates and can moreover share advice on proposed enhanced site preparation strategies. This is done by conducting a questionnaire to be filled in. The (filled-in) questionnaire (Appendix E) consists of the following subjects:

- Current problems or drawbacks at estimating/modeling subsidence (explained in Section 2.3.5).
- Soil raising methods (explained in Section 2.4.2).
- Acceleration of the consolidation process (explained in Section 2.4.5).
- Drainage and de-watering (explained in Section 2.4.3).
- Reasons to enhance site preparation strategies (reaction on analyses results).
- Possible solutions to drought impacts (reaction on proposed enhanced site preparation strategies).

Construction of buildings

Parijsch, Culemborg

February 2021

4

Study areas: Diemen & Kampen

Analyses of various locations are used in order to describe drought impacts on subsidence rates. This chapter introduces the two areas analyzed: Diemen and Kampen. The chapter covers both a spatial description by maps and a description of converted and categorized parameters discussed in Chapter 3.

4.1. Diemen

Diemen is a municipality located in the south-east region of Amsterdam, in province Noord-Holland, within borders of water board Amstel, Gooi en Vecht. The analyzed neighborhood shown in Figure 4.1 is called 'Vogelweide'.

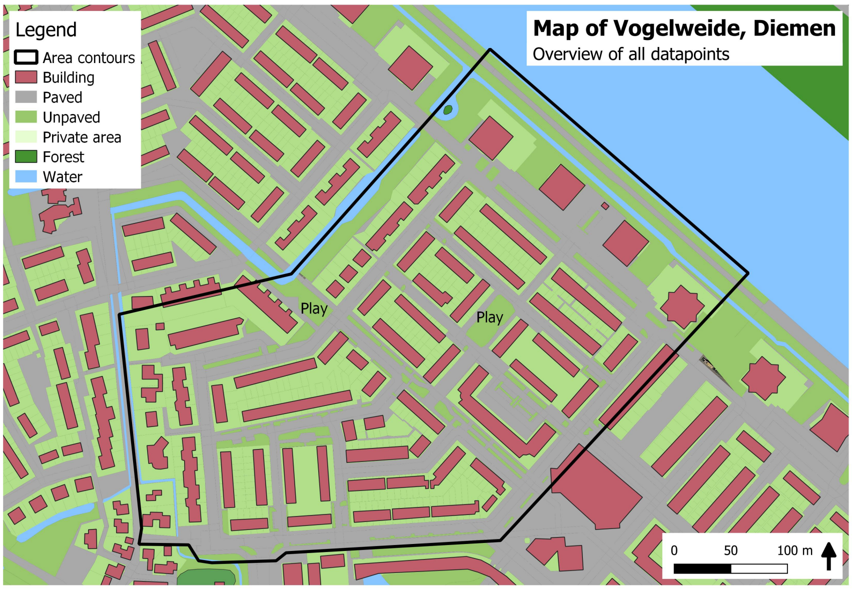


Figure 4.1: *General overview of Vogelweide, Diemen.* Locations where the phrase 'play' is located are green playgrounds.

Vogelweide was built in the late 90s as part of a larger urban area. The area is bounded north by Amsterdam-Rijnkanaal (large canal) and a small ditch. At south, east and west boundaries Vogelweide is bounded by other neighbourhoods or small ditches. The houses are structured in blocks including private gardens. In the north-east four high-rise buildings are located. These four buildings and the large canal are separated by a thin green area including a large ditch and many (large) trees (also shown in Figure 4.8). Furthermore two green playgrounds ('play' in Figure 4.1) are located in center.

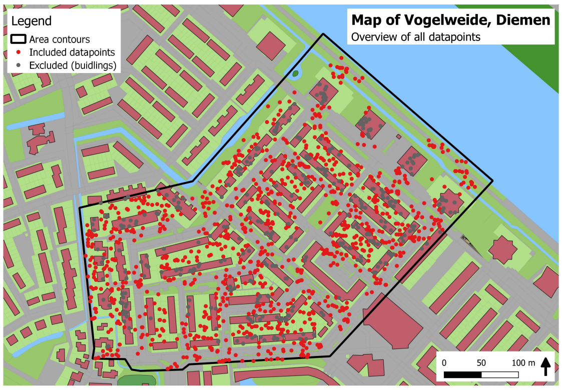


Figure 4.2: *Overview of all monitoring locations (surface levels and buildings) in Vogelweide, Diemen.*

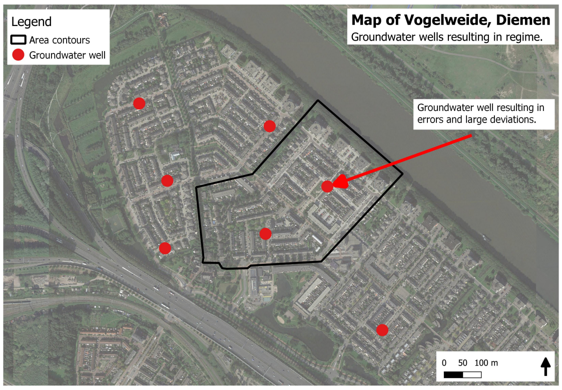


Figure 4.3: *Overview of groundwater well locations in and surrounding Vogelweide, Diemen.*

The 1400 subsidence monitoring locations, acquired from the initiative bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020), are shown in Figure 4.2. The locations are evenly spread over the area. Distinction is made between the included observations of surface levels, and the excluded observations of buildings (roofs), for further analyses. As explained in Appendix B observations have the exact same location through time however they might have spatial inaccuracy of 2 to 3 meter. The data set time series covers a time interval of winter 2015 until winter 2019. In Figure 4.3 six well locations used to describe the groundwater regime are shown. The well pointed out is located within the area, but gave many errors (no communication with device/ battery low) during the analyzed period (winter 2015 to winter 2019) and is therefore excluded from analyses.

4.1.1. Soil structure

In Figure 4.4 cone penetration test locations are shown. The numbers correspond to Figure 4.5. The locations are evenly spread over the area but are all on public terrain. The cone penetration tests are acquired from a company (Tjaden Advies, Alkmaar) which conducted the drills in 2016 for a geo-technical report of Vogelweide composed by another company, ADVIN (Te Groen, 2016).

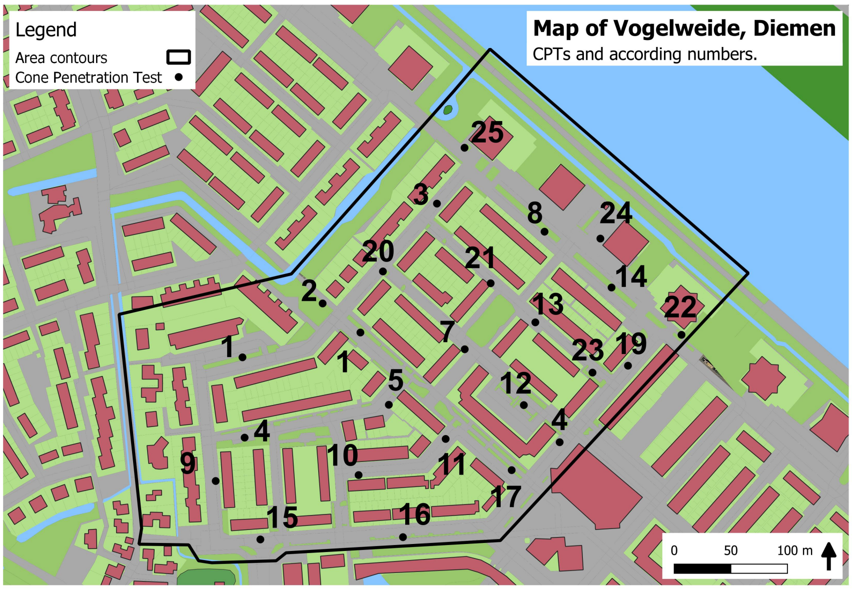


Figure 4.4: *Overview of cone penetration test locations conducted in 2016 in Vogelweide, Diemen.* Reprocessed from Te Groen (2016).

Figure 4.5 illustrates the soil structures resulting from cone penetration tests given in Figure 4.4. The soil in Diemen is in general structured by a deep solid clay layer, an in-between sand layer, with a mix of smaller clay and peat layers on top resulting in a soft layer of approximately 5 meters. Due to previous soil raises, explained in Section 4.1.3, a cover layer of sand with varying thickness is present in the entire area. Specifically CPT number 10 is pointed out, since it is different than other CPTs in clay/ peat layer thickness and sand cover thickness. The CPT is most-likely located in an old filled-in ditch, as shown in Appendix G. The soil compressibility, calculated by combining thicknesses of the different soil structures as explained in Section 3.3.2, varies between approximately 1.5 and 3 meter.

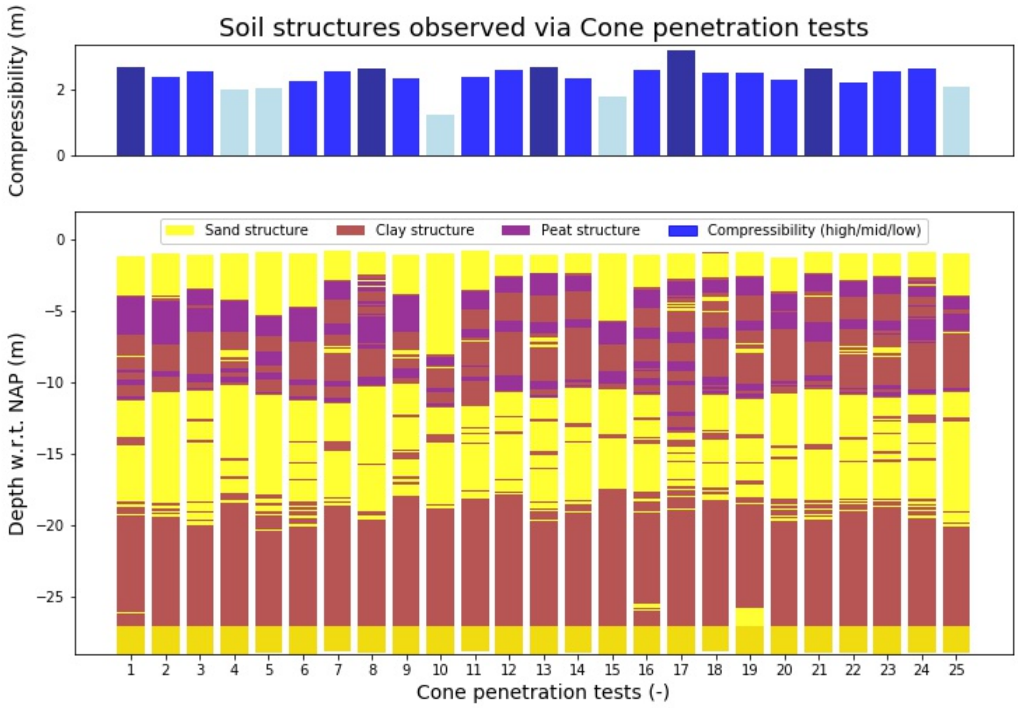


Figure 4.5: *Soil structures constructed from results of cone penetration tests in Vogelweide, Diemen.* The test numbers correspond to locations in Figure 4.4.

Figure 4.6 shows resulting categorized compressibility map of the area in Diemen. The CPT locations are polygonized based on the Voronoi method, as explained in Section 3.3.3. The spatial distribution of compressiblity is mixed. In mid-south and north corner of the area the compressibility is smallest, while in west corner and mid-east of the area the compressibility is largest.

4.1.2. Local characteristics

In the figures below local characteristics in Vogelweide are shown. Subsequently pavement types, vegetation percentages, and vicinity of surface water is discussed. The soil structure is discussed in last section.

Pavement type

Information regarding pavement types is acquired from the open-access database of PDOK (PDOK, n.d.). All subsidence locations in the area are categorized based on four pavement types (roofs of buildings, open-paved, unpaved, and unknown pavement). The close-paved type is however not present in the area. Private gardens result in unknown pavement since it is not known what type of pavement is present. Therefore, only distinction is made between unpaved and open paved areas, as shown in Figure 4.7. The area has dense streets with little unpaved areas. The unpaved terrain is mainly situated at edges and at playgrounds within the area.

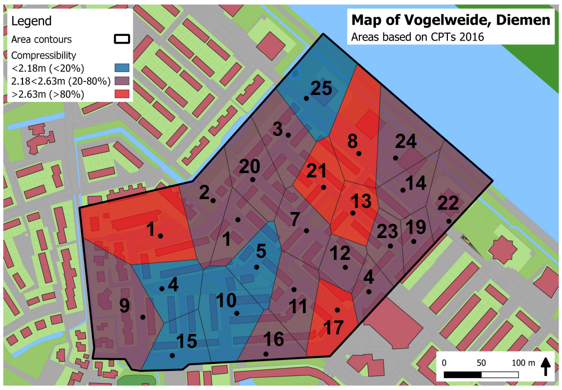


Figure 4.6: *Compressibility in zones based on polygonization of CPT locations in Vogelweide, Diemen.*

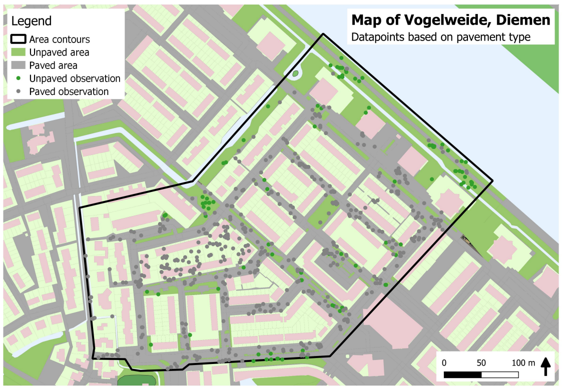


Figure 4.7: *Pavement types (unpaved, open-paved) in Vogelweide, Diemen.*

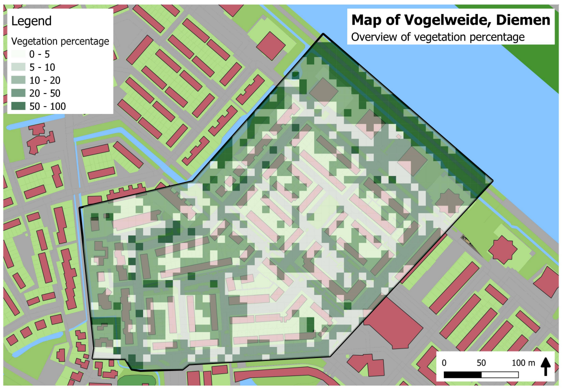


Figure 4.8: *Vegetation percentages in Vogelweide, Diemen.*

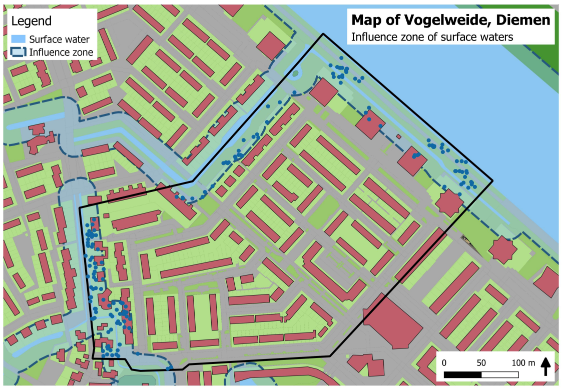


Figure 4.9: *Surface water influence zones in Vogelweide, Diemen.*

Vegetation

In Figure 4.8 the area is divided into 10x10 meter raster regarding percentage of these areas covered by vegetation acquired from Atlas Leefomgeving (Atlas Leefomgeving, 2016). The map shows clearly low vegetation percentages at urban parts of the neighbourhood with its streets, houses and gardens. Most streets however do have (small) trees aligned, positioned approximately every 10-20 meters. The surrounding north-east and -west boundaries result in a high percentage of vegetation.

Surface water

Information regarding surface waters in Diemen is acquired from an open-access map corresponding to the *Legger* from water board Amstel, Gooi en Vecht (Waterschap Amstel Gooi en Vecht, n.d.). The influence zones of surface waters are shown in Figure 4.9. Since surface waters are mainly located at boundaries of the neighbourhood, their influence zones only cover a small percentage of the area. The influence of the large canal north and ditch more inland overlap each other. The large canal has a water level (-0.4 meter NAP) above surface levels in the neighbourhood (design level of -0.8 meter NAP). The induced seepage is not taken into account since its detailed extent is unknown. In Figure 4.10 the length of influence zone (maximum of 20 meter) as result of surface level and surface water level is illustrated.

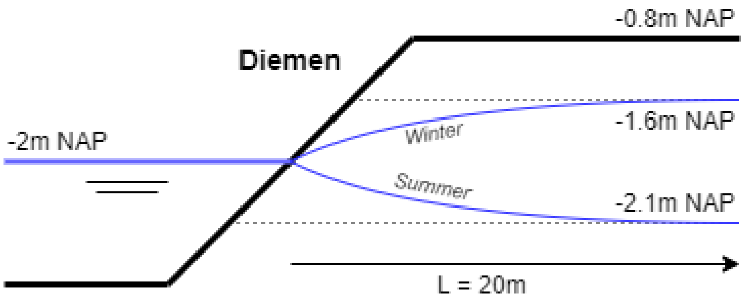


Figure 4.10: *Design surface level and surface water levels resulting in an influence on groundwater levels in Vogelweide, Diemen.* Length (L) of the influence zone is estimated by Perrochet & Musy (1992).

4.1.3. Former site preparation activities

Current subsidence in Diemen is mainly consequence of past surface level raises. Information about former site preparation activities is important to understand observed soil behaviours. The former strategies are covered in a geo-technical study of the area (Te Groen, 2016). Figure 4.11 displays the area division in zones based on the year of last raising. The 2014 zone is actually a demolished and newly built area, including buildings and private areas, finished in 2014 (Te Groen, 2016). The previous soil raises resulted in the varying sand cover layer thickness shown in Figure 4.5.

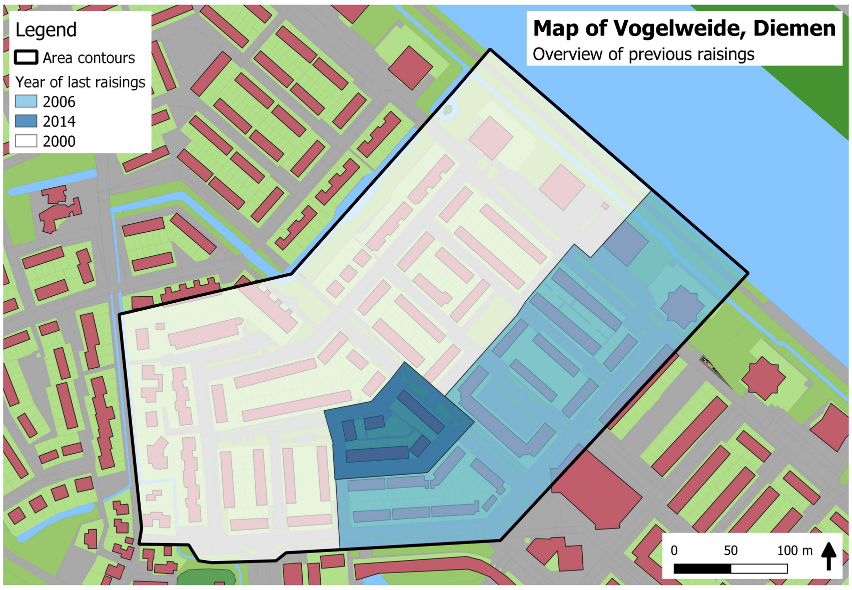


Figure 4.11: *Previous raises and newly built area in Vogelweide, Diemen.* Reprocessed from Te Groen (2016).

4.1.4. Subsidence

Surface level movements in Diemen are extracted from bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020). The relative surface levels are measured with a Sentinel-1 satellite, as explained in Appendix B. The satellite passing the Netherlands in descending direction is used since it monitors surface levels approximately at 06:00 in morning (instead of 18:00 in afternoon), having less daily temperature and evaporation influences. The so-called 'point quality' given per location indicates its measurement quality. Points with a low quality (smaller than 0.6 on range 0 to 1) are discarded at processing, indicating that the data is trustworthy. The exact atmospheric influence on each measurement is however not known.

In Figure 4.12 an example is given of the surface level observations of one location. As shown the observations have a large spread, which is explained in Appendix B to be caused by atmospheric conditions affecting satellite radar signals. Due to the low precision of surface level observations a simple moving average is constructed (Section 3.3.2) which is optimized by minimizing mean absolute differences between observation points and SMA calculations for a range of moving average window sizes (Appendix C). The optimal simple moving average, with minimal mean distance between observation points and moving average graph, has a window size of 21 days (10 days at both sides and the observation itself). As shown in Figure 4.12 the optimized SMA covers overall surface level movements but consists less peaks and valleys. The first 10 and last 10 SMA calculations are excluded from analyses since it is not known what surface level movements were prior and after the observation time interval resulting in inaccurate SMA calculations.

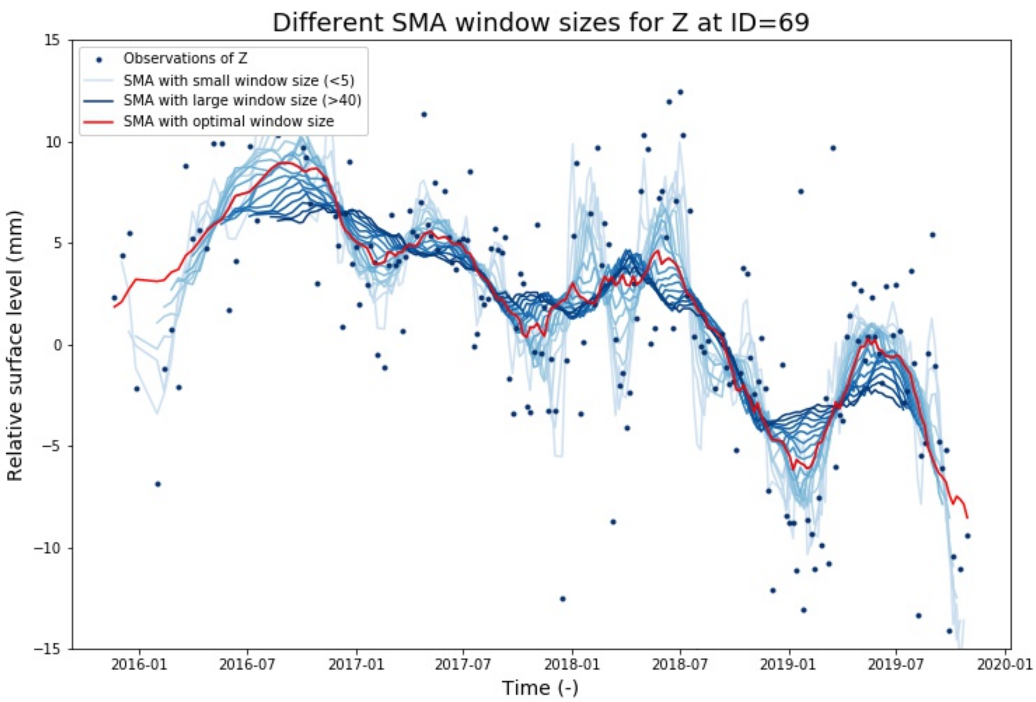


Figure 4.12: *Surface level observations, considered and optimized simple moving averages at one location in Vogelweide, Diemen.* The simple moving average is optimized (Appendix C) to have a window of 21 days (10 at both sides).

4.1.5. Cumulative precipitation surplus

Data from Schiphol weather station (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a) is used as representative cumulative precipitation surplus for the area since this location is closest to the analyzed neighbourhood in Diemen. Figure 4.13 shows an overview of both KNMI method and this research's used calculation via Deltares' Urban Water balance Model (actual evaporation). As shown the data of this research's method results in less evaporation (downward parts) than the KNMI method since actual evaporation is used instead of potential evaporation. The extent of precipitation (upward movements) is same-like.

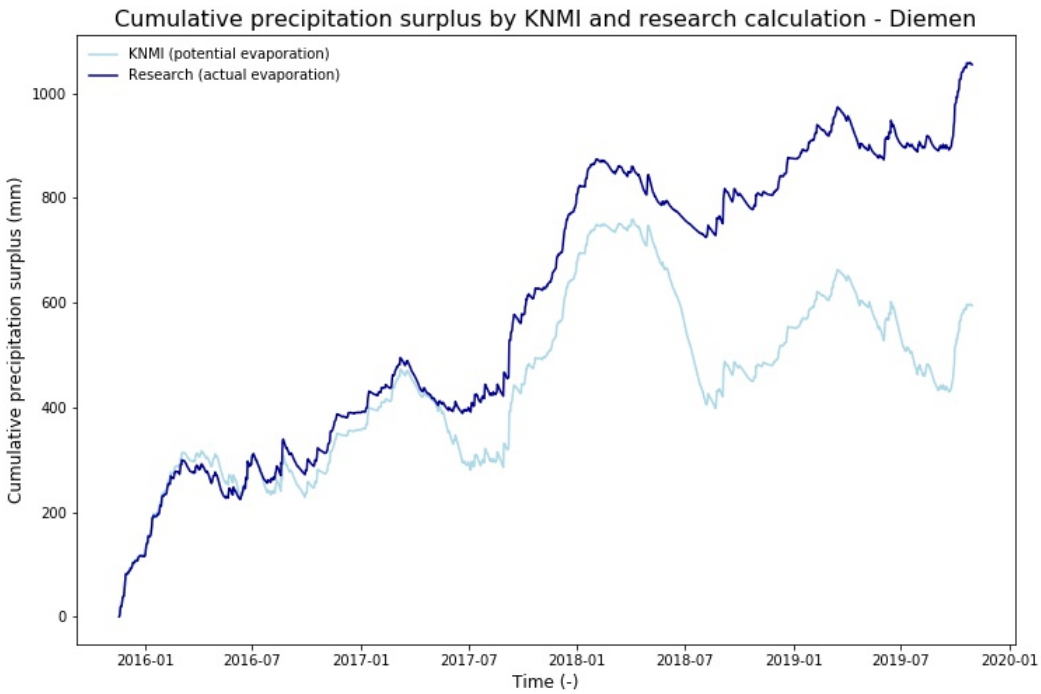


Figure 4.13: *Cumulative precipitation surplus calculated via the KNMI method (potential evaporation) and this research's used method via Deltares' Urban Water balance Model (actual evaporation) in Vogelweide, Diemen.*

4.1.6. Groundwater level

Groundwater measurements are acquired from the municipality Diemen. Several wells are present in the surrounding area of Vogelweide as shown in 4.3, resulting in approximately samelike groundwater levels. Figure 4.14 shows the resulting groundwater regime from 6 wells. Groundwater levels are measured in these wells every five minutes, however since such high temporal resolution is not needed (subsidence is measured once per 7-11 days) daily measurements are used. Daily measurements made at 06:00 are used since the satellite monitoring surface levels passes by approximately at same times. The median is used as representative for overall groundwater level movements in the area.

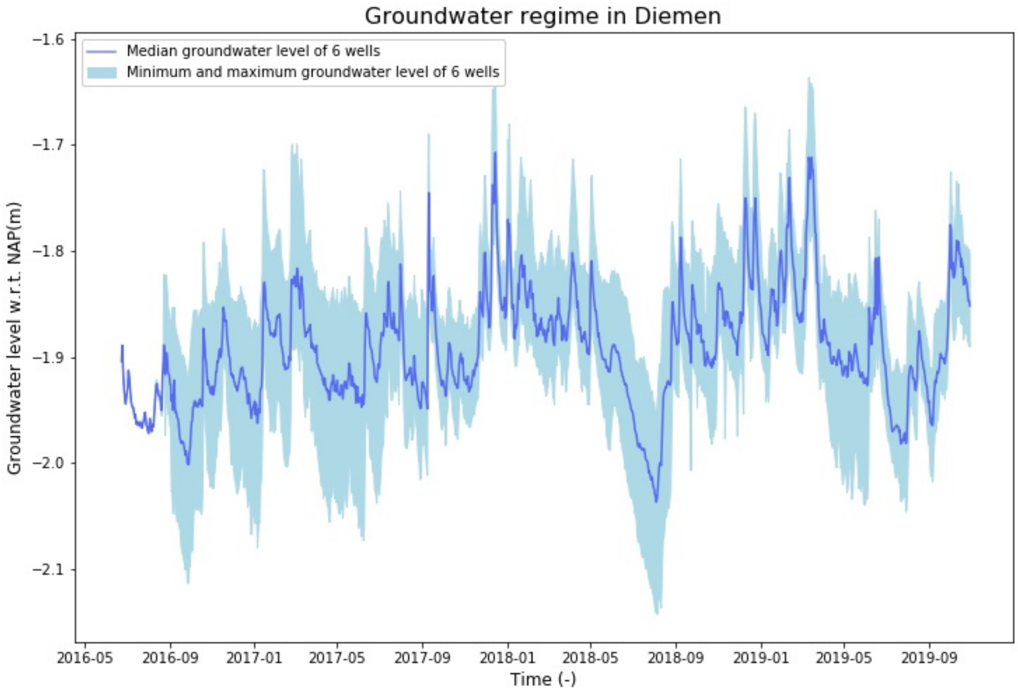


Figure 4.14: *Groundwater regime in Vogelweide, Diemen.* Groundwater regime is constructed out of 6 different wells positioned in surrounding area.

4.1.7. Soil moisture content

The soil moisture content acquired via Deltares' Urban Water balance Model (Brolsma & Vergroesen, 2020) is shown in Figure 4.15. The input needed (atmospheric conditions) for the Urban Water balance Model are acquired from KNMI (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a). Within the Urban Water balance Model some assumptions are made and input parameters are used, which are given in Appendix D. The resulting soil moisture content from UWBM is not further modified.

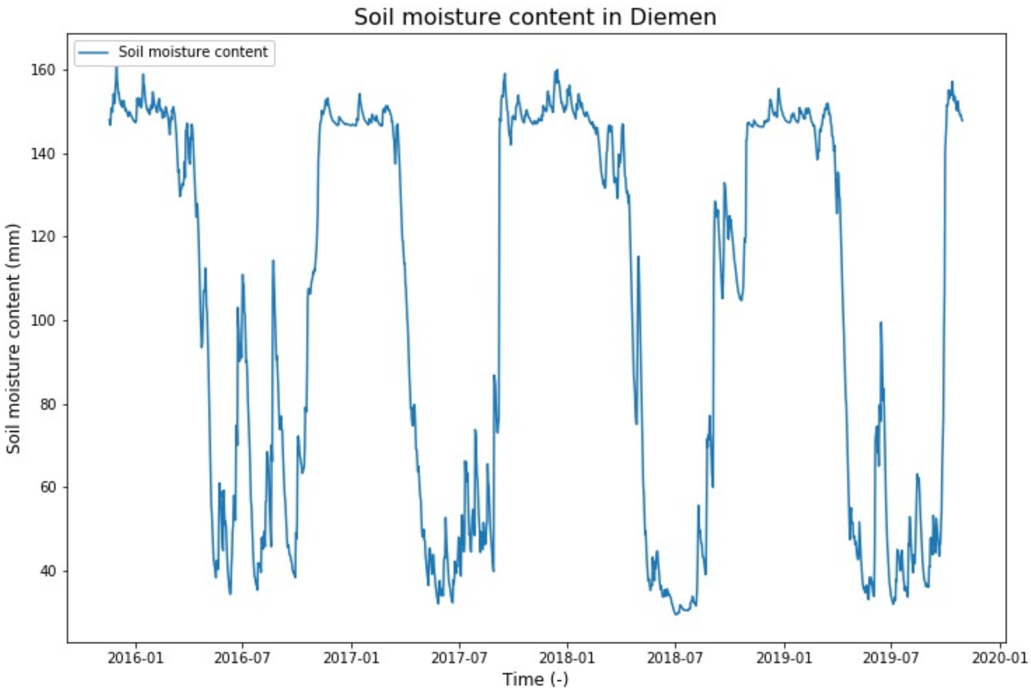


Figure 4.15: *Soil moisture content in Vogelweide, Diemen.* Soil moisture content is assessed with the Urban Water balance Model of Deltares.

4.2. Kampen

An area in the village of IJsselmuiden, municipality Kampen, in province Overijssel and within borders of of water board Drents Overijsselse Delta is used as second (case) study area. The area is called 'Het Meer' and is shown in Figure 4.16. Construction of the area started in 2016 and is approximately finished mid 2021. The area is bounded south and west by a canal, east by a large road, and in north by buildings and rural area. A green zone in the area center splits the area into two zones.

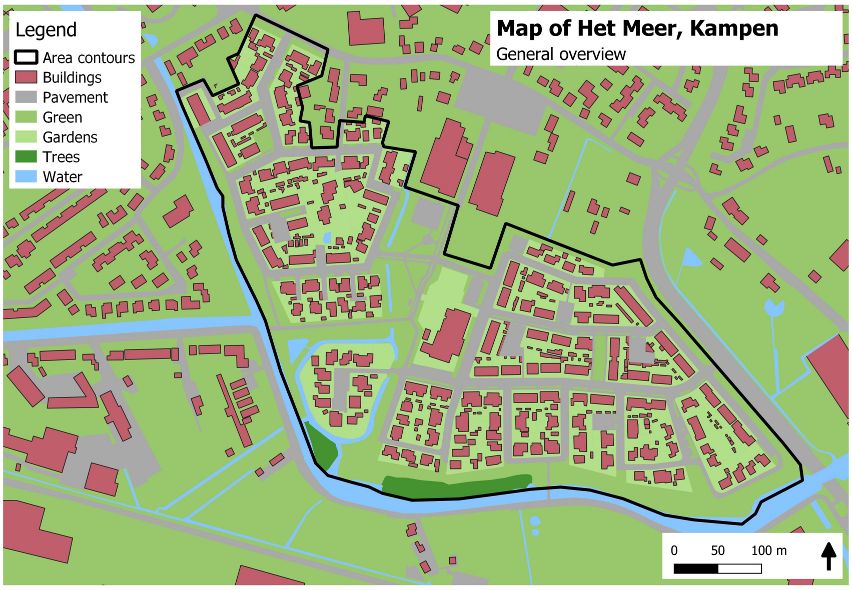


Figure 4.16: *General overview of Het Meer, Kampen.*

Figure 4.17 shows the approximately 650 subsidence monitoring locations acquired from the initiative bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020) in Het Meer. Distinction is made between the included observations of surface levels, and the excluded observations of buildings (roofs), for further analyses. Most of these are located in north-west, while in south-east almost none surface levels are monitored. Reason is that only in north-east the area was already constructed at start of the observation period (winter 2015 - winter 2019). Same-like in Diemen the spatial inaccuracy of monitoring locations is 2 to 3 meter, however during the time interval observations are made at exact same locations.

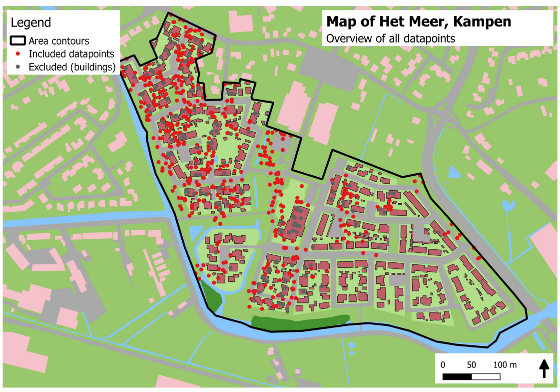


Figure 4.17: *Overview of all monitoring locations (surface levels and buildings) in Het Meer, Kampen.*

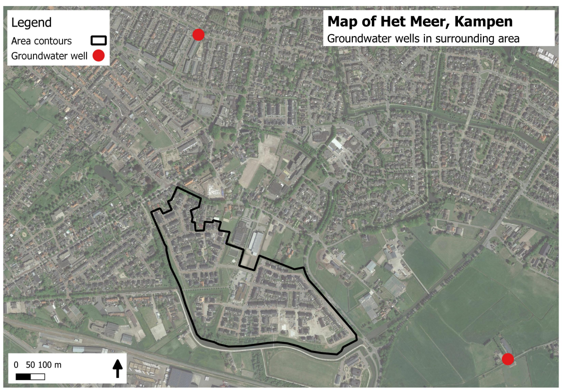


Figure 4.18: *Overview of groundwater well locations surrounding Het Meer, Kampen.*

In Figure 4.18 two well locations, acquired from water board Drents Overijsselse Delta, used to determine the groundwater regime in Kampen are shown. Although these locations are far from the analyzed area, they result in same-like minimum and maximum groundwater levels as groundwater levels within the area in an earlier period (2012). Therefore these well locations are used to determine the groundwater regime for the analyzed area.

4.2.1. Soil structure

The cone penetration locations are shown in Figure 4.19. The CPTs are commissioned by the municipality and made in 2007. The results are used in the geo-technical report of the company Witteveen+Bos for site preparation (Joppe, 2012a). The results are acquired from the company conducting the CPTs (Wiertsema & Partners, Tolbert). The numbers correspond in Figure 4.19 correspond to CPT numbers in their report.

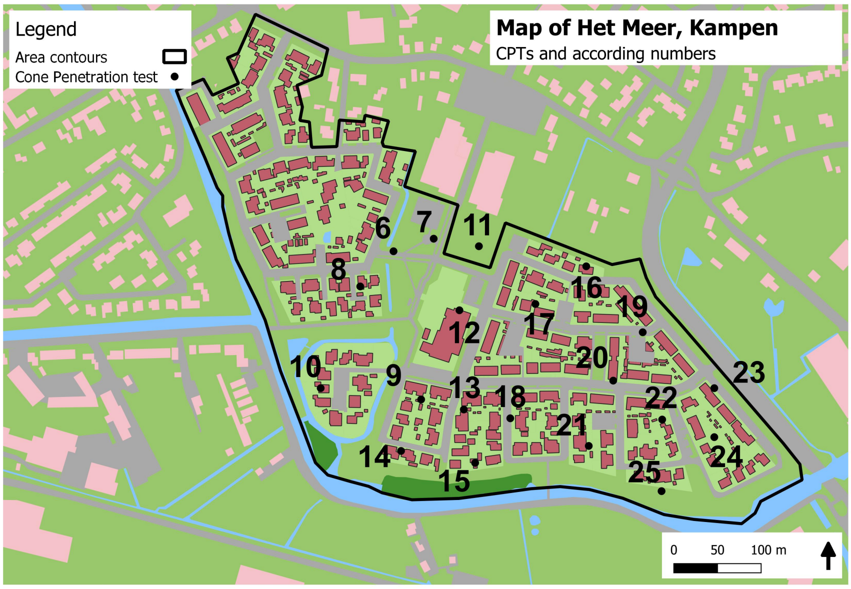


Figure 4.19: *Overview of cone penetration test locations conducted in 2007 in Het Meer, Kampen.* Reprocessed from (Wiertsema & Partners, 2007).

The soil structure estimated from cone penetration tests is showed in Figure 4.20. It does not show any cover layers since the CPT drills were executed before start of raising (2007 versus approximately 2012-2014 respectively). In general the soil structure consists of a peat layer of approximately 5 meter on top of a solid sand layer. In some locations small clay layers (or peaty clay) are however present. The compressibility, estimated by combined thicknesses of sand, peat and clay (Section 3.3.2) varies between approximately 1 and 3 meter and is thus equal in magnitude to compressibility in Diemen. The sand cover layer varies between 0.9 and 1.3 meter (Joppe, 2012a). This might cause the groundwater level to drop to the peat layers below (Figure 4.29). This is important to keep in mind in further analyses.

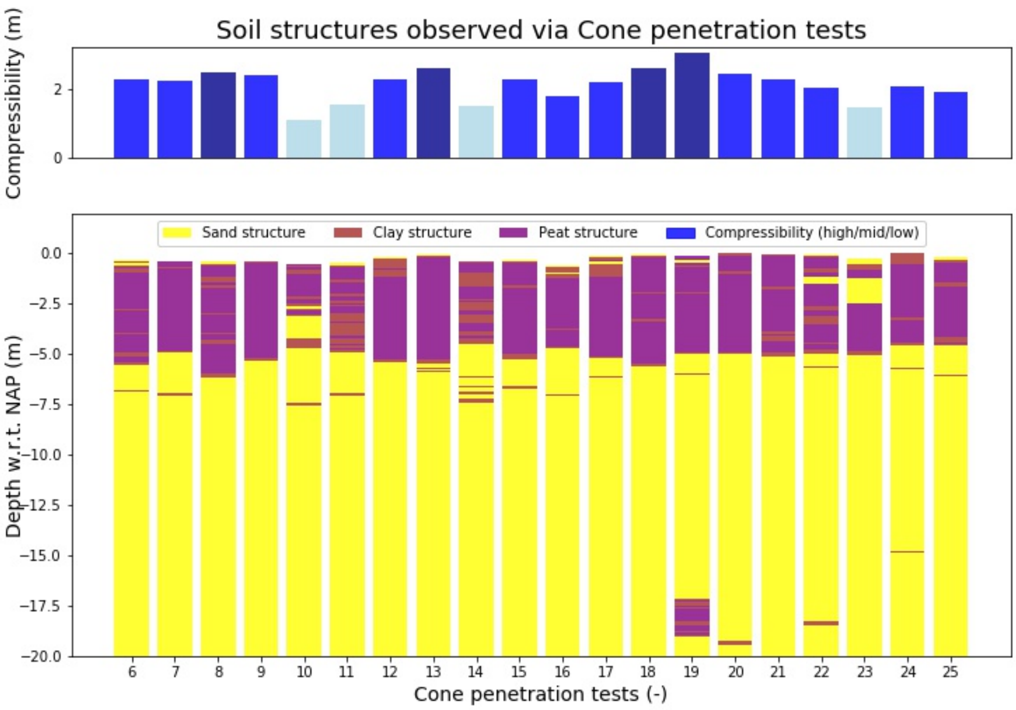


Figure 4.20: *Soil structure constructed from results of cone penetration tests in Het Meer, Kampen.* The test numbers correspond to locations in Figure 4.21.

As shown in figure 4.21 the Voronoi division of the area based on CPT locations results in a very rough estimation in north-west due to lack of CPTs. This increases the uncertainty since most subsidence observations are located here (Figure 4.17). The compressibility is spatially mixed distributed.

4.2.2. Local characteristics

The four local characteristics considered are showed below. The soil structure is explained beforehand. Pavement type, vegetation percentage and surface water is explained subsequently below.

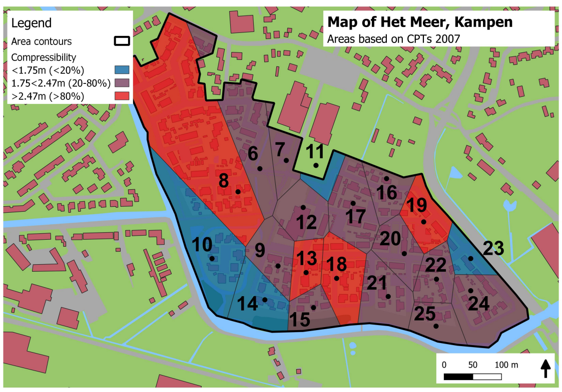


Figure 4.21: *Compressibility from CPTs in Het Meer, Kampen.*

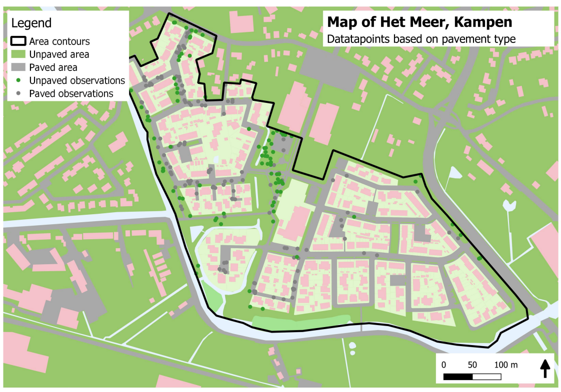


Figure 4.22: *Pavement types in Het Meer, Kampen.*

Pavement type

Information regarding pavement types is acquired from the open-access database of PDOK (PDOK, n.d.). Pavement in the area consists of either open-paved, unpaved, roofs or unknown pavement. Close-paved type is however not present in the area. Private gardens result in unknown pavement since it is unknown what type of pavement is present. The first two categories (open-paved and unpaved) are therefore used in further analyses. It is clear from Figure 4.23 that the middle and south edge of the area is mainly unpaved compared to the dense paved streets.

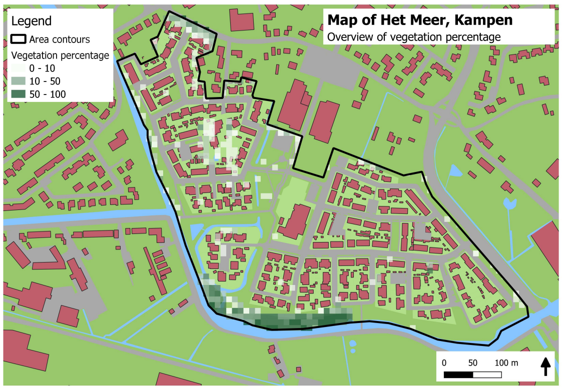


Figure 4.23: *Vegetation percentages in Het Meer, Kampen.*

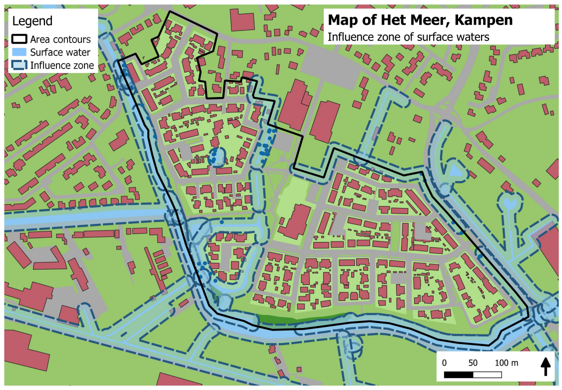


Figure 4.24: *Surface water influence zones in Het Meer, Kampen.*

Vegetation

The vegetation map, acquired from open database of Atlas Leefomgeving, in Figure 4.23 shows almost no estimated vegetation percentages in the area. Clearly the area was in construction (2012 - 2021) during the generation of these vegetation percentage maps by Atlas Leefomgeving in 2016 (Atlas Leefomgeving, 2016). This increases analysis uncertainties. A dense zone of trees is present at south borders of the area. Also in north-west vegetation (trees) is present near houses and roads.

Surface water

Information regarding surface waters is acquired from an open-access map corresponding to the *Legger* from water board Drents Overijsselse Delta (Waterschap Drents Overijsselse Delta, n.d.). Surface water is present at the edges and greenery zones of the area, as shown in Figure 4.24. The extent of influence zone of these waters into urbanized parts is therefore limited. In Figure 4.25 the length of influence zone (maximum of 10 meter) as result of the freeboard is illustrated. Moreover it is noticeable surface waters in Kampen have two design levels (winter and summer) which influences surrounding groundwater levels.

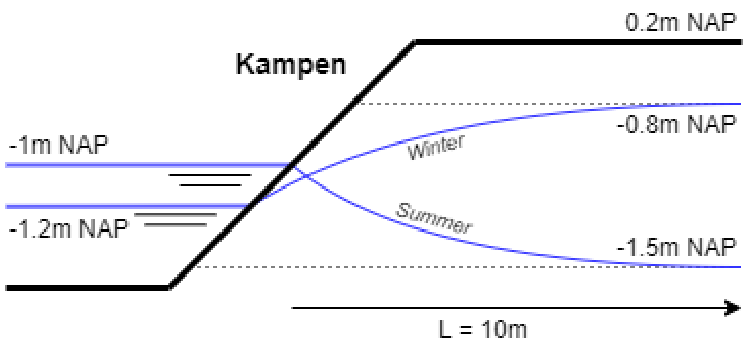


Figure 4.25: *Design surface level and surface water level in Het Meer, Kampen.*

4.2.3. Former site preparation activities

Since part of Het Meer is still in construction or just has been constructed, there are no multiple past site preparation activities to be analyzed. However, Figure 4.26 shows three zones with different preparation strategies used in 2012. The map is a rough estimation of zones from the site preparation report of Het Meer (Joppe, 2012a). The zones differ in sand cover height: approximately 1.1 meter for zone A, 1.3 meter for zone B, and 0.9 meter for zone C. Moreover, a temporary over-height of 30 days is placed on all areas with various thickness (0.6, 0.7 and 0.2 meter respectively).

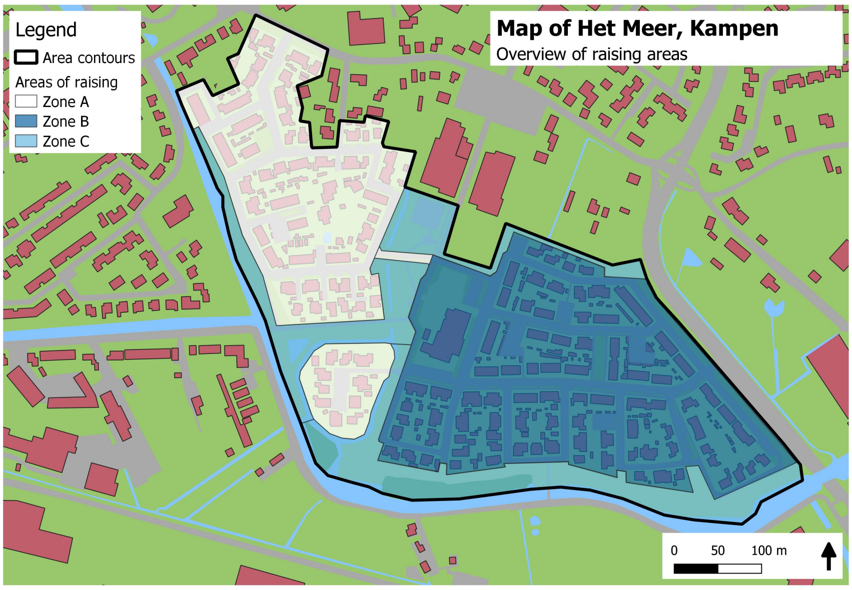


Figure 4.26: *Estimation of zones with different preparation strategies in Het Meer, Kampen.*

4.2.4. Subsidence

Surface level movements are extracted from bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020). The relative surface levels are monitored with a Sentinel-1 satellite. Data from the same satellite (descending) is used to have coherent data in Diemen and Kampen and to minimize daily temperature and evaporation influences. The so-called 'point quality' given per location indicates its measurement quality. Points with a low quality (smaller than 0.6 on range 0 to 1) are discarded at processing, indicating that the data is trustworthy. The exact atmospheric influence on each measurement is however not known.

Figure 4.27 shows an example of surface level observations of one location. As shown the spread of measurements is large due to atmospheric conditions affecting satellite radar signals (Appendix B). The simple moving average constructed (Section 3.3.2) covers overall surface level movements without having too many peaks and valleys. The SMA has an optimal window, resulting in minimal mean distance between observation points and moving average graph, of 21 (10 at both sides), which is same as in Diemen. It is not concluded if this SMA window is coincidentally exactly the same as in Diemen, or if this is since data from the same satellite and same corrections (Appendix B) is used. The first and last 10 SMA calculations are excluded from analyses since it is not known what surface level movements were prior and after the observation interval resulting in uncertain SMA calculations.

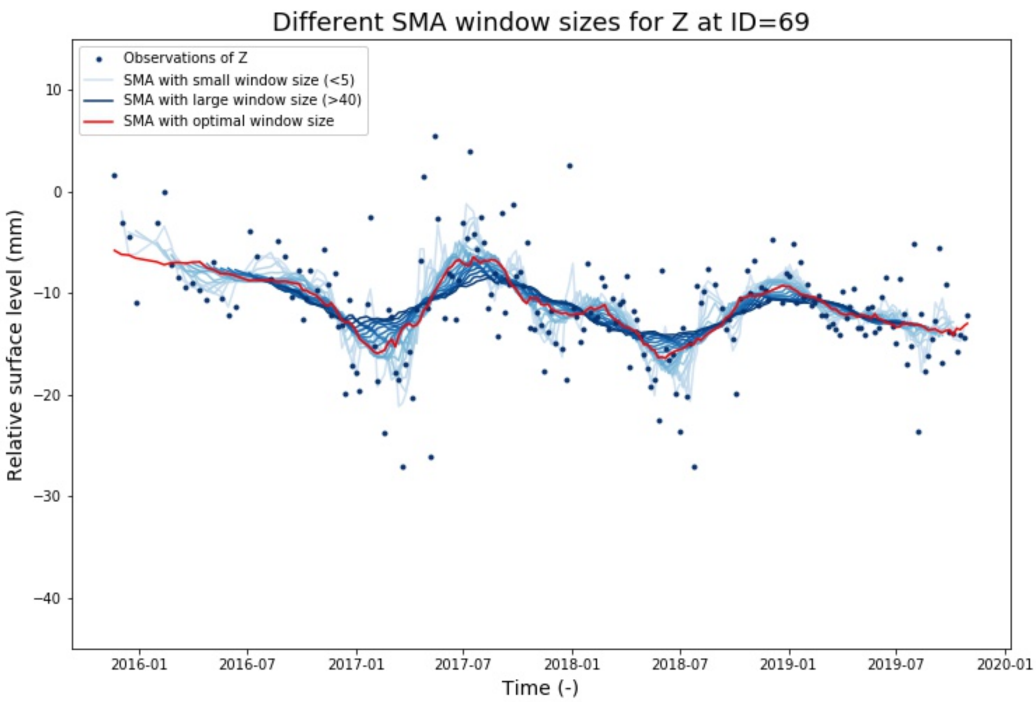


Figure 4.27: *Surface level observations, considered and optimized simple moving averages at one location in Het Meer, Kampen.* The simple moving average is optimized (Appendix C to have a window of 21 days (10 at both sides).

4.2.5. Cumulative precipitation surplus

At the calculation of representative cumulative precipitation surplus data from nearby Marknesse weather station is used (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a). Figure 4.28 overviews the difference between KNMI method and this research's method via Urban Water balance Model (Brolsma & Vergroesen, 2020) for calculations. As shown the data of this research's method results in less evaporation (downward parts) than the KNMI method since actual evaporation is used instead of potential evaporation. The extent of precipitation (upward movements) is samelike.

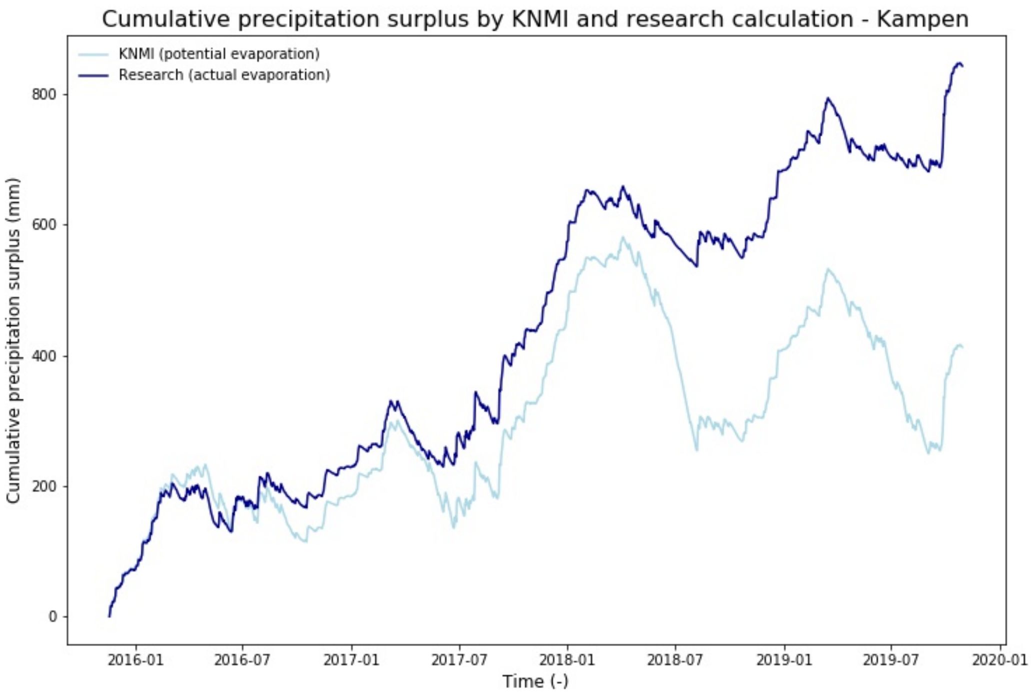


Figure 4.28: *Cumulative precipitation surplus calculated via the KNMI method (potential evaporation) and this research's used method (actual evaporation) via Urban Water balance Model in Het Meer, Kampen.*

4.2.6. Groundwater level

Groundwater measurements in Kampen are acquired from Waterschap Drents Overijsselse Delta. Monitoring wells which overlap subsidence data are not present in the area, as shown in Figure 4.18. Two surrounding wells are compared with a groundwater level analysis conducted (Roeleveld, 2012). The resulting groundwater regime of these two wells in Kampen is shown in Figure 4.29. The groundwater is observed daily, every 2 hours. Measurements made at 06:00 are used since these overlap the satellite passing and the observations in Diemen. The median of two wells is used as representative for overall groundwater level movements in Kampen.

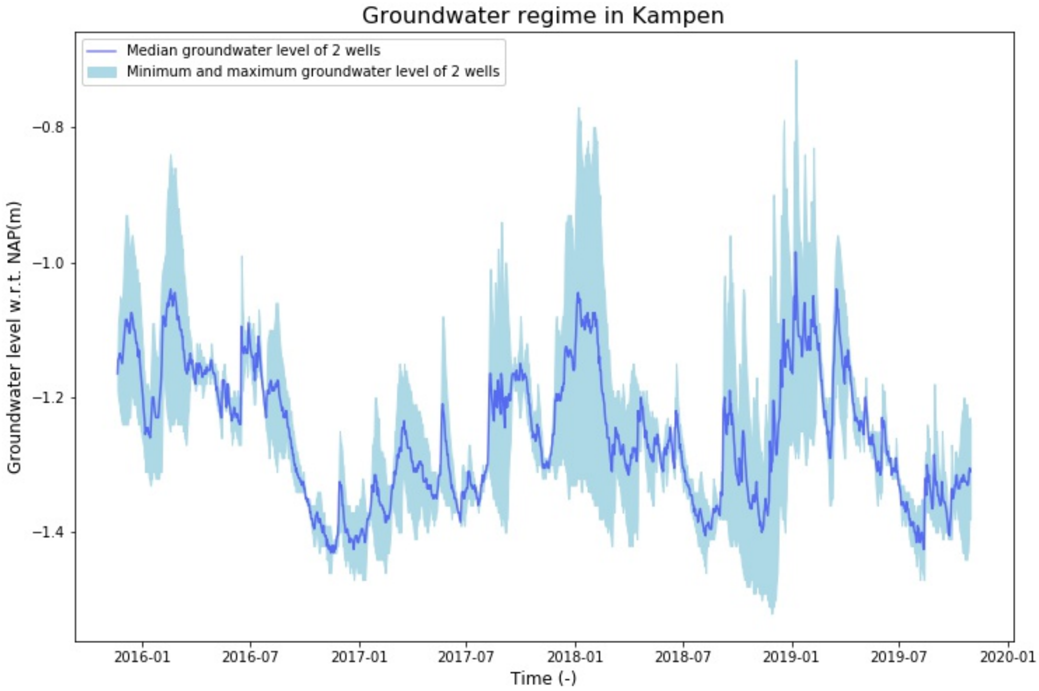


Figure 4.29: *Groundwater regime in Het Meer, Kampen.* Groundwater regime is constructed of 2 wells positioned in surrounding area.

4.2.7. Soil moisture content

The soil moisture content shown in Figure 4.30 is acquired via Deltares' Urban Water balance Model (Brolsma & Vergroesen, 2020). The input for the Urban Water balance Model is acquired from the database of Marknesse weather station of KNMI (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a). The assumptions and input parameters used in this model are explained in detail in Appendix D. The resulting soil moisture content from UWBM is not further modified.

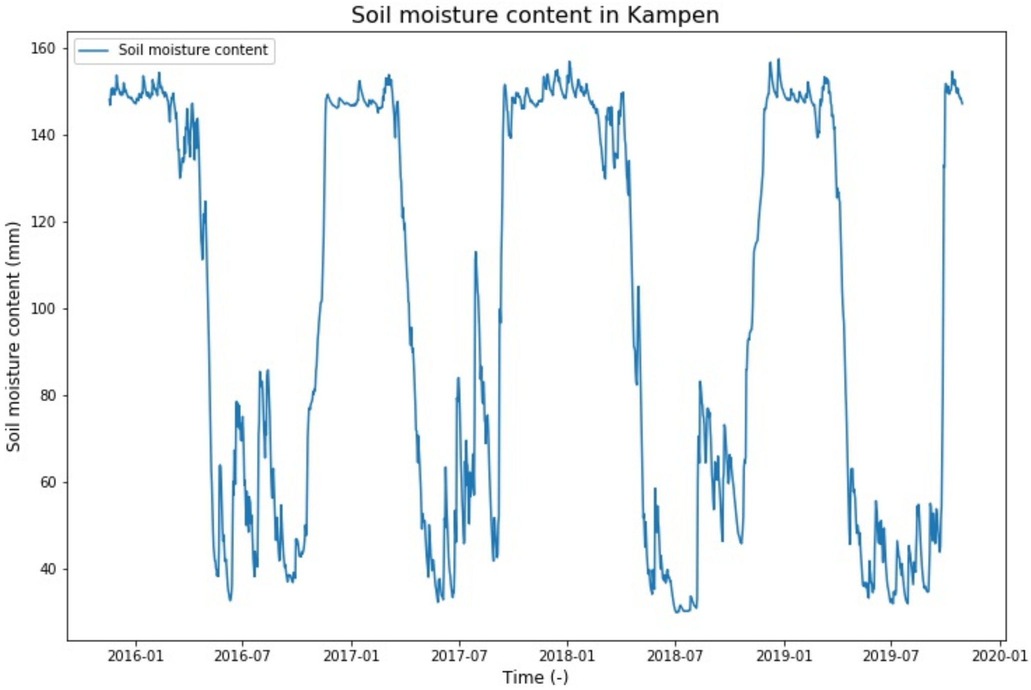


Figure 4.30: *Soil moisture content in Het Meer, Kampen.* Soil moisture content is assessed with the Urban Water balance Model of Deltares.

Construction phase

Het Meer, Kampen

February 2021

5

Results and analyses

In this chapter the research results are presented and analyzed. The analysis of general drought impact on subsidence is conducted before the influence of local characteristics is assessed. Afterwards the results are compared to a second (case) study. The triggering processes of drought-induced subsidence found in the results are shortly covered subsequently. The chapter ends with a brief overview of the results in a broader spatial and temporal perspective.

The hypothesis composed in Section 2.5 forms the general expectation of drought influence on subsidence and is tested by results presented in this chapter:

Soft-soil (with present clay and/ or peat layers) urban areas in the Netherlands are prone to irreversible surface level subsidence of 1 to 2 millimeter as consequence of extreme (groundwater and/ or soil moisture) drought in summer 2018.

5.1. Influence of drought on subsidence rates

The general influence of drought on subsidence rates is assessed via three distinct approaches. Firstly, the temporal interdependence of drought and soil processes is analyzed. Afterwards, the impact of drought upon relative surface level movements is assessed. Lastly, the chronological development of these surface level movements is examined.

5.1.1. Drought impact on soil processes

The time series plot, shown in Figure 5.2, displays the variation of surface levels, cumulative precipitation surplus, soil moisture content and groundwater level simultaneously in order to qualitatively describe their interdependence. In Figure 5.1 the various components of the time series plot are shown to make it better interpretive.

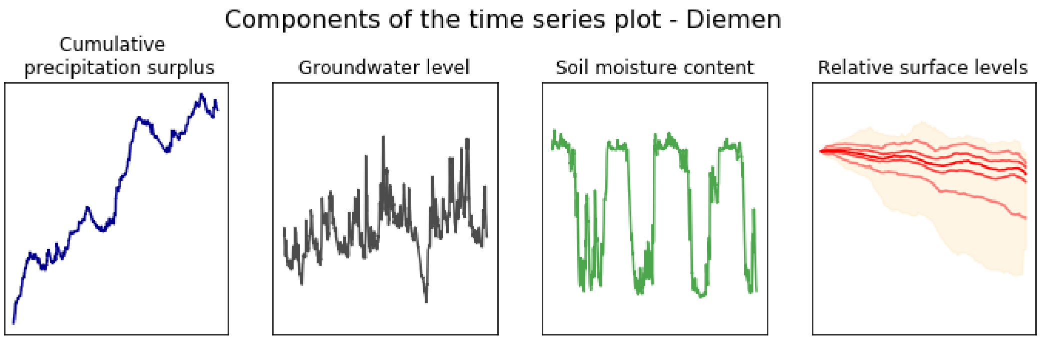


Figure 5.1: *Components of the time series plot of Diemen, shown in Figure 5.2.*

Cumulative precipitation surplus
Difference between wet and dry periods is shown in Figure 5.2 by increasing and decreasing cumulative precipitation surplus respectively. Compared to other years the 2017/2018 winter period has a steep slope, indicating a high precipitation surplus (approximately 450 millimeter). The 2016 summer was relatively wet, while the 2018 summer resulted in an extreme drought, having a change in cumulative precipitation surplus of approximately -200 millimeters (negative since drought). The duration of drought is only considered in analyses of soil hysteresis (Sections 3.3.3, 5.1.4), since no correlation with surface level movements has been found, probably because the amount of data is insufficient.

Groundwater level variations
Figure 5.2 shows that the average groundwater level during the observed period in Diemen is approximately -1.9meter NAP. The groundwater level depends mainly on changes in cumulative precipitation surplus since it fluctuates accordingly. It reacts impulsively: minor changes in cumulative precipitation surplus might directly result in groundwater level changes of approximately few centimeters. The impulsive behaviour results in only small variations between winter and summer seasons, although a general trend of increasing (wet period) and decreasing (dry period) groundwater level is observed. The 2018 summer was extremely dry and resulted in a drop of the groundwater level of approximately 30 centimeters.

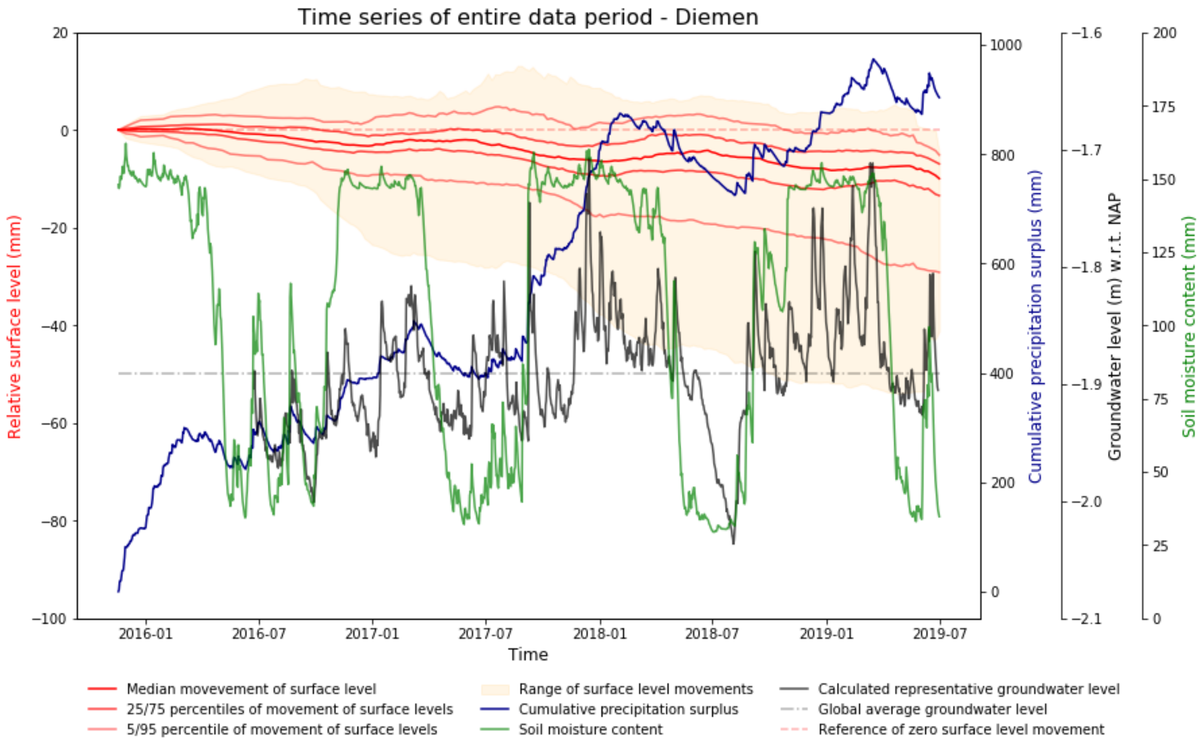


Figure 5.2: *Temporal behaviour of surface levels (median, percentiles and full range), cumulative precipitation surplus, calculated representative groundwater level as median of 6 surrounding wells and soil moisture content as assessed by Urban Water balance Model (Deltares), Diemen.*

Soil moisture content depletion
In winters the soil moisture content is rather constant at approximately 150mm since precipitation is excessive and evaporation is minimal. The time series plot shows however a depletion of soil moisture content in case evaporation intensifies. The depletion is extreme in its extent in 2018 compared to other summers. Due to the thick sand cover layer present in the area (Chapter 4) the depth of the unsaturated zone varies within a sand layer. Due to the (very) low compressibility of sand, the soil moisture variations are less likely to be of influence on soil compaction and swell than the groundwater level variations.

Surface level movement
The time series plot shows the behaviour of all subsidence observation locations in the study area. The median surface level shows a seasonal compression and swell behaviour. Also the other percentile plots show

same-like behaviour. On average the locations subside approximately 10 millimeters during the observed time interval, which is roughly 2.5 millimeters per year. Most locations show same-like average subsidence as can be analyzed from adjacent percentiles plots. The net subsidence during the observational period is negative for all locations, although also the observation with smallest subsidence rate (top edge of range of all surface level movements) shows a fluctuation in compaction and (net) swell behaviour. This might indicate that the seasonal surface level fluctuation has minor impact on corresponding average subsidence rates. Some locations are however prone to relatively extreme subsidence of more than 10mm/year as shown by the relative large drop of range of surface levels in the time series plot in comparison to the percentile plots. Also the surface level with most intense subsidence rate shows a compaction/ swell behaviour in dry and wet periods. The observation of the seasonal fluctuation raises the question if extreme subsidence is related to (seasonal) drought or rather to other factors? This is further analyzed in Section 5.1.4.

5.1.2. Drought impact on surface level movements

The time series plot discussed in Section 5.1.1 shows the interdependence of (soil) processes and surface level behaviour. The extent of varying surface level movements in wet and dry periods is however hard to interpret. The box plot in Figure 5.3 however shows relative surface level movements for varying cumulative precipitation surplus (at corresponding time intervals, Section 3.3.2) of all locations in Diemen. The relative surface level movements indicate soil movements on top of accompanying average subsidence rates, as explained in Section 3.3.2. The boxes corresponding to the first and last analyzed time intervals are discarded, as explained in Section 3.4, and hence displayed transparent in the plot.

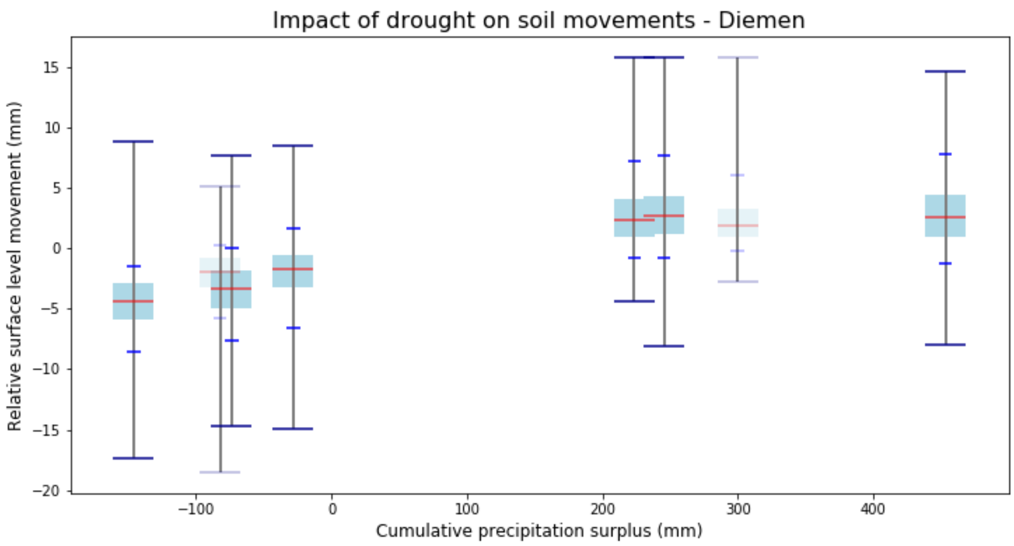


Figure 5.3: *Variation in relative surface level movement on extent of cumulative precipitation surplus, Diemen.* The interpretation of the box plot is given in Figure 3.11.

The plot shows a median negative relative surface level movement in periods having a negative precipitation surplus (drought), and a median positive relative surface level movement in periods having a positive precipitation surplus (wet). The negative relative surface level movement refers to an intensified subsidence rate (compaction) during a time interval relative to its average behaviour. The positive relative surface level movement illustrates the opposite: a swell behaviour relative to the average subsidence rate of locations during a time interval. The swell however does not necessarily imply an absolute raise of surface levels.

Many of the relative surface level movement observations (5/95 percentile) in the time intervals are relatively close to each other, both for dry and wet periods. However, there is a large spread of the whiskers of each plot, indicating that 10% of the surface level movements are more extreme. This might be due to existing factors (local characteristics), or due to the noisy InSAR data and errors in the applied methodology/ model. The magnitude of relative surface level movement intensity is for both dry and wet periods approximately the same. This indicates that the relative compaction and swell in respectively dry and wet periods are to same magnitude. However this is also (partly) induced by the applied methodology, since the surface levels are relative to a calculated linear average subsidence rate of the same observations and hence have a sinusoidal movement around this linear average. Lastly, the difference between the calculated relative and the absolute compaction and swell behaviour of the surface levels is that the latter results in a downward (negative) shift of the box plots (since the average subsidence rates then are included), but hence the box plots are less comparable.

5.1.3. Development of surface level movements

The box plot showed in Section 5.1.2 shows differences in relative surface level movements in wet and dry periods. The chronological development of (the median of) surface levels can however not be estimated. This development is required to interpret the influence of the seasonal occurrence of drought (Section 2.2.2) on the variation in relative surface level movements in time. The median plot in Figure 5.4 shows this development for winters and summers during the observed time interval. The plot shows median relative surface level movements and cumulative precipitation surplus per summer and winter. The vertical lines represent 25/75 (dark) and (more extremely behaviour) 5/95 (light) percentiles of observed relative surface level movements and hence indicate the spread and thus uncertainty of analyses of the median behaviour. The outer periods are discarded as explained in Section 3.4, and hence made transparent in the plot.

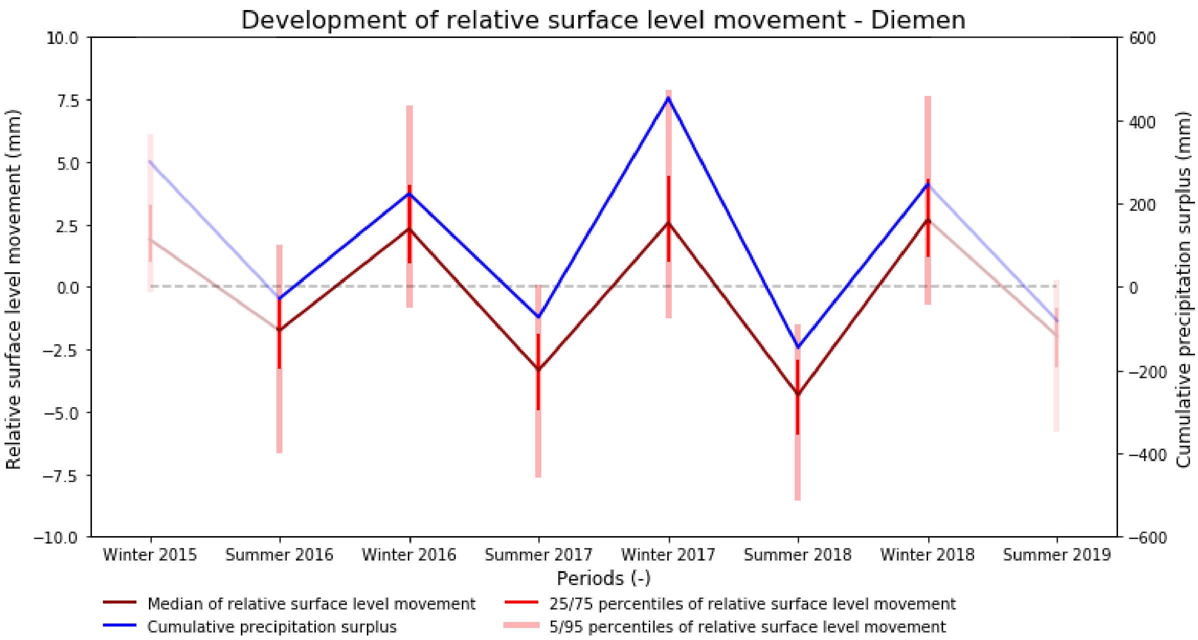


Figure 5.4: *Chronological development of relative surface level movements, Diemen.*

Very well observable from the median plot is the seasonal fluctuation in relative surface level movement. It is shown that due to the reoccurring wet and dry periods of the Dutch climate (winters and summers respectively) there is a fluctuation in the relative surface level movements. This sinusoidal movement of the surface levels has an general extent of approximately 2.5mm (the median) and might thus have a larger or smaller extent for individual surface level locations, as shown by the percentiles. It is clear from the percentiles that the amount of observations resulting in opposite relative surface level movements (for example a relative swell during a drought) is limited. A small analysis has been conducted to see whether this sinusoidal surface level movement can be modelled for the drought in 2018 using Koppejan's (1948) equation (Appendix G), but it is found that the soil reacts stiffer than estimated from the calculations, possibly due to changing compression coefficients, and hence this type of calculations lack precision yet.

There are merely changes in relative surface level movement between the observed wet periods (peaks). The constant extent of the peaks indicates that the soil swells same-like for different cumulative precipitation surplus (wetness). In general the extent of these swells seems however bounded by the extent of prior compaction. On contrary, the negative relative surface level movement intensifies for drier periods (negative valleys of cumulative precipitation surplus). In case of extreme drought, for example the observed summer in 2018, the soil compaction is extreme and outweighs the (bounded) swell of the subsequent winter period. The difference between compaction due to the 2018 drought and swell in winter 2018 is observed to be approximately 1-1.5mm. The distribution of percentiles of relative surface level movements is however quite wide indicating large spread and hence an uncertainty of the analysis of this extent. The wide distribution of surface level movements might be created by local differences, which will be explained in Section 5.2.

5.1.4. Spatial and temporal differences between drought and surface level movements

The lag between drought and subsidence, defined in Section 3.3.3, is calculated to be approximately 100 days, as shown in Figure 5.5. This means that the intensified subsidence (negative relative surface level movement: compaction) only starts roughly a quarter year after the start of the seasonal drought. However, the lag has a large spread, including negative values. To explain the negative values a brief analysis is conducted upon the possible difference in time between groundwater level peaks and starts of intensified subsidence (compaction) by comparing the peaks of the groundwater level with the peaks of cumulative precipitation surplus (Appendix G). This analysis shows that groundwater levels peak simultaneously or even earlier than the cumulative precipitation surplus. However still a large spread, including negative values, exists between peaks in groundwater level and starts of intensified subsidence. The negative value is hence expected to be result of errors within the methodology (Appendix G). The analysis nonetheless substantiates the qualitative observation of impulsively reacting groundwater levels.

The same figure shows that the duration of droughts is approximately 20 days longer than the duration of intensified subsidence. This indicates intensified subsidence occurs in a smaller time interval than the subsequent swell, relative to the duration of a drought as explained in Section 3.3.3.

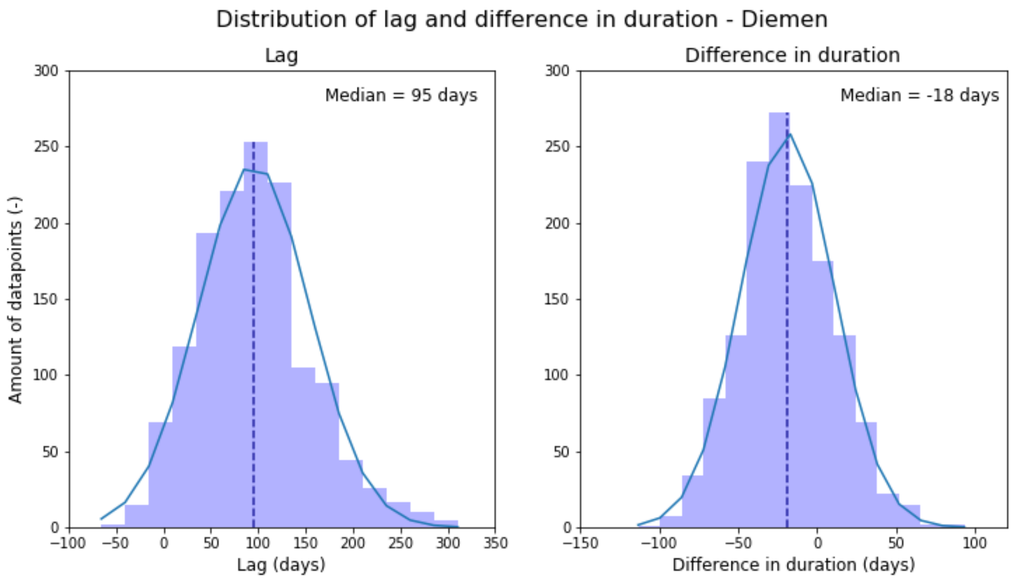


Figure 5.5: *Distributions of lag and difference in duration between intensified subsidence and drought, Diemen.*

Figure 5.6 shows individual relative surface level movements of observation locations compared to accompanying average surface level movement rates. As expected from the similar magnitude of relative surface level movements in Figure 5.3, the negative and positive individual observations of relative surface level movements are roughly mirrored at their zero-line in Figure 5.6 resulting in this same magnitude.

It can be seen that locations with more extreme subsidence rates do not relate to more extensive relative (seasonal) surface level movements. Rather it seems that due to extreme subsidence rates the seasonal surface level fluctuation is same-like or even reduced, since the surface level fluctuation is smaller for extremer negative average surface level movement rates, although limited data is available to fully support this. Droughts thus might influence subsidence by inducing seasonal differences, but this seems uncorrelated to average subsidence rates. Even observation locations with an average rise of surface level show similar fluctuation.

This indicates that seasonal surface level fluctuation (thus drought impacts) is not a large trigger of land subsidence in soft-soil urban areas, specifically in comparison to other factors in urban areas, such as external loads (sand raises).

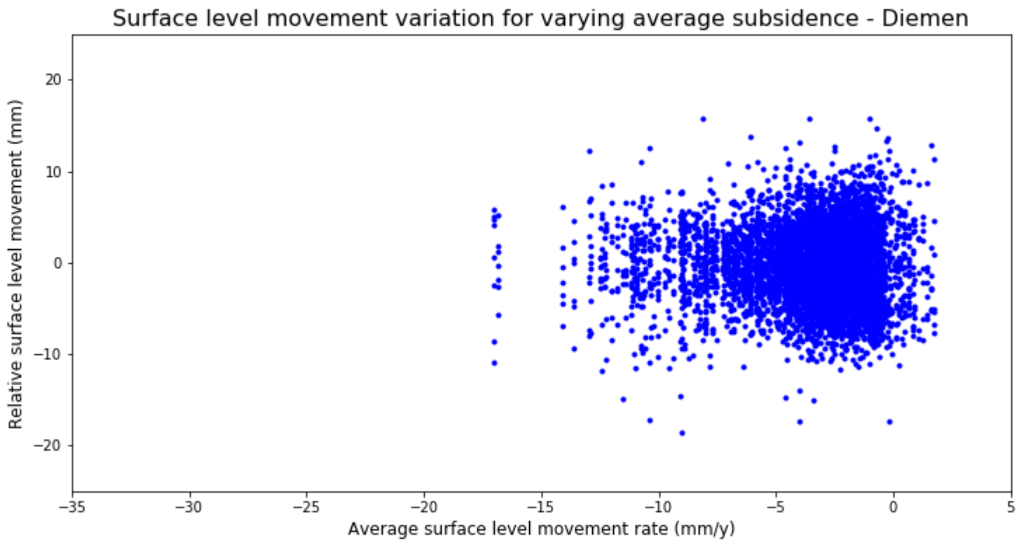


Figure 5.6: *Relative surface level movements compared to their accompanying average surface level movement rates.* The average surface level movement rates correspond to the negative of average subsidence rates.

Lastly, the influences of former site preparation strategies upon spatial differences are analyzed. An overview hereof is given in Appendix G. The chronological development of the relative surface level movements is hereby specified upon zones regarding the year of latest raise. It is found that in Diemen the thickness of the (sand) cover layer, as result of prior raises, influences the extent of surface level fluctuation. A larger thickness of the (sand) cover layer is observed to correlate with less surface level fluctuation.

5.2. Influence of local characteristics

Additional to the influence of prior preparation strategies, covered in last section, several other local characteristics might affect the impact of drought on subsidence, as explained in Chapter 3: soil structure, pavement type, vegetation and vicinity of surface water.

5.2.1. Soil structure

The differentiation described in Section 3.3.2 divided subsidence observation locations based on soil structure into low, medium or high compressibility. Figure 5.7 shows the development of surface level movements for low and high soil compressibility. Only minor differences at the median relative surface level movement between low and high compressible soils are seen (winter 2016, summer 2017 and winter 2018 show less extreme surface level movement for high compressibility). Highly compressible soils are prone to same-like or slightly less extreme relative surface level movements, both compaction and swell, than soils with low compressibility. Moreover, the percentiles of observations at both low and high compressibility soils show a same-like distribution. This substantiates that the differences are almost nihil.

There is no large difference found in net subsidence caused by extreme drought (2018) on areas with low or high compressibility since both compaction (summer 2018) and swell (winter 2018) are more negative for high compressibility. Despite the differences being small, this slightly larger relative surface level movement at areas with low compressibility is not expected (see also Chapter 7). An analysis of differences in development of relative surface level movements differentiated for individual cone penetration test results is conducted to attempt to explain the observed difference (Appendix G), however no explanation has been found yet.

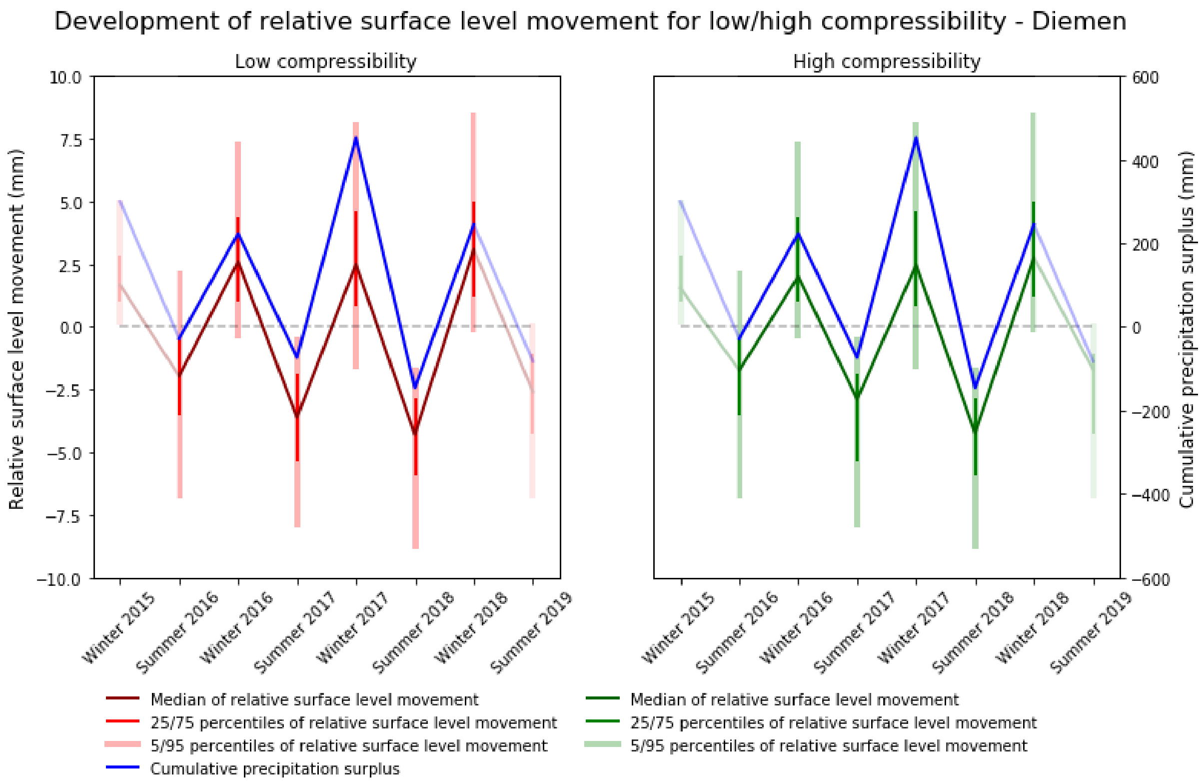


Figure 5.7: *Chronological development of relative surface level movements for low and high compressible soils in Diemen.*

5.2.2. Pavement type

Figure 5.8 shows the difference in surface level behaviour for paved and unpaved surfaces. As explained in 3.3.2 private areas including buildings, and surface waters are excluded from the analysis. Moreover, closed pavement is not present in Diemen.

Unpaved surface types result in more surface level movement than paved surface types, as seen in slightly more extreme peaks and valleys. However, the differences are small since in general the percentiles of paved and unpaved surfaces overlap. Specifically of interest is the difference in relative surface level movement between paved and unpaved surfaces in 2018. The drought in 2018 causes a larger compaction for unpaved surfaces. The swell behaviour afterwards at unpaved surfaces is to a lesser extent than prior compaction. It seems that unpaved surfaces are more subject to net subsidence as consequence of extreme (2018) drought.

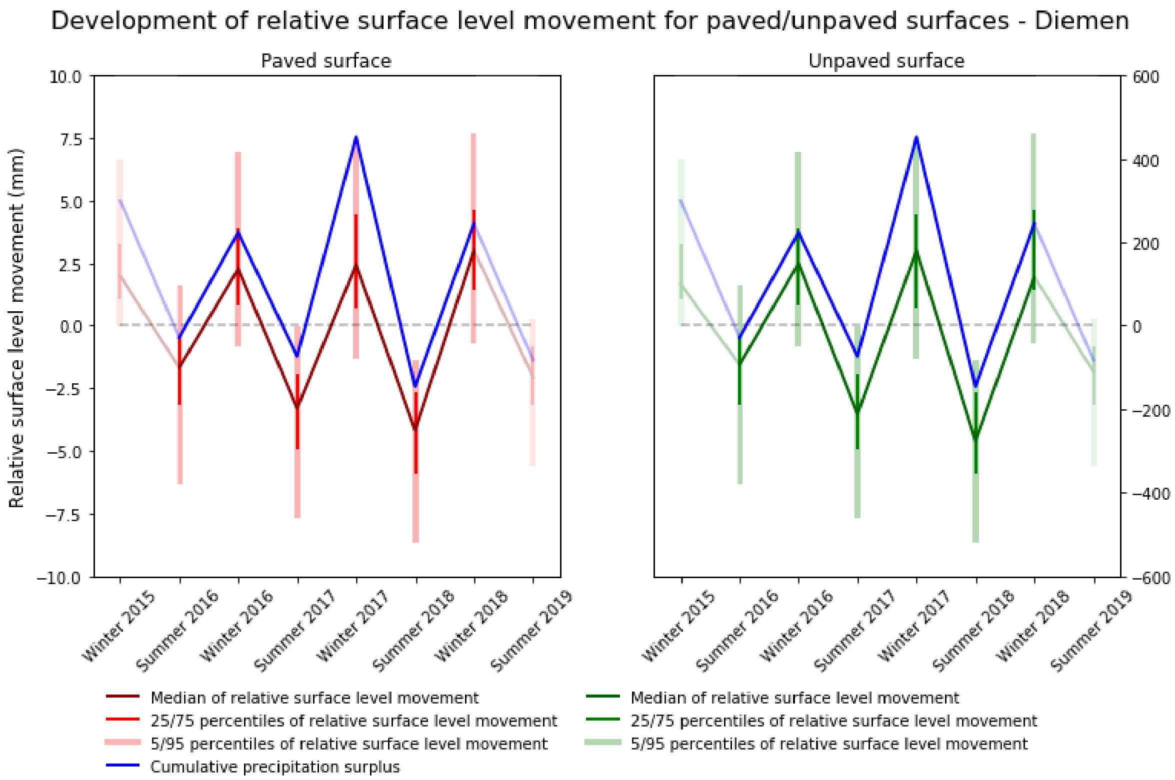


Figure 5.8: *Chronological development of relative surface level movements for paved and unpaved surface types in Diemen.*

5.2.3. Vegetation

Differentiation of the development of relative surface level movements based upon vegetation percentages is shown in Figure 5.9. The typologies are based on a 10/50 percentile distinction (instead of e.g. a 20/80 percentile distinction) since most surfaces in the dense urban area have little vegetation. No further distinction is made on vegetation types or sizes, as explained in Section 3.3.2.

Highly vegetated areas clearly show more relative surface level movement than areas with low vegetation percentage. The extent of relative surface level movements intensifies for more extreme years at highly vegetated areas, both at compaction during drought as swell during wet periods. The latter is of interest since it was expected from Section 5.1 that the extent of swells might be bounded by a maximum. However, the prior drought (summer 2018) at highly vegetated areas is also extreme in comparison to other years and hence a larger swell in winter 2018 might be expected. Highly vegetated areas are observed to result in a slightly larger net subsidence during the drought of 2018.

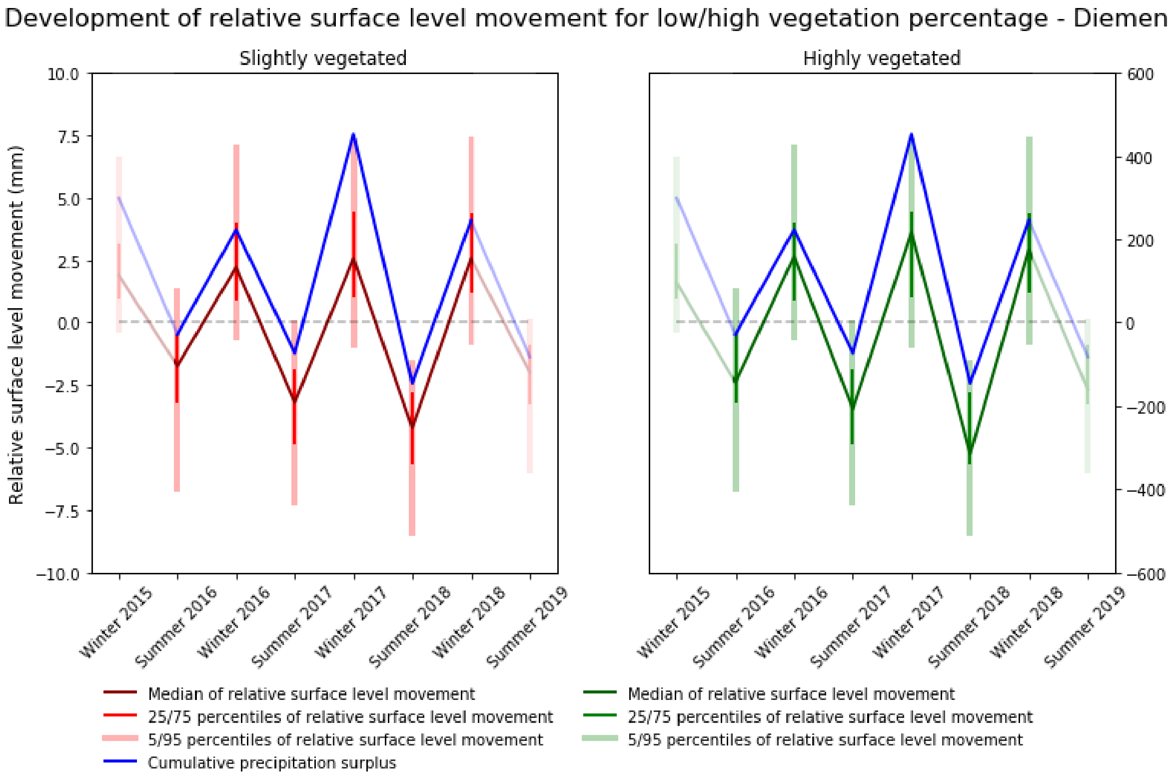


Figure 5.9: *Chronological development of relative surface level movements for slightly and highly vegetated areas in Diemen.*

5.2.4. Surface water

The difference between subsidence observation locations being either within or outside influence zones of surface waters is shown in Figure 5.10. The lengths of the influence zones are estimated based on the freeboard and permeability (Perrochet & Musy, 1992), as explained in Section 3.3.2.

The surfaces within influence zones show slightly more relative movement than outside of these zones, both during wet periods (peaks) and dry periods (valleys). Thereby, no difference between areas within or outside the surface water influence zones is seen in the extreme drought in summer 2018 and subsequent winter 2018 resulting in a difference in net subsidence. Moreover, no distinction in percentiles between areas within or outside surface water influence zones is observed. This substantiates that differences are rather small.

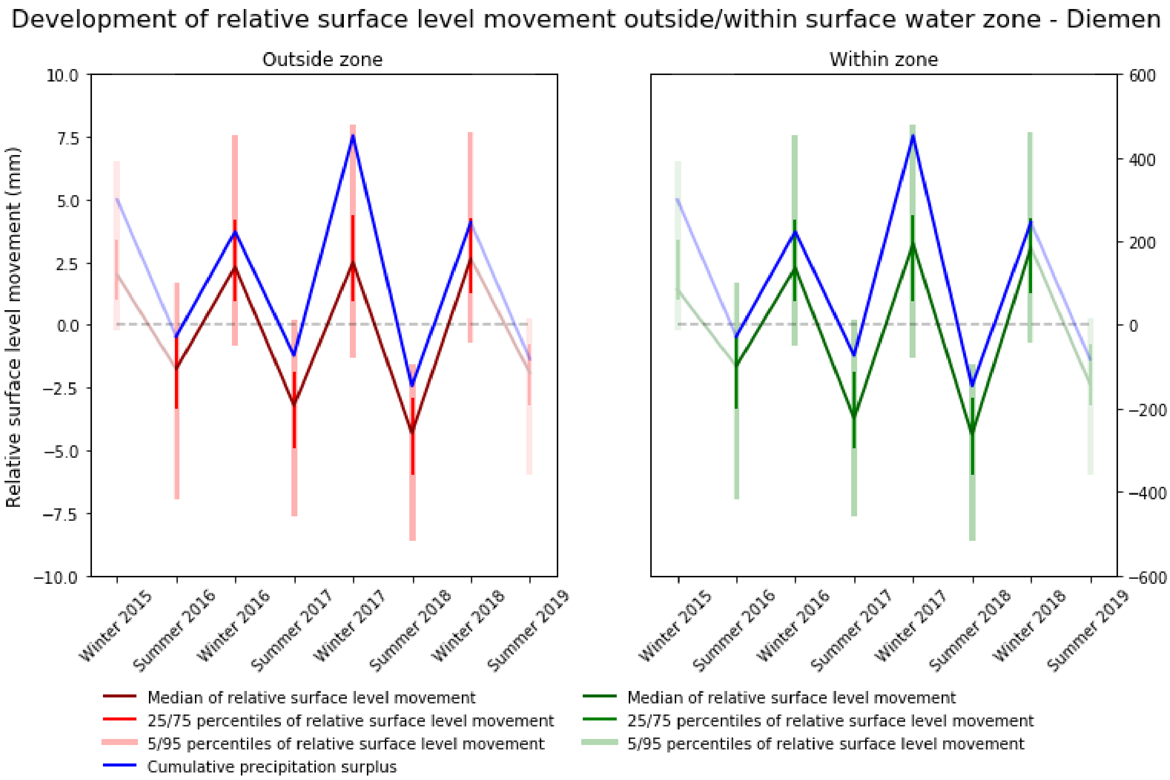


Figure 5.10: *Chronological development of relative surface level movements for either being located within or outside influence zones of surface waters in Diemen.*

5.3. Comparison to (case) study results

Results from the Kampen study area are analyzed and compared to results of the Diemen study area. The comparison of overall impacts of drought on subsidence is discussed first. Next, influences of soil characteristics are compared briefly. The entire analysis is found in Appendix F.

5.3.1. Comparison of drought impacts on subsidence

Drought impact on soil processes

Figure 5.11 illustrates the various components of the time series plot of Kampen in order to make the latter more interpretive. As shown in the time series plot (Figure 5.12) the calculated cumulative precipitation surplus in Kampen is similar to Diemen. Minor difference is the slightly wetter summers of 2016 and 2017 and slightly drier winter of 2017. Although the groundwater level reacts, same-like as in Diemen, impulsively, it behaves more in a seasonal trend: winter/ summer shifts of up to 0.3 meter are observed. The groundwater level variation in 2017 is small in comparison to other years (2016 and 2018) having similar lowest groundwater levels. Moreover, the soil moisture content is same-like in Kampen as in Diemen. In Kampen the soil moisture content plot however shows in 2018 a larger and longer depletion in comparison to other years and to Diemen.

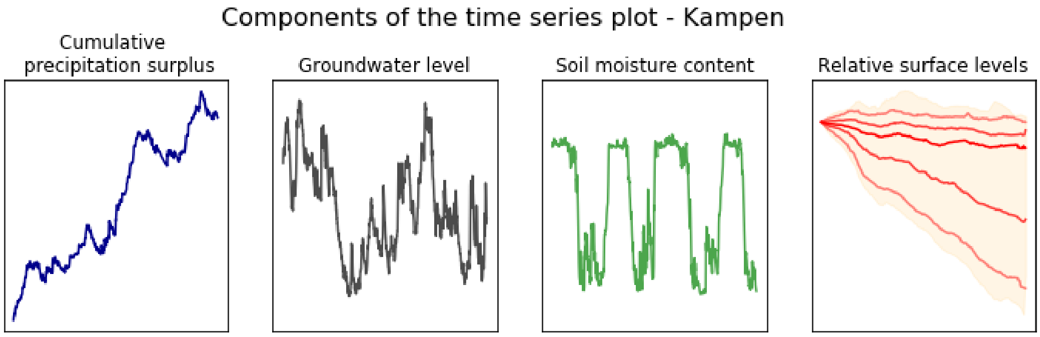


Figure 5.11: *Components of the time series plot of Kampen, shown in Figure 5.12.*

Surface levels in Kampen seem to have similar seasonal fluctuating behaviour as in Diemen. However, less clear sinusoidal behaviour of the median and the percentiles is observed. This might be due to larger dispersion (range) of surface levels through time in Kampen, which affect the development of the median and percentiles. Another explanation might be that the analysis accuracy is less precise (it is more difficult to find the correct peaks and valleys at intenser average subsidence rates) than in Diemen.

Almost all surface level observations have a net subsidence in the observed period. The net swell in the time series observed at approximately 10% of the surface levels (most upper percentile plot) is mainly due to the time series not closing fully in its last year (it starts approximately in November 2015, but ends in May 2019). Moreover the Kampen area is prone to more intense subsidence than Diemen (up to 20 mm/year). This is mainly due to relatively recent raises.

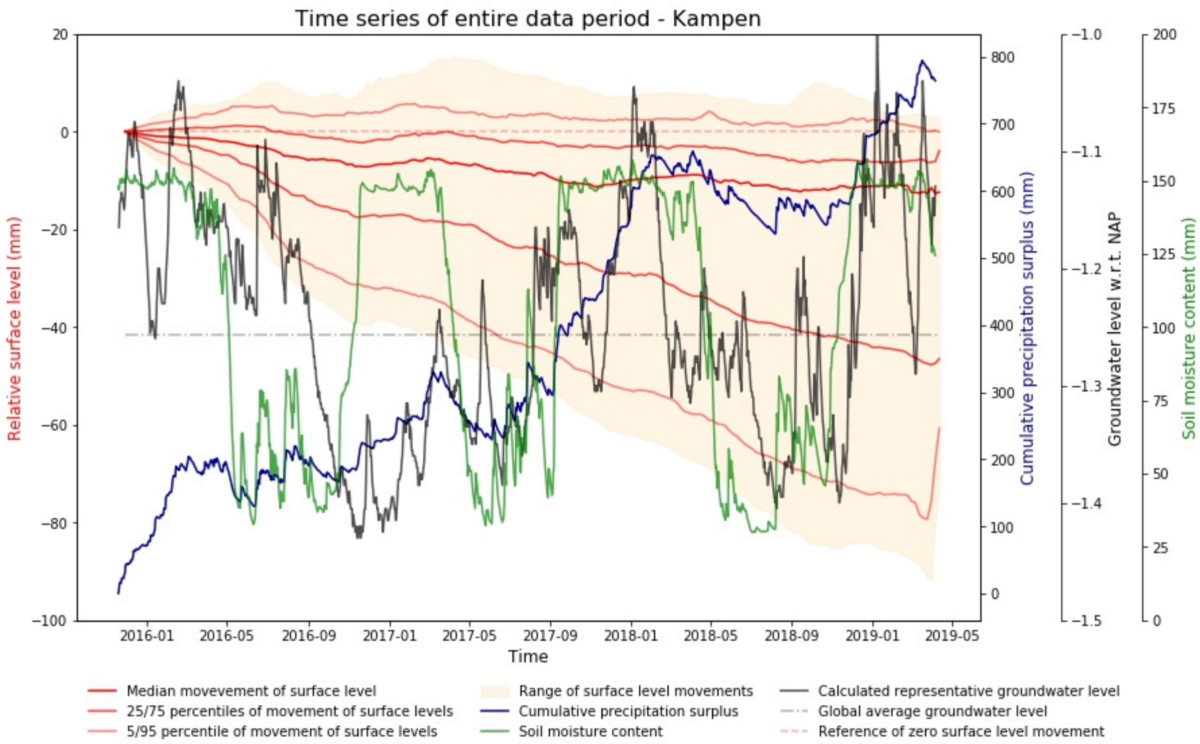


Figure 5.12: *Temporal behaviour of surface levels (median, percentiles and full range), cumulative precipitation surplus, calculated representative groundwater level as median of 2 surrounding wells and soil moisture content as assessed by Urban Water balance Model (Deltares), Kampen.*

Drought impact on surface level movements

Although the cumulative precipitation surplus is less extreme, the box plot in Figure 5.13 shows that relative surface level movements in Kampen are more extreme in both directions than in Diemen. This is most observable by the width of the 25/75 percentiles (light-blue boxes) and 5/95 percentiles (small blue horizontal lines), which seem to be more negative for a negative cumulative precipitation surplus and more positive for a positive cumulative precipitation surplus. This might substantiate the explanation that the analysis accuracy of the time series plot is less precise in Kampen than in Diemen. Despite having more extremes, most relative surface level movements have same magnitude (0 to 5 millimeter - Figure 5.14)) as in Diemen. Thus, only a fraction of surface level movements is more extreme. It is nonetheless interesting to study what causes the more extreme relative surface level movements.

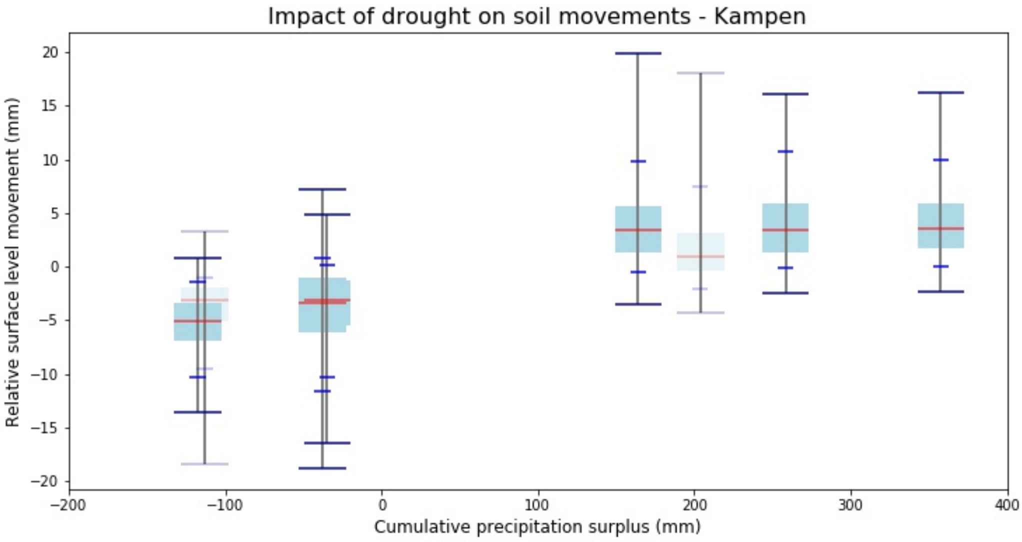


Figure 5.13: *Variation in relative surface level movement on extent of cumulative precipitation surplus, Kampen.* The interpretation of the box plot is given in Figure 3.11.

Development of surface level movements

Figure 5.14 shows the chronological development of surface level movements in winter and summer periods, from which the net drought-induced subsidence can be derived. The extent of swells seems similar in the various winters, which is also found in Diemen. Clearly the 2018 summer results in an extreme relative surface level movement (compaction) in comparison to the other dry periods. This compaction is not balanced by the swell in subsequent winter 2018. This supports findings in Section 5.1 of approximately 1 to 1.5 (or even 2) millimeters of net subsidence due to the extreme drought in 2018. The distribution of data (percentiles) however is even more wide in Kampen in comparison to Diemen as explained in earlier paragraphs, making the analysis uncertainties large.

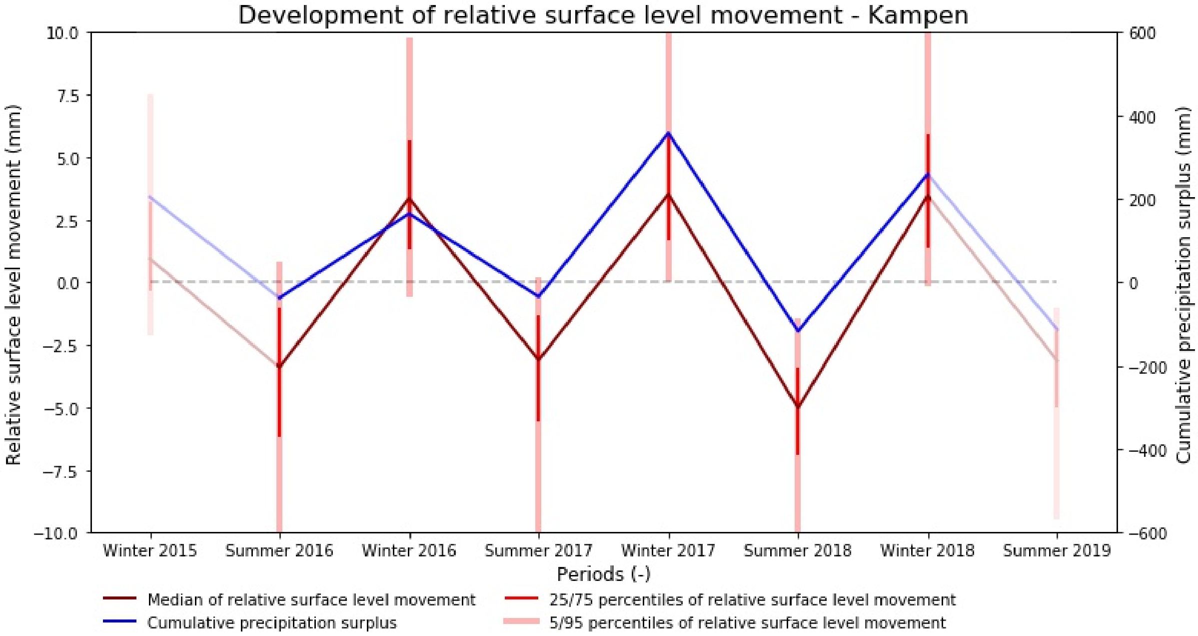


Figure 5.14: *Chronological development of relative surface level movement, Kampen.*

Spatial and temporal differences between drought and surface level movements
The calculation of the lags results in a same-like extent but larger spread in Kampen than in Diemen, as shown in Appendix F. The larger spread of lag substantiates that the model has a worse precision for Kampen in choosing peaks and valleys of the surface levels, which was also shown by less sinusoidal behaviour in Figure 5.12 and larger distribution of percentiles in Figure 5.14 in comparison to Diemen. Moreover, the difference in duration of drought and intensified compaction is in Kampen also same-like to Diemen, substantiating the relatively shorter time interval for compaction than swell.

Likewise in Diemen there is no correlation found in Kampen between the average subsidence rates and extent of (seasonal) surface level movements, as shown in Appendix F. The more extreme relative surface level movements are thus not affected by the recent raising. Moreover, although the soil structure between Diemen and Kampen differentiates, the calculated compressibility of both locations has similar magnitude. This suggests there might be other causes of the more extreme relative surface level movements.

The explanation for a larger relative surface level fluctuation might be found in the difference in groundwater levels and sand cover thicknesses of the two locations. Groundwater levels in Kampen fluctuate in both sand cover and top layer of the original soil whereas in Diemen the groundwater levels rarely drop below the sand cover bottom, as mentioned in Chapter 4. Figure 4.20 shows that the original top soil layer in Kampen consists mainly of peat, sometimes including small clay layers. If groundwater levels drop within these layers the present water content drops (unsaturated conditions). This causes additional shrinkage of peat (and clay) and peat degradation by penetration of oxidation through the sand cover. The soil moisture content thus gains importance if groundwater levels drop within soft soil layers. The exact extent of these processes however cannot be estimated.

The analysis of prior preparation strategies in Kampen differs to Diemen since only one raising sequence happened yet resulting in only small differences to be evaluated. However, the difference in thickness of the cover layer for various zones is analyzed in the specified plots of the chronological development of the relative surface level movements. It is found that, contradictory to the results in Diemen, the zone having the smallest sand cover layer results in the lowest extent of surface level fluctuation.

5.3.2. Comparison of soil characteristics influences

As explained in Section 4.2 the input information of local characteristics in Kampen lacks details. This absence results in higher analysis uncertainties in Kampen of the influence of local characteristics on drought-induced subsidence. Nonetheless, the analyses of these local characteristics are discussed briefly in order to compare the two locations and somehow verify analyses from results in Diemen. The categorized median plots of local characteristics are given in Appendix F. The larger analysis uncertainties caused by the lack of information are shown in these plots by the (extremely) wide distribution (percentiles) of relative surface level movements.

Firstly, the results of analyses specified to the soil structure categorization based on compressibility illustrates that, contrary to Diemen, soils with higher compressibility result in more surface level movement in both dry and wet periods. This results in slightly increased net subsidence (2 millimeter) as consequence of the difference in compaction and subsequent swell in summer and winter 2018 respectively.

Next, unpaved surfaces in Kampen move minimally in 2017 compared to other years and therefore show a high equivalence with present groundwater variations. The extent of net subsidence in 2018 is approximately 2 millimeter for unpaved surfaces in Kampen. The paved surfaces however compress and swell more or less to same extent in wet and dry periods.

The highly vegetated areas in Kampen show difference in extent of compression and swell in summer and winter 2018 respectively. The smaller swell in winter 2018 results in Kampen in a large net subsidence induced by the prior extreme drought (approximately 3 millimeter). This substantiates results in Diemen where a slightly larger net subsidence in 2018 is found at highly vegetated areas.

Lastly, influences of surface waters are analyzed in Kampen. More extensive relative surface level movements within the influence zone are found in comparison to Diemen, without resulting in a larger net subsidence. Moreover, the relative surface level movements within these influence zones of surface waters seem equivalent to the observed representative groundwater level combined from observation wells nearby. The extent of swell and compaction is similarly throughout the years outside the influence zones of surface waters in Kampen.

5.4. Triggering processes of relative surface level movements

A few reoccurring processes seem to be the trigger of the seasonal surface level behaviour in the results observed in this chapter. These triggering processes are discussed in this section before suggestions upon enhanced site improvement strategies to reduce (consequences of) these processes are given in Chapter 6.

Mainly observable in all analyzed plots was the development of seasonal relative surface level movements. The soil decreases and increases in volume and hence surface level elevation in dry and wet periods respectively. Due to the seasonal occurrence of droughts in the Netherlands, it hence indicates that soft-soil urban areas have an ever-continuing yearly sinusoidal compaction and swell. This is a process which seems not to be correlated to the general subsidence rates since same-like extent of relative surface level movements is observed for a range of different subsidence rates.

Moreover, the extreme drought of 2018 is observed to cause a larger compaction of soils than in other years. The extreme negative surface level movement (compaction) cannot be compensated by the smaller subsequent swell (winter 2018) and hence a net subsidence is the result. This indicates that drought-induced subsidence is mainly result of these seasonal relative surface level movements. It is hence required to understand this sinusoidal trend in order to minimize (net) drought-induced subsidence.

It is observed in the time series that groundwater levels react impulsively on small changes in precipitation or (actual) evaporation. However, both groundwater and soil moisture have a seasonal flux of a high (winter) and low (summer) water content. Yet, it seems that groundwater levels are of greater importance to relative surface level movements in soft-soil urban areas than the soil moisture content. In subsidence terminology: clinch is of greater importance than shrinkage for drought-induced subsidence. Reason is that soil moisture mostly varies only in the barely compressible (sand) cover layer present in analyzed (and almost all) urban areas. The thickness of the cover layer thus determines the triggered soil processes (shrinkage and peat oxidation additional to clinch) and hence the extent of relative surface level movements.

The variation in groundwater levels results in a fluctuating unsaturated top soil weight carried by the deeper saturated soft soil layers which hence compress and expand (compaction and swell). Drought-induced subsidence in soft-soil urban areas is thus mainly a process of variations in stresses due to variations of groundwater levels. This is discussed in more detail in Chapter 7.

5.5. Results in a broader perspective

In this section the results are positioned in a broader temporal and spatial perspective in order to determine if further actions regarding (future) site preparation strategies are needed.

A similar magnitude of 1 to 1.5 millimeter of irreversible subsidence during the drought in summer 2018 is found in the two distinct analyzed soft-soil urban areas. This suggest the acceptation of the hypothesis formulated in Section 2.5. However, a full proof cannot be given due to lack of information, a longer time span is required and more areas are to be analyzed, and a lack of further details of soil processes. Nonetheless, the question raised is if the observed net irreversible subsidence at soft soils during the extreme drought is substantial with respect to other subsidence causes?

KNMI predictions covered in Section 2.2.4 suggest a future return period of extreme drought (with same magnitude as summer 2018) of approximately 10 years. The resulting average drought-induced subsidence rate would then be roughly 0.1 to 0.15 mm/year (found net compaction divided by factor 10). As shown in analyses of time series graphs the average subsidence rate is approximately 2.5 to 20 mm/year in extreme cases. This means possible drought-induced subsidence rates are at least a factor 15 (roughly comparing 0.15 to 2.5) smaller than subsidence due to artificial loads such as raises. The estimated impact of a single extreme drought therefore seems small compared to other subsidence causes.

Rates of artificial settlements however reduce in time, as explained in Section 2.3.2. If no new artificial weight is laid upon soils, subsidence rates would eventually become almost negligible (Ten Bosch, 2020). The relative surface level movements differ in this aspect, since it might be triggered as long as compressible layers of substantial thickness are present. It is observed that even surfaces with nearly nihil subsidence rates continue to compact and swell due to seasonally changing soil moisture content and groundwater levels. It seems inevitable from KNMI predictions (Section 2.2.4) that future intensity and frequency of droughts will increase. Drought therefore might affect surface level elevations in soft-soil urban areas in coming decades or even centuries. No research has yet been conducted on these seasonal relative surface level movements, and thus no damage has yet been linked to this fluctuation. However, these seasonal variations in surface level elevation could possibly be a larger risk to infrastructure than the estimated net subsidence during an extreme drought event.

Lastly, since in general the extent of relative surface level movements, and also net drought-induced subsidence, is similar within and between two distinct soft-soil urban areas in the Netherlands, and moreover similar to prior study, it is expected that similar drought-induced subsidence occurred in 2018 in other soft-soil cities in the Netherlands. The influence of drought on subsidence in abroad cities cannot be estimated due to different climate conditions and local influences, and hence these locations were not included into the research scope.

Suggestions on enhancing site preparation strategies to encounter surface level movements and hence drought-induced subsidence are given in the next chapter.

Ready-to-live phase
Het Meer, Kampen
February 2021

6 Towards enhanced site preparation strategies

Drought currently impacts surface levels and subsidence rates, as shown in Chapter 5, despite various site preparation methods are used prior to construction of buildings and infrastructure. This chapter presents suggestions on enhancing the site preparation strategies, and reflects on their feasibility using answers on the conducted expert questionnaire in Appendix E. The questions and accompanying answers of the questionnaire for given subjects below are referred to by (Q.A1), giving question 1 of Section A.

The suggestions given in this chapter consist of two main perspectives. Besides improving site preparation methods (mitigation) also adjustments at long-term strategies (adaptation) are suggested to better anticipate drought-induced subsidence.

6.1. Main principles to minimize drought-induced subsidence

In order to minimize drought-induced subsidence, its triggering processes need to be understood. As explained in Chapter 5, irreversible drought-induced subsidence in 2018 is a net result from differences in seasonal relative surface level movements. Hence, in order to reduce this subsidence, the minimization of latter is discussed in this section.

The surface level fluctuation is caused by a decrease or increase of soil volume, due to variations in effective stress in soil and water flowing in or out. As explained in Section 2.1.2 the effective stress is affected either by the load on top of the soil, or by the present water stress present. The water stress changes due to a fluctuation in groundwater level or soil moisture content. As shown in this research, the main trigger of changes in the effective stress are a varying groundwater level. This variation causes changes in weight of the top soil's layers carried by deeper saturated (soft-soil) clay or peat layers and hence causes the soil to compact or swell due to the varying effective stress. Moreover, groundwater level variations might trigger (additional) shrinkage and peat oxidation resulting in even larger surface level movements. Soil moisture is of minor influence since barely compressible (sand) covers in urban areas mostly prevent the unsaturated zone to compact or swell.

Thus, drought influences soils and surface levels in urban areas mainly via fluctuating groundwater levels. In order to minimize the consequential variations in effective stress two approaches can be applied:

- Preventing extensive groundwater level variations.
- Minimizing the top soil's weight.

Prevention of extensive groundwater level variations has two objectives. Firstly, as explained above the variation of effective stress is minimized and hence surface level variations are minimized. Secondly, the (sand) cover layer in an urban area might not be sufficiently thick to continuously cover the groundwater regime. In case of shallow cover layers it is important to keep groundwater levels within these in order to prevent shrinkage or peat oxidation to be triggered (accordingly also soil moisture content is of influence).

Moreover, minimizing the top soil's weight reduces the variations in weight induced by groundwater level variations. In case the groundwater level decreases the increased thickness of unsaturated soil acts as additional 'dead' weight to be carried by deeper saturated (soft) layers. In case the unit weight of the top soil is decreased, the fluctuation in 'dead' weight due to a groundwater level fluctuation is decreased too. The change in effective stress and hence surface level elevation is thereby minimized.

The approaches of preventing the fluctuation of the groundwater level, and minimizing the top soil's weight, are the starting points to suggest on mitigation strategies.

6.2. Mitigation of drought-induced subsidence

Mitigation strategies focus on minimizing the severity of processes, for example drought impacts on subsidence. Mitigation strategies thus affect an urban area's water (drainage) system or present soil structure and hence might be implemented into existing site preparation methods. For each suggestion the affected site preparation methods (Section 2.4) are mentioned (indirectly).

6.2.1. Drainage design

Drainage designs in urban areas are based on coping hydrological processes. Focus within drainage design however is mainly on drainage depths underneath urban functions with respect to extreme precipitation events and subsequent rising groundwater levels, rather than on *variations* of groundwater levels (Q.D1). This would suggest also to keep low groundwater levels in mind. Drainage systems might be optimized on both wet and dry periods. Drainage depths and distances between drainage pipes might be reduced resulting in higher groundwater levels, having less variations or less extensive drops.

6.2.2. Storage and infiltration of water

In former situations urban water systems were mainly designed on discharging excessive precipitation water as quickly as possible. Early 21st century the national (Dutch) Water Management Committee, part of Ministry of Infrastructure and Water Management, already recommended a three-step procedure to improve urban water (discharge) systems: retain, store and infiltrate water (Reinders, 2000). The usage of these three steps increases water storage capacities of cities and hence helps in dry periods to reduce groundwater level drops by infiltrating more rainwater. Internationally same-like concepts are used, example given the Sponge City Program in China (Ulku et al., 2018).

Instead of directly discharging precipitation water towards surface water bodies or sea, it thus might be stored (infiltrated) within the urban areas resulting in higher groundwater levels. Various disconnection techniques exist in order to store and infiltrate water instead of discharging it by sewers, for example wadis, infiltration crates, -beds, -trenches, -basins, and downward seepage provisions (Van de Ven, 2016). An overall highly permeable top layer moreover increases infiltration capacities (Hoogvliet et al., 2020). Storage might also be possible in deeper soil layers, example given in first or second aquifer, by pumping water in via vertical wells (Hoogvliet et al., 2016).

6.2.3. Reverse drainage

Reverse drainage is a technique wherein drainage networks are used in dry periods to feed water into soils. Two types of reverse drainage are distinguished: underwater drainage and pressurized drainage (Nationaal kennisprogramma bodemdaling, n.d.). At underwater drainage systems the drainage pipes run directly into surface waters. This technique is unconsciously already used (more) in practice in urban areas (Q.F1). In dry periods surface water is thereby able to flow through these drainage pipes and infiltrate into the soil. This way extensive groundwater level drops are prevented.

Pressurized drainage works samelike, however drainage pipes run into a small reservoir (for example a concrete tub) where the water level is kept high by a pump or weir. This way, the reservoir water level might be higher than surrounding surface water levels in dry periods and thus water is pressured to flow into drainage pipes. Varying these reservoir water levels also induces variable drainage levels. This way distinction can be made between wet and dry periods and thus groundwater management can be optimized for given circumstances (STOWA, n.d.). Example given an optimization of reservoir weir height in Bergschenhoek, the Netherlands (Nederlof, 2020).

6.2.4. Minimal soil cover thickness

As concluded in analyses in Section 5.3 the extent of surface level movements is probably increased in case groundwater levels may drop into soft peat or clay layers, due to additional shrinkage or oxidation. This suggests usage of a minimal soil cover thickness in case soil raise is required in order to prevent the trigger of these processes and hence a larger surface level fluctuation. The extra thickness however induces additional (heterogeneous) subsidence (Q.F2). In case the designed freeboard and groundwater levels remain constant, increasing the cover thickness thus also increases the hydro-dynamic period. The settlement requires a longer time to reach the design surface level and freeboard. This should be accounted for by (further) accelerating the settlements of the soil raise, increasing the initial raise costs.

6.2.5. Light-weight raising

Sand is currently mostly used when soils are raised. Various other materials and techniques might be considered in order to reduce the top soil's weight and hence minimize (drought-induced) subsidence. Lighter sand or mixed sand with a lighter material can be used in order to reduce the top layer's unit weight. Other examples of light-weight raising methods are light granular, Bims, lava stones, EPS, foam concrete. Also self carrying constructions might be used. These methods are mostly used at existing urban areas (Q.B1). Light-weight raising reduces maintenance (raising) frequencies and hence long-term costs (Egyed et al., 2006). Raising with traditional materials like sand is however in general less expensive.

6.2.6. Building crawl-space free

Its a Dutch practice to build crawl-spaces under buildings. These crawl-spaces mainly store (sewer) conduits and moreover function as protection (of floors) against groundwater. Although building crawl-space free is already used in-practice for long time, almost no new housing development is designed without crawl-spaces (Q.D2). Wet crawl spaces cause growth of fungi and humid conditions might cause rotting floors and mouldy living spaces (Van de Ven, 2016). In order to keep crawl-spaces dry drainage pipes are located underneath buildings. In case buildings are constructed without crawl-spaces there is more room for groundwater level variation or higher design groundwater levels (Q.E3), decreasing the compaction (differences) of the soil.

6.2.7. Vegetation types

Shadow from large vegetation like trees is increasingly used in urban areas (streets) in order to reduce heat stress (Kluck et al., 2020). As explained in Section 3.3.2 water usage of vegetation depends, amongst others, on its size and type. The correlation found between vegetation and surface level movements suggests that transpiration from vegetation causes groundwater level drops nearby which results in more (variation in) surface level movement. Therefore the type of vegetation in urbanized areas as streets can be considered based on their water usage in urban design (de Lange et al., 2009), in order to prevent a spatially heterogeneous seasonal surface level fluctuation. In order to compensate possible loss of shadow due to smaller or less compact vegetation types the positions of vegetation in streets can be optimized (Kluck et al., 2020).

6.3. Adapting to drought-induced subsidence

Mitigation strategies implemented in site preparation might reduce fluctuation in surface levels, and thus subsidence. However, relative surface level movement and hence (net) subsidence is nearly inevitable due to the seasonal precipitation deficits, complexity of urban (water) infrastructure and required present vegetation. Adaptation strategies focus on reducing consequences of processes like drought-induced subsidence. The main consequences of urban subsidence are discussed briefly in Section 2.3.6.

Erkens and Stouthamer (2020) provided a so-called 6M approach (Figure 6.1) on emerging from land subsidence lock-in: the cycle of subsidence, groundwater nuisance, groundwater level reduction, and subsequently more subsidence. The various adaptation strategies are based on principles of this approach.

Figure 6.1: *The 6M approach to emerge from land subsidence lock-in.* Acquired from Erkens and Stouthamer (2020).

6.3.1. Subsidence measuring/ monitoring

In the Netherlands subsidence is mainly measured during the hydrodynamic period in the preparation phase of sites (Q.A4) in order to assess if the settlement duration fits the considered construction planning. Subsidence is however barely measured during the living phase in these soft-soil urban areas. Main reason might be the complexity and costs of large-scale measuring. Aim of measuring subsidence is to obtain insight where and to what extent subsidence processes are of importance, what temporal and spatial trends occur, and to verify modelled intensities (Hijma & Kooi, 2018). Moreover, by monitoring and evaluating the effects of taken mitigation measures, fit adjustments can be made to further reduce subsidence consequences. Measuring subsidence might expose risks or future damage on which actions can be taken, possibly reducing the long-term maintenance costs.

Due to upcoming (satellite) techniques, resulting in for example datasets like bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020), the measurement covering of larger areas is possible. Maintenance plannings can be optimized and future costs can be expected if subsidence is continuously measured during the living phase. For example the temporal and spatial variation in elevation difference between constructions on foundations (houses) and street levels can be monitored to predict the timing and places of faulty connections of the houses with sewers underneath the streets and act hereupon. Measuring subsidence is moreover required to better predict the long-term consequences of the lower surface levels. This is necessary for example by evaluating the risk on flooding (also with respect to sea level rise) or for example increased risk of salt intrusion via groundwater.

6.3.2. Subsidence modelling

As described in Section 2.3.5 subsidence is modelled in order to estimate settlements of urban areas after raising its surface level. Application of more complex models including various subsidence processes is still rare (Erkens & Stouthamer, 2020). Moreover, in current subsidence modelling merely a constant average groundwater level is used for calculations, for example at the Kampen study area (Joppe, 2012a). Modelling with a varying groundwater level would improve estimations of seasonal variations of surface levels. Furthermore, for example peat oxidation equations (e.g. (Van den Akker et al., 2007)) might be implemented in models additional to consolidation and creep equations in order to better estimate seasonal surface level variations and long-term subsidence rates. Lastly, subsidence can be modelled for distinct cone penetration test results instead of only the CPT resulting in largest compressibility in order to better predict future spatial differences within urban areas.

6.3.3. Management and maintenance

In past but also current situations site preparation strategies are based on short-term costs, for example costs for the amount of sand used in raising soils. This seems ideal for short-term, but could cause a large increase in costs decades after constructing urban areas. Planning of site preparations should therefore be focused more on long-term costs, via example given Life Cycle Analysis (Q.E3). The covenant drafted in the Netherlands for climate adaptive building is an example of managing site preparation strategies and subsidence measures via a cost-effectiveness strategy in a scope of 60 years (Provincie Zuid-Holland, 2019). Furthermore, handling groundwater nuisance might be an adaptive urban management strategy. The long-term costs of groundwater nuisance might be less than the long-term costs of subsidence damage to infrastructure due to seasonal extensive groundwater drops. The comparison of the long-term effects of both might thus be a greater topic of discussion in policy and technical (advisory) reports.

Moreover, soils subside (unevenly) after constructing infrastructure such as roads and hence require maintenance. The timing of repeatedly soil raises can be optimized in site preparation strategies to overlap maintenance cycles of the sewer systems, or for example during installation of new cables, pipes or conduits in the subsurface. Additionally, light-weight raising (see earlier this chapter) is also an adaptive measure at new raising sequences to control or minimize the surface level fluctuation. These suggestions mainly reduce future maintenance costs of urban areas.

6.4. Feasibility of mitigation and adaptation strategies

Mitigation strategies (hamper subsidence processes) mainly focus on improving current site preparation methods, whereas adaptation strategies (reduce subsidence consequences) focus on long-term strategies. The feasibility and practicality of suggested solutions is discussed below.

Some of the given suggestions in this chapter give opportunities for an integral approach to several urban problems. For example using green-blue infrastructures to store water benefits biodiversity and supports healthy urban living (Gehrels et al., 2016), or active groundwater management reduces rotting wooden pole foundations (Brolsma et al., 2012). Integral approaches increase liveability, advance climate-adaptation, and might reduce future costs for municipalities and citizens.

Changing current drainage systems is costly and difficult since drainage is integrated in other urban (water) management infrastructures (Q.D1 & F3). Preference is thus not to use this strategy at maintenance cycles. Moreover, decreasing drainage distances implicates more drainage pipes, increasing maintenance costs (Q.F3). This might be undesirable for municipalities and thus the feasibility is to be considered per case.

Storage and infiltration of water has proven to be feasible in numerous in-practice examples (Buma et al., 2017). Higher groundwater levels and water storage in soils as mitigation measurements moreover has preference of experts (Q.F4 & F6). Additionally, highly permeable raising material increases infiltration capacities, and thus improves storage, and is feasible according to experts (Q.F1 & F3).

Explicit usage of reversed drainage in urban areas is not common since municipalities are cautious regarding maintenance of (complex, variable) subsurface drains (Q.F1 & F3). Reversible drainage results moreover in extra surface water usage in dry periods, which should be firstly addressed and discussed with water boards (Hoogvliet et al., 2020). The pros and cons should thus be investigated per case.

A minimal cover layer thickness induces longer hydro-dynamic periods, whilst experts already experience time pressure completing consolidation processes (Q.C1). Moreover, it results in larger subsidence and hence uncertainties (Q.F2). Temporal over-height or vertical drainage is commonly used to reduce hydrodynamic periods (Q.C3) and is to be used more extensively to compensate drawbacks of a thicker cover layer. Using a minimal raising thickness is only valuable in case it prevents other (larger) complications (Q.F2), through a more extensive (seasonal) surface level fluctuation.

Light weight raising is considered feasible to reduce the worrisome reoccurring impact of drought on the variation of surface levels in existing (and new) urban areas (Q.E1 & E2). Crawlspace-free designing is feasible since it is already practiced (but not often) for long time. Moreover, the choice of vegetation types in urban designs based on water usage is feasible according to experts, but is yet not practiced (Q.F5).

Measuring and monitoring subsidence via e.g. InSAR is feasible to integrate in maintenance plans/ budgets of municipalities. This way municipalities might timely take action to prevent future subsidence complications (Q.A4).

In most cases, CPT results giving largest compressibility are used to predict (model) subsidence over a larger area (Q.A1). Hence, the modelling results locally in both less and more (mainly peat layers, Q.A3) subsidence than expected (Q.A1). Moreover, compressibility parameters from literature or in-situ measurements prior to site preparations are used while these parameters vary in time (Appendix G). This decreases the precision of subsidence predictions. Natural subsidence and drought-induced subsidence is often not taken into account during these estimations (Q.C4). Although not all experts consider taking into account drought-induced subsidence and spatial heterogeneity in calculations (Q.E2), it might improve predicting subsidence.

Different stakeholders are involved in choosing fit site preparation strategies. This results in conflicting interests and deflection or postponement of problems (Kamphuis, 2008). Priority is given to short-term costs (of e.g. sand-use) instead of long-term problems like uneven subsidence (Q.B2). Strict residual settlement demands however result in lower maintenance costs (Q.E3). Long-term analyses like LCA's (Q.E3) of multiple aspects (including e.g. groundwater nuisance) might result in higher initial costs regarding site preparations but reduce long-term risks of damage and hence high maintenance costs and are thus considered feasible.

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7
Discussion

This chapter firstly discusses the research results by comparing them to expectations from theory and current literature. Afterwards the research limitations and their impact on the research results are covered. Subsequent the used research methodology is shortly evaluated. The chapter ends with a brief overview of the importance of this research within its literature framework.

7.1. Discussion on research results

In this section the results are interpreted and compared to expectations from theory and current literature. 'Soils' and 'urban areas' in this section are referred to as soft-soil (urban areas (in the Netherlands)), thus containing a clay and/ or peat layer below the present (sand) cover layer.

7.1.1. Drought impact on soil processes

The interdependence of cumulative precipitation surplus with several soil processes (groundwater, soil moisture, surface levels) is analyzed qualitatively by plotting their time series simultaneous in one plot. The observed behaviour of the soil processes as result of changing cumulative precipitation surplus is discussed briefly below.

Soil moisture content

The soil moisture content is observed in the analyzed areas to approximately have a maximum value in wet periods (winter), which is assumed to be result of the excessive precipitation in Dutch winters, and to approximately have a minimum value in dry periods (summer) due to the less transpiration via present vegetation as the suction pressure decreases towards the wilting point (Geohring et al., 2016). The variation in soil moisture content in the analyzed urban areas is however modelled via the Urban Water balance Model based on precipitation, potential evaporation, and some local parameters of the urban areas (Brolsma & Vergroesen, 2020). The soil moisture content therefore in advance changes on the variation in meteorologic data, and thus does not represent reality, but gives a good indication of its overall change.

Groundwater level

The groundwater level is observed to react quite impulsively on small changes in precipitation (higher groundwater level) or evaporation (lower groundwater level). The groundwater level varies on percolated precipitation, seepage, drainage (as inflow and/ or outflow), and capillary rise from the unsaturated zone (for transpiration) (Brolsma & Vergroesen, 2020). Despite reacting impulsively, the groundwater levels show a seasonal trend upwards (winter) and downwards (summer) which is expected from increasing and decreasing cumulative precipitation surplus respectively.

The groundwater levels observed in Diemen and Kampen seem not related with the soil moisture content. It is not clear in what portions the variation in groundwater levels is caused by precipitation, the present drainage, possible (negative) seepage, or capillary rise. It is however assumed that mainly the present drainage system instead of capillary rise causes the decrease of groundwater levels. The absence of a relation between groundwater and soil moisture can moreover be due to the precision and simplifications of the input of data in the Urban Water balance Model, or due to groundwater levels not being measured within the area.

Surface levels

In Kampen, a large difference between the median surface level trend and lower percentile plots (extreme subsidence) in time is observed, compared to Diemen, where most surface levels show similar subsidence rates. This might be explained by the year and iteration of last raising in both areas. In Diemen the last raise was between 2000 and 2014 latest, knowing the soil was raised before in 1987. Contrary, the area in Kampen has had its first raise approximately around 2013. Since soils react stiffer (in time) when being compacted via for example raises (Verruijt, 2010), it is expected that the soil in Kampen shows intenser subsidence rates. This is thus also observed in the results.

Moreover, in both analyzed urban areas a sinusoidal trend is observed indicating a seasonal compaction and swell behaviour of the soil. The extent of this behaviour is however better interpreted by quantitatively analyzing the seasonal trends, as explained in next section.

7.1.2. Drought impact on surface level movements

The relative surface level movements (sinusoidal behaviour of a surface level relative to its linear estimated subsidence rate) for a given extent of drought or wetness of a period is analyzed by comparing surface level movements to the cumulative precipitation surplus in time intervals. An intensified subsidence rate (compaction) is observed in dry periods, whereas a lower subsidence rate (swell) is observed in wet periods. Several (sub-) topics regarding this behaviour are discussed below.

Decrease of surface level elevation

The decrease of surface level elevation is result of a decrease in soil volume (Verruijt, 2010), if natural causes and excavations are neglected. This decrease in volume is caused by degradation of organic materials (peat), and/ or two simultaneous processes: the decrease in water volume in the soil; and the increase in effective stress between the soil's granules causing a compression and distortion of granules and, if (shear) stresses increase extensively, a change of granule stacking (through distortion).

As explained in Chapter 2 the effective stress between granules is determined by the total stress (including external loads) and the water stress present (Van de Ven, 2016). In this research the total stress at the analyzed surface level observation locations is assumed to not change within the analyzed time interval, since SkyGeo filters the InSAR radar signals if large unexpected changes (e.g. soil raises or excavations) are detected (Appendix B). An example hereof is the south-east part of the area in Kampen which has nearly zero surface level observation locations, since the area was constructed during the observed time interval. The seasonal surface level fluctuation is hence assumed to only change via the variation in water stress.

Soil behaviour at dry periods

The intensified subsidence, or compaction, observed in the box plot as consequence of a drought is expected from the decrease of water stress (decrease in groundwater level and soil moisture content) in both the saturated and unsaturated zone.

The water stress (or pressure) in saturated soil layers decreases in dry periods since their elevation relative to the phreatic line decreases (lower hydraulic head) (Verruijt, 2010). Subsequently to the decrease in groundwater level, the granules in saturated soft-soil layers have to carry more 'dead' weight of the (increased thickness of the) unsaturated top soil. Initially, this weight is carried to larger extent by the present water in these layers, and gradually increasingly by the contact points between the present (saturated) granules (Van de Ven, 2016). Water is pressed out of the compressible saturated soil layers via surrounding aquifers due to this initially increased water stress, through which gradually the stress decreases to its original state. This results in larger ordinal stresses on the contact points between granules compressing them (decrease of their volume). Moreover, this causes distortion of the granules (change in shape) which results, due to decrease of pore space, in a smaller soil volume. The exact extent of change in strain (compaction) as result of changed stresses is however unknown.

Simultaneously in dry periods, the water stress decreases in the unsaturated zone due to decrease in soil moisture content. Shrinkage or oxidation (compaction) in the unsaturated zone in soft-soil urban areas is unlikely to occur due to its position in barely-compressible (sand) cover layers, which were initially required to increase the bearing capacity or freeboard. In case this cover has sufficient thickness (until the depth of the (lowest occurring) groundwater level) only the very upper layer of the unsaturated zone consists of (fertile) compressible material for plants (Section 2.4). Moreover, the water content in the unsaturated zone increases in depth (Van de Ven, 2016), hence resulting in less allowance of shrinkage or oxidation in the lower parts of unsaturated zones. The effect of a decreasing soil moisture content in the unsaturated zone on soil compaction is thus nearly negligible. Oxidation of organic material and shrinkage of clay or peat in soft-soil urban areas are thus only triggered in case the groundwater level drops lower than the (sand) cover layer, into the underneath clay or peat layers (hence making them partly unsaturated).

Soil behaviour at wet periods
The relative swell behaviour of the soil observed in the plot is expected due to the decrease of effective stresses and oxidation rates during a wet period.

During a wet period the groundwater level and soil moisture content increase (back to their original state). Oxidation of organic material and/ or shrinkage is hampered, if not stopped, if the groundwater level increases to a higher level than the top of present peat or clay layers. The additional water results in a decrease of the weight of the unsaturated zone (smaller thickness due to increase in groundwater level). The water stress increases, and the top soil is carried to greater extent by the water present in the pore spaces between the granules. The ordinal and shear stresses at the contact point of granules decrease, resulting in smaller compression and distortion of the granules. Water which was pressed out via aquifers flows back into the expanding pore spaces in the soft layers. The soil's volume increases and surface levels rise back.

The observed (net) swell behaviour of the peat soil in Kampen requires an additional (possible) explanation. As explained in Section 2.3 unlike clay layers, having an elastic behaviour, peat layers are assumed to have nearly no swell due to their low unit weight (close to water) and their structure (organic materials instead of granules). Physically this swell of merely few millimeters could be result of such a large increase in hydraulic head that the peat layers are fully unloaded (Van den Akker et al., 2007). This will however also weaken the soil and hence is unimaginable to occur in urban areas. Another explanation might be that the cover layer, which is expected to consist purely of sand, is mixed with for example clay, and might therefore slightly shrink and expand in seasons. Same-like it can be expected that the fertile top layer at unpaved areas (root zone) might compact and swell (slightly). However, this fertile layer is absent below the seasonal fluctuating paved surfaces, and hence is considered not to be the cause. Lastly, the observed behaviour can be caused by atmospheric conditions altering InSAR data of surface levels, although the company SkyGeo, which corrects the acquired data hereupon, verifies that this can only be partly a cause (Appendix B). It thus needs further research to conclude upon possible explanations of the net rising peat layers.

Other remarkable topics on soil behaviour
It seems logical that in case of a dry period the decrease of water content (and thus weight) in the unsaturated zone counteracts the increasing 'dead' weight due to lowering of the groundwater level. Similar but opposite happens in wet periods. The exact processes occurring in the unsaturated zone are however complex and hence this zone is in general not directly included into equations and theory. The estimated balance of the soil's stresses, given by for example the equation of Koppejan (Section 2.3.2) (Koppejan, 1948), refers only to saturated layers. The extent of this counteracting process is therefore difficult to estimate. However, since the surface levels decrease (compaction) during dry periods in comparison to wet periods, it can be expected that the decrease of weight due to a lower soil moisture content is to lesser extent than the increase of 'dead' weight due to the lower groundwater level.

Moreover, a very brief analysis (Section 5.1.3) has been conducted upon possible calculations of consolidation and creep due to changes in stresses via groundwater level drops in the summer of 2018. It is observed that less surface level movement are shown via InSAR than is estimated for this summer via the calculations (even excluding oxidation) (Appendix G). This is expected to be due to temporal changing compression coefficients (on dry and wet periods) which are calculated prior to the observed time span (2018) or even taken as default from standardized tables (e.g. from NEN-EN-ISO 224760). The change in these coefficients is assumed to be caused by the loading (and unloading) of the soil: an increased compression causes the soil to react stiffer to subsequent (small) changes in stresses, and hence changes the compression coefficients. The gradual change of these in time however needs further research.

7.1.3. Chronological development of relative surface level movements
In order to estimate the influence of seasonal occurring dry and wet periods the (median) relative surface level fluctuation in corresponding distinct time intervals is analyzed in chronological order. A difference of relative

surface level movements between and within dry and wet periods is observed, resulting in a net drought-induced subsidence during summer 2018. This section briefly discusses the difference in development of surface levels in dry and wet periods.

Surface level movements in wet periods

The positive relative surface level movements (swell) in the analyzed wet periods are observed to be similar in extent, despite having a variation in the extent of wetness of these periods. Hence, it seems that the swell of the soil is bounded by a maximum value. This can be explained by the presence of a subsurface drainage system in Dutch soft-soil urban areas, which are needed to prevent (over-) saturated soils, and to keep urban infrastructure dry & unfrozen (Van de Ven, 2016). The drainage pipes are placed a certain distance (e.g. 1 meter) below the surface level. This implies that in wet periods the groundwater levels bulge between the present drainage pipes or surface waters due to the abundance of precipitation. A larger bulge thereby increases the gradient between highest groundwater level and the drainage, and hence increases the water flow towards the discharge elements (Verruijt, 2010). This further implies that groundwater levels are hampered to a maximum height. This is substantiated by the in-practice experience that exceedance of the designed maximum groundwater levels (nuisance), based upon the subsurface drainage system, occurs on average only limited (10-15) days per year (Van de Ven, 2016). Distinct wet periods therefore result in similar maximum groundwater levels, what explains the identical extent of swells in the analyzed wet periods.

Surface level movements in dry periods

Contrary, the relative surface level movements are observed in the median plot to be more negative (compaction) at increasing severeness of drought of periods. The extent of compaction for regular summers (such as 2016 or 2017) is similar to the extent of swell, assuming a (perfect) elastic behaviour of the saturated soft soil layers (Verruijt, 2010). Extreme drought, such as 2018, is however observed to correlate to a larger compaction of the soil. In Kampen this might be expected due to additional shrinkage and peat oxidation since the groundwater levels drop within peat layers. However, in 2016 a similar extent of groundwater level is observed as in 2018. Moreover, in Diemen the sand cover is assumed to be large enough to prevent additional oxidation and shrinkage. Hence, another explanation is to be found.

Physically it is possible that the shear stresses between granules increase to such extent that clay granules start to 'roll'/ move (through distortion) additionally to the (annual) compression and distortion of the granules. These movements might change the granule structure. A change in the stacking of granules causes a loss of energy (to heat) within the soil and thus is an irreversible change (Verruijt, 2010). It is however not known if the groundwater level drop (and decrease in soil moisture content) in the summer of 2018 was to such an extraordinary extent, in comparison to the other observed years, that it caused extensively large shear stresses. This moreover depends on, and hence should be compared to, the variability of these water components prior to the observed time interval (generally since the last large change in stresses - raise). Since reference time series, resulting in e.g. a standard deviation of groundwater levels, are lacking, it is thus not known if the variations in 2018 are significantly different from prior years. Hence, it is not possible to fully substantiate, but only strongly suspect, that in 2018 there was indeed insufficient water in the water components resulting in irreversible subsidence (as defined by Machairas (2020) in Section 2.2).

It can be concluded that during the dry summer in 2018 such large soil compaction occurred, in comparison to the subsequent swell (winter 2018), that it results within the analyzed urban areas in a net (irreversible) subsidence of 1-1.5 millimeter. This is in line with earlier studies (Tolk, 2020). The exact understanding of the occurred processes however is not sufficient enough yet to fully substantiate that dry conditions are the (only) cause. The topic thus requires further study.

7.1.4. Spatial and temporal differences between drought and relative surface level movements

Within the research spatial and temporal differences between and within the study areas are analyzed. The influence of local characteristics on spatial differences within the study areas is covered in next section.

Lag between drought and (intensified) subsidence

The lag between the start of a drought and the start of the intensified subsidence (compaction) is observed to have a median value of approximately 90 days. Although Xue et al. (2005) cover the existence of this lag, they do not include an estimation of its extent. There are two physical processes which are assumed to perhaps cause the protracted extent of the lag: a lag of decrease of groundwater level with respect to the start of a drought; and a lag in soil compaction with respect to decrease in groundwater level. An analysis is conducted which rejects the first explanation (Section 5.1.4, Appendix G), however a lag in soil compaction (consolidation) of 90 days seems protracted. The explanation of Xue et al. (2005) that the lag is caused by creep therefore might be correct. Further research on this topic is however required to fully understand its physical processes. The research hence also lacks an assessment of (the need for) mitigation strategies on counteracting lags.

Difference in duration of drought and (intensified) subsidence

The difference in duration of a drought period and intensified subsidence (compaction) period is observed to differ approximately 20 days, indicating that, with respect to the duration of seasonal droughts, the process of soil compaction occurs faster than the subsequent soil swell. Explanation might be found in the hysteresis of soil wetting and drying (van Asselen et al., 2018). Due to the non-uniformity of pores, the contact angle of water to pores in drying and wetting conditions, entrapped air in pore spaces, and the swelling and shrinking property of soils a difference in sorption and desorption processes (wetting and drying respectively) exists (Dey et al., 2017). This mainly results in a quicker change in suction pressure when the soil moisture content decreases (drying) than for wetting. This results in a faster change of groundwater level and water (and hence effective) stresses and thus a smaller duration of compaction than swell. This is also observed in the results and thereby verifies prior studies on soil hysteresis.

Influence of subsidence rates on relative surface level movements

It is observed (qualitatively) that there is no correlation between the extent of average subsidence rates and the extent of (seasonal) relative surface level movements. This indicates that the extent of surface level fluctuation is to same magnitude within the analyzed areas for places with intense or nihil subsidence.

The physical explanation for the similar fluctuation might be that the climate conditions (precipitation, potential evaporation) are spatially constant within urban areas. The potential impact of drought on groundwater levels and soil moisture content and thus surface level movements might thereby be spatially approximately constant if the soil structure is generally identical within the urban area. This should not be confused with the spatially variable average subsidence rates (due to soil heterogeneity). Moreover, the soft soil layers might have such thickness they result in only limited differences: pressed out water from the soft layers can only escape via above and/ or below aquifers. The thickness of the soft layer might thereby be ignorant due to the limited change in stresses and the relatively short time interval of drought compared to long-term consolidation. No concluding explanation hereupon is however found and hence more detailed research is required to fully understand the (spatial) differences in seasonal surface level fluctuation.

Influence of site preparation strategies on relative surface level movements

Lastly, the influence of the difference in site preparation strategies within the urban areas is analyzed (in Appendix G). In Diemen, the zones having a larger cover thickness due (zone of 2014) shows the least relative surface level movements. This might be explained by the larger load of the thicker sand cover, resulting in a more extensive compression of the soft-soil layers and hence a larger stiffness of the soil at variations of effective stresses. Contradictory, in Kampen the zones having thicker sand cover layer result in less surface level fluctuation. This might be explained by the research methodology limitations, covered in later sections. Nonetheless, the influence of prior site preparation strategies on relative surface level movements needs further research.

7.1.5. Influences of local characteristics

The analysis of the chronological development of surface level movements is specified several times upon typologies of distinct local characteristics in order to determine their influence on the surface level fluctuation. The influence of the local characteristics: soil structure; pavement type; vegetation percentage; and vicinity of surface waters, are briefly discussed below.

Soil structure

Soils with higher compressibility are observed to fluctuate slightly more in Kampen than soils with lower compressiblity. Despite having large uncertainties due to lack of CPT information in part of the urban area, this is expected, since a higher compressibility physically results in a higher strain for a certain difference in stresses, as explained by e.g. the equation of Koppejan (Verruijt, 2010). The opposite however is shown in the analysis of soil structure differences in Diemen. The assumption therefore is that there might be another explanation for the observations in Diemen.

Firstly, although differentiation for soil types is made, the compressibility in both analyzed areas is calculated by a rule of thumb using the thickness of clay and peat (and sand). The compaction and swell of layers however is more complex and depends on varying compression constants (Appendix G) and temporal changes, due to for example cyclic loading and unloading, in the relation between stress and strain (Verruijt, 2010). Furthermore, only a difference of approximately one millimeter is found between high and low compressible soils in the seasonal surface level fluctuation in both Diemen and Kampen. This is little if compared to the difference in compressibility of layers, with magnitude of one or two meters, in the analyzed urban areas. The observed differences might therefore be nearly negligible and even be accidentally occurring within the analyzed time interval. Lastly, the spatial transformation of CPT data is done by the Voronoi method and thus only represents an estimation of the spatial variability in soil structure and compressibility.

Hence, it seems that, in line with theory, the highly compressible layers result in slightly more seasonal surface level movement (Kampen), although it can also be considered nearly nihil, and the results are very uncertain. Thus, no strong conclusions hereupon can be drawn and more specific research on the topic is required.

Pavement type

The unpaved surfaces are observed to have a larger seasonal fluctuation than the open paved surfaces in both analyzed areas. Unpaved terrains might be bare soil, house vegetation such as bushes and trees, but mostly consist of grass in the analyzed areas. Difference with paved terrain in dry periods is therefore mainly the larger evaporation (transpiration) flux. Moreover, unpaved terrains have a larger infiltration flux since at open paved surfaces water can only infiltrate in-between the bricks (or other tiles) (Brolsma & Vergroesen, 2020). Water on paved surfaces is therefore more likely to flow into the sewer system via gutters or towards unpaved area to infiltrate there (Van de Ven, 2016). Unpaved areas are thus expected to have a larger fluctuation between dry and wet periods in groundwater level and soil moisture content due to the higher infiltration and evaporation fluxes. Hence, unpaved areas are assumed to have a larger seasonal surface level fluctuation. This is observed in the analyses.

Vegetation

The highly vegetated areas in the analyzed areas are observed to show more relative surface level movement than areas with little vegetation. No distinction is made based upon the (average) size and types of the vegetation. In general however, (larger) plants and trees require (more) water (de Lange et al., 2009) to transport nutrition and water from soils via their roots and stem towards their leaves in order to use it for photosynthesis and hence to grow. The exact amount and difference in water usage per type and size of plant or tree is however not studied thoroughly yet. Nonetheless, areas with a larger amount of plants and trees are expected to have more extensive water usage in dry periods. This is observed within the study areas, especially in the large drop in relative surface level movement in 2018. This is probably due to the extreme extent of drought causing plants and trees to extensively take up water from the unsaturated zone, thereby preventing percolation of water to the (thus decreasing) phreatic line, and hence resulting in more compaction.

However, the extent of swell in winter 2018 differs significantly for the two study areas. In Diemen the extent of swell is approximately similar to other years, whereas in Kampen the extent of swell is significantly lower. This seems like an error within the model since the 25/75 percentile plot reaches almost entirely above the median, nonetheless no error in the model could be found. Although no further analyses have been carried out, only a rough proposed explanation is given. Explanation might be that subsidence observation locations and highly vegetated areas in Kampen mainly overlap dense urbanized area (streets) as shown in Section 4.2, while vegetation is mainly present at the edges of the neighbourhood in Diemen. The presence of a (deeper) subsurface drainage system in Kampen preventing high groundwater levels for the urban infrastructure and thus substantial swells might therefore cause differences in 2018 in comparison to Diemen, where due to the location at the edge a drainage system might be absent (or less deep). This does not yet explain the little swell in winter 2018 in Kampen. The analysis however illustrates the need for further research regarding vegetation influences during drought on surface levels.

Surface water

It is observed that the surface levels within the influence zones of surface waters show a larger surface level fluctuation than outside these zones. This is not what is expected from observation of the surface water levels showing their position within the minimum and maximum groundwater levels (regime). Therefore, it is expected that the surface waters hamper the variation in groundwater levels (Perrochet & Musy, 1992) and hence surface levels nearby. Despite Kampen having a difference design water level (summer, winter), which in advance induces a variability in groundwater levels, it is not expected that this is the cause of the observed larger surface level fluctuation close-by. Reason mainly is that the surface level fluctuation within the influence zones are more irregular throughout seasons in their extent than relative surface level movements outside the zones, contradicting the regular seasonal change of design surface water levels.

The relative surface level movements in Diemen not only show the opposite of what is expected, the behaviour of the surface levels moreover seems similar to the variations at highly vegetated areas. Since these zones mostly overlap, and thus equifinality of their influence on the surface level fluctuation cannot be excluded, no further analysis on the vicinity of surface waters is conducted. However, it is assumed, based on literature (Brolsma et al., 2012), that the influence of surface water levels on groundwater levels and hence surface level variations is at shorter distances than estimated in this research (few meters). It is clear the exact influence of surface waters on nearby surface levels requires a more detailed research.

7.1.6. Enhanced site preparation strategies

Although the feasibility of the enhanced strategies is covered within Chapter 6, the innovativeness of the suggestions is not yet discussed. This is discussed briefly below.

As explained in Chapter 6 most mitigation strategies are already used in-practice. For example reversed drainage is unconsciously applied by placing the pipes below the surface water level; light-weight raising and crawl-space free building is practiced already for longer time; and storage- and infiltration provisions are used (to more extent) in urban areas. The consideration to use a minimal soil cover thickness however is not commonly known yet. Similarly, the choice of vegetation types based on their water usage is barely practiced yet. Therefore, these two need further research to study their effectiveness on minimizing the surface level fluctuation and hence being implemented into site preparation.

The suggestions on adapting to subsidence are, similarly to mitigation strategies, mainly already used in-practice. Subsidence measuring via e.g. InSAR is used to greater extent at soft-soil urban areas where subsidence already occurs, but can be implemented into future maintenance plans at new housing developments. Subsidence is currently modelled at site preparation or raising sequences and hence this strategy is not new, however the models might be optimized on the seasonal surface level fluctuation. Lastly, the long-term strategy of urban management and maintenance cycles is becoming more common practice and hence the suggested strategy substantiates its development.

Additionally, the suggestions on mitigation and adaptation strategies might create more awareness of the existence of (alternative) site preparation strategies, and the presumably emerging (future) consequences of a (larger) surface level fluctuation.

7.2. Research limitations

This section covers an overview of the research limitations and their influence on the analyses and results. The limitations are discussed by looking at restraints in acquired data, data processing, and data analysis.

7.2.1. Data acquisition

Subsidence observations

As explained in Section 2.3.5 and Appendix B corrections at satellite data of relative surface levels are needed in order to reduce noise of atmospheric conditions. Although these corrections are made at acquired data by SkyGeo (Bodemdalingskaart.nl, 2020), their data used in this research is still prone to noise of approximately 6-8 millimeter for individual measurements. This noise can be seen as inaccuracy of relative surface level observations. The exact extent of influence of atmospheric conditions on the seasonal movement of surface levels is not known. This seasonal fluctuation of surface levels is however not assumed to be fully result of the noise (Sataloff et al., n.d.), also since its existence can be explained by physical processes. The noise makes it more difficult to interpret the data and hence needs to be filtered out of the analyses.

The noise is mainly induced by the large covered area of focus (nationwide) over which the same corrections are made resulting in less accuracy of these corrections. If focus is at local scale, for example a city or neighbourhood, the corrections for local atmospheric conditions can be made very specific reducing almost all noise. The noisy data set however is used since it covers the entire Netherlands and hence makes results in distinct urban areas comparable. The similarity of corrections by SkyGeo over a large area results in an underestimation of the subsidence rates in places prone to subsidence (example given Diemen or Kampen), and an overestimation in places with barely subsidence. This underestimation is not further analyzed since the focus is mainly on seasonal relative surface level movements rather than average subsidence rates.

Furthermore, the satellite's spatial error is up to 2 to 3 meter (Appendix B). This means that the real radar reflector locations might be few meters distance from locations used in the analyses. Subsidence observation points might thereby be categorized wrongly on local characteristics. This inaccuracy widens the distribution in the results. It is however not known what local characteristics are affected nor to what extent. This increases analysis uncertainties of their influence and weakens possible conclusions drawn hereupon.

Meteorology data
Meteorology data used at the analyses of the study areas is gathered from nearby KNMI weather stations. Thereby the assumption is made that differences in data due to distances -approximately 10 to 15 kilometers- between study areas and weather stations can be neglected. This decreases the precision of cumulative precipitation surplus calculations. The spatial patterns in yearly precipitation and (potential) evaporation is not analyzed and hence it is not known if the gathered data underestimates or overestimates the cumulative precipitation surplus. However, since cumulative precipitation surplus data is only used as representative indicator of global extent of drought or wetness of the study areas, without looking in detail into the exact extents, the (relatively small) differences are assumed to be negligible.

Groundwater measurements
Groundwater data is collected by wells nearby and within the study areas. Groundwater measurements therefore give a good indication of the area's groundwater regime, but might not be representative due to different local conditions (proximity of subsurface- and surface drainage system, soil structure). Although the groundwater regime is only analyzed qualitatively this increases inaccuracies of these groundwater regimes to be analyzed and hence might lead to misinterpretations of the influence of the cumulative precipitation surplus upon groundwater levels and of the influence of groundwater levels on relative surface level movements.

Soil structure
Cone penetration test results are directly acquired from geo-technical companies. The results give resistance measurements every 2 centimeters, which make them very precise. The CPTs in Diemen are made in 2016 giving a good indication of the soil structure. The CPTs in Kampen are however made in 2007, while soils are raised only after 2012. The time interval (winter 2015- winter 2019) of the analyses do not overlap the time CPT drills are performed and therefore it is unknown what changes in soil structure occurred meanwhile. This might lead to miscalculation of the soil's structure and hence errors in the categorization of its compressibility. Moreover, the exact reach of the groundwater level drops towards soft soil layers might be wrongly estimated in Kampen since the soil structure changed.

In Diemen the CPTs are spatially divided over the area, hence which the Voronoi method results in an equal distribution of the area into subareas. In Kampen however, there are no CPTs made in north-west corner of the area. This greatly affects the uncertainty of the analysis of compressibility in Kampen, since most surface level observations cover this part of the study area.

Pavement type maps
Open data from the PDOK database is used to indicate pavement types in the study areas. These maps cover the entire country, which makes places comparable in sense of pavement types. However, these maps are inaccurate and lack details, such as small green areas and flowerbeds in streets. More details could be added to the maps by comparing them with for example satellite images. Moreover, these maps do not provide detailed insight in pavement types of private areas, example given gardens. Therefore the spatial estimation of pavement types is only roughly. This affects the pavement type analysis by increasing its uncertainty (expectation of wider distributions).

Vegetation maps
Vegetation maps are same-like pavement type maps prone to inaccuracy. Open data from Atlas Leef-omgeving is used since these maps cover the entire country giving comparable results of different areas. However, the spatial resolution is 10x10 meter. Therefore, these maps lack details of vegetation which are needed in small spaces such as streets. This might overestimate or underestimate the vegetation percentages resulting in a higher uncertainty at the analyses. Conclusions drawn from analyses thereby cannot be substantiated strongly.

In Diemen the vegetation map covers the entire study area. In Kampen however, large part of the study area is not covered since it was still under construction during the time the vegetation map was made. Many observation locations are thereby excluded from the analysis. This increases the uncertainty of the analysis in Kampen since only few surface level observation locations can be compared.

7.2.2. Data processing

Temporal processing

Although non-linear alternatives are tested but rejected (due to more noisy results), the simplification of the average subsidence rate to be a linear process in time might be inaccurate since soil compression has a (slowly changing but) logarithmic behaviour in time (Section 2.3.2). The used least squares method (Appendix C) results in advance already in approximately same magnitude of relative surface level observations being located (in time) above and below the average subsidence rate since this is the definition of the method. Hence, the similar extent of swell and compaction is induced directly by the method. A slight different chosen average (due to change in methodology) might result in different swell and compaction calculations. This increases the uncertainty of the median observed change in relative surface level movements and thus might greatly affect the acceptance or rejection of the hypothesis (1-1.5 millimeter of net subsidence in summer 2018). The impact of drought can thereby be both underestimated, since it is expected to have no yearly influence on calculated average subsidence, and overestimated, since e.g. the corrections made by SkyGeo underestimate the subsidence rates. The inaccuracy of the average chosen to be linear instead of non-linear might moreover be intensified in Kampen since here only recently the soil was raised, having greater chance of non-linear soil behaviour. However, the methodology is assumed to represent reality since the results in this research substantiate prior study (Tolk, 2020) and the similar extent of compaction and swell can be physically explained.

Furthermore, details are missed by only taking into account start and end of time intervals to calculate the difference between surface level and cumulative precipitation deficit. The daily or weekly development of a drought and other drought characteristics as duration or pooling (Machairas, 2020) are therefore missed. This does not directly affect the analyses, but research on variations within time intervals might result in a better understanding of processes.

Moreover, calculations of duration and extent of surface level movements are based upon location and height of peaks and valleys of simple moving averages of subsidence data. The determination of these peaks and valleys in time series graphs is prone to errors. Although simple moving averages over relative surface levels data decreases outliers and hence reduces the number of peaks and valleys, still several peaks and valleys might exist per season. This induces a large inaccuracy since the model is required to 'choose' per start and end of the seasons one fitted extreme between these several peaks and valleys and thus might misinterpret data, as referred to in Appendix G. The inaccuracy is illustrated in large (vertical) spread of relative surface level movements shown in box plots. Furthermore it is illustrated by the calculated lag between drought and intensified subsidence, which ranges from negative values up to 300 days. The negative values might be caused by a prior peak of groundwater level in comparison to the peak in cumulative precipitation surplus (Appendix G), however still this range of negative values up to more than 300 days exists. Negative lags thereby indicate a start of soil compaction prior to the decrease of the soil's water content due to extensive evaporation, which is not realistic. The range of lags therefore illustrates a low data precision (noise and process).

Lastly, the input of parameters into the Urban Water balance Model are estimated based on default parameter indications of soil structure, infiltration and storage capacity, and seepage, given by Deltares. Since the input parameters are default or estimated rather than calculated or measured the precision of resulting infiltrated precipitation and soil moisture content might be low. It is not known if this leads to a underestimation or overestimation of the soil moisture depletion and actual evaporation. However, soil moisture contents and extents of cumulative precipitation surplus are analyzed qualitatively (and roughly) and thus the possible deviations are considered to be ignorable.

Spatial processing

Main limitation of the research methodology is the spatial heterogeneity of actual evaporation, precipitation and soil structure, resulting in local differences in soil moisture content and groundwater level. Actual evaporation differs greatly within neighbourhoods due to local differences in surface type, water system, and soil structure. This limitation does not directly affect the analyses, but is required to be improved to better understand the impact of drought on soil processes and hence the surface level fluctuation.

Moreover, through Voronoi interpolation the study area is divided into zones corresponding to soil structures based on cone penetration tests results. However, soil structures differ locally resulting in varying soil processes and surface level movements on short distances. Specifically in Kampen the lack of CPTs increases the uncertainty of estimation of soil structures and compressibility. This therefore affects the analysis on influence of soil structure in Kampen and no strong conclusions of the analysis can be made. Moreover, due to lack of information no details could be given for local changes in soil moisture content and groundwater level resulting in merely a qualitatively analysis of these parameters.

Categorization

The categorization of soil layers into sand, clay or peat is a simplification of Robertson's (2009) method and therefore lacks details. The difference upon further analyses is however small: it mostly reduces the specific details to possible further explain the observed surface level movements. Furthermore, the compressibility estimation (rule of thumb) based on Te Groen (2016) is a simplification causing an inaccuracy. Therefore, no strong conclusions can be drawn upon the compressibility of soils and corresponding analyses.

The indication of vegetation percentages is estimated to be sum of percentage of bushes and trees. This results in 2% of the cells in a percentage of over 100, indicating an overlap in what is estimated to be a bush (<2.5meter) or a tree (>2.5meter). Vegetation percentages might thus be slightly overestimated, resulting in slight underestimation of the influence of plants on drought-induced subsidence.

Influence zones of surface waters are estimated based on a (simplified) formula of Perrochet & Musy (1992). Values for given parameters are chosen to maximize the influence zone length. The zone is maximized to include all subsidence observation points which are possibly induced. The estimation of the length of influence zones is therefore inaccurate and probably overestimated. Drawback of these maximized areas is that points might be included into the zones which are not influenced, resulting in less extreme differences between results within and outside the zones.

7.2.3. Data analysis

Firstly, local characteristics overlap each other spatially and moreover various factors are not considered in the study, for example seepage or the subsurface drainage layout. Local characteristics and relative surface level movements are interpreted to be correlated in results, but might not have a causal relationship. After analyses it is still not exactly known what factors caused (differences in) the surface level movements (equifinality). This results in uncertainty of the causation of the observed relative surface level movements. Thus, only rough estimations of causation could be given and hence no strong conclusions hereupon can be drawn. However, by comparing results to expectations from literature conclusions are somewhat substantiated and hence open options for further research.

Unpaved surfaces, mainly housing vegetation (e.g. grass) are included into the analyses despite InSAR radar signals barely function on vegetation. It is not known whether the location of observations being on unpaved terrain might have low precision or are correct measurements of the bare soil. The analysis however gives a first insight into differences between paved and unpaved surfaces.

Buildings are excluded from all analyses since these constructions have foundations into deep, solid, sand layers and will therefore behave differently through seasons than other surface types (unpaved, paved). This is done by removing the observation locations spatially overlapping buildings in the PDOK (n.d.) map. It is not considered however to compare these to the point/DEM height of the points to verify the exclusion. The buildings show a similar, but less extreme, seasonal fluctuation as other (subsurface) infrastructures. It is unknown if these observations locations lack precision spatially; if atmospheric conditions affect the data; if the soils below buildings compact and swell; or if the building materials have considerably large thermal expansion (Appendix G) This needs further research.

Furthermore analyses lack in distinguishing between several subsidence mechanisms. Only estimations are given concerning possible occurring mechanisms in given time interval at studied areas. This causes a blindness in extent of example given shrinkage or peat oxidation. More detailed research of subsidence mechanisms in soft-soil urban areas is thus required.

Moreover the research's time interval, approximately 4 years, is rather short. The data however is interpreted to be exemplary for other periods with samelike extent of wetness or drought. Subsidence is a slow process wherein for example consolidation intensities only differ greatly throughout multiple years. Furthermore, consequences of drought on the water system, vegetation, and soil structure, might only emerge after several years. The small time interval is representative on short term variations but lacks information on long-term changes in soil movements.

Lastly, the analysis of both study areas is done using data from one satellite since it is acquired from only one source (Bodemdalingskaart.nl, 2020). Using different data sources and comparing these increases the reliability of the (noisy) results.

Limitations in data acquisition, -process or -analysis affect the reliability of the research results. The research's focus however was not on the uncertainties of analyses results, which were only given by distribution of percentiles of relative surface level movements rather than by statistical approaches (for example tests as student's t-test or Wilcoxon's rank sum test, or regression analyses). No strong conclusions can be drawn due to the uncertainties and inaccuracies. Therefore, more detailed research is needed to statistically prove preliminary results of this research.

7.3. Evaluation of used research methodology

Generally the research methodology consists of a modification and comparison of acquired data in order to answer the research questions. These research steps do not include an established methodology, such as a statistical analysis, or modelled scenarios (with exception for the UWBM), via for example DSettlement (Section 2.3.5). The reliability of this data modification and analysis is therefore to be questioned.

The used model, Urban Water balance Model, is assumed to give a correct indication of the variation in soil moisture and actual evaporation data, although rough estimations of (default) model parameters are used and moreover the model results in no spatial differences. However, since the soil moisture results from the UWBM are solely used in qualitative analyses, and the exact extent of actual evaporation resulting in a certain cumulative precipitation surplus is only used in the quantitative analysis as indication of drought severity, impact of the model precision on the conclusions is assumed to be negligible.

The developed model uses acquired observations of relative surface levels for estimations of subsidence variations. Calculations are made to 1. reduce the noise of this data (simple moving averages); and 2. estimate the average subsidence rates. Since additionally only partitioning of the data, temporally (periods) and spatially (local characteristics), is done, the model symbolizes physical soil behaviour and is considered applicable to answer the first two research questions.

The main advantage of the used methodology is its simplicity, since it uses low amount of openly accessible data and requires little modification steps. The model computes results in short time (few minutes for entire neighbourhoods). Furthermore, the model is applicable for any (soft-soil) urban area as long as InSAR and meteorology data is available. Data of groundwater levels and local characteristics is however required to fully interpret the results.

The methodology however does not include any detailed uncertainty analysis of the noisy surface level data nor sensitivity analysis of the local characteristics. Results can thereby be interpreted wrongly. A detailed evaluation of the results and the methodology thus lacks. This results in merely rough indications of the interdependence of ongoing processes and local influences. More detailed research on the (sub-) topics including uncertainty and sensitivity analyses is required to substantiate this research's findings.

The research uses an expert questionnaire in order to verify suggested solutions on enhancing site preparation strategies. The proposed suggestions thus have their origin in the questionnaire and literature. The mitigation strategies are not modelled or tested in-practice in order to study their effectiveness, which is optional via further research. Several experts however gave (similar) opinions on the in-practice feasibility of the suggested strategies. Therefore, the questionnaire is expected to give a reasonable base in order to answer the third research question.

Results in a broader perspective

The generalization of the research results in temporal perspective (future drought) is rough but reliable, since it is based upon expectations on future changes in atmospheric conditions and hence drought frequencies of KNMI and IPCC (Section 2.2.4). The severeness of net drought-induced subsidence in coming decades might therefore be both an under- or overestimation, and therefore requires further research.

The generalization of the research results in spatial perspective is based upon the interpretation that no correlation is present in the observed time span in both study areas between the extent of relative surface level movements and varying subsidence rates. A similar fluctuation in surface levels, and net subsidence, might thus be found at other soft-soil urban areas in the Netherlands. The found net subsidence matches a prior study (Tolk, 2020) about drought-induced in 2018 at another soft-soil urban area in the Netherlands. These findings however do not directly imply a similar behaviour of surface levels in other soft-soil urban areas in the Netherlands. The uncertainty of this spatial generalization towards other soft-soil urban areas is thus high. In order to verify similar surface level behaviour at elsewhere soft-soil urban areas in the Netherlands, more study locations (having different local characteristics) can be analyzed.

7.4. Importance of this research within its literature framework

Despite the research methodology having its limitations and uncertainties, the results presented are valuable within the literature framework around drought impacts on subsidence. Firstly, the contributions of this research to the knowledge gaps given in Chapter 1 are briefly discussed, after which other valuable findings are covered.

In-practice knowledge of the extent of drought-induced subsidence

As explained in Section 5.5 the research results substantiate earlier findings (Tolk, 2020) and estimations (Van De Ven et al., 2017) of drought-induced subsidence, although the hypothesis proposed in Chapter 2 cannot be fully proved. In comparison to these earlier findings moreover, this research based its findings on a more thorough data analysis of surface level fluctuations.

Furthermore, the brief analysis of local characteristics gives a first insight into their influence on drought-induced subsidence. These influences have mainly been described theoretically. This research therefore supplies these theoretical influences by in-practice data.

Portion of the various subsidence processes

No further contributions can be made to the portion of the various drought-induced subsidence processes with respect to the settlements in soft-soil urban areas. However, it is clarified that the cover layer thickness depends what subsidence processes are triggered. This supplies new topics for further study.

Influence of climate change on drought vulnerability and hence subsidence rates

Machairas (2020) defines drought vulnerability to be the combination of the exposure and sensitivity of urban areas to drought. The analyses in this research show that the sensitivity of soft soils in urban areas depends on the thickness of the (sand) cover layer and various local characteristics (mainly vegetation). Combining this with an increased exposure due to climate change results in a first insight into future drought-induced subsidence and its consequences.

Further contributions

The theoretical framework regarding (drought impacts on) subsidence mainly focuses on long-term subsidence, and more specifically on influences of groundwater extractions. No study is found on the sinusoidal movement of surface levels yet. This study thus gives first insight into the extent of the seasonal surface level fluctuation.

The lag between the start of a drought and the start of increased compaction of soils has been briefly touched in a recent study (Xue et al., 2005), however without estimating its extent. This study therefore gives first insight in the extent of lags, despite not yet giving a physical explanation for the observations. Moreover, the found difference in duration between drought and intensified subsidence substantiates that soil hysteresis has also impact on (seasonal) compaction and swell (Van Asselen et al., 2019).

Lastly, despite most suggestions given to minimize drought-induced subsidence are in general already considered within site preparation strategies, they result in a framework of practical guidelines on minimizing relative surface level movements. Although their effectiveness is not further studied in this research, the suggestions on enhancing mitigation and adaptation strategies can thus directly be implemented into site preparation to reduce future consequences.

Operational (living) phase

Het Meer, Kampen

February 2021

8 Conclusion and recommendations for further research

8.1. Conclusions

Extent of drought-induced subsidence
This research observed a net subsidence of 1 to 1.5 millimeter within the period 2015 to 2019, during the extreme drought in 2018, in two distinct soft-soil areas in the Netherlands (Diemen, Kampen). The observation is in line with the conclusion of a prior study regarding drought-induced subsidence in Den Haag. This suggests extreme drought might cause a net subsidence in (other) Dutch soft-soil urban areas, however a full proof of this hypothesis cannot be given, due to lack of sufficient (reference) data and a statistical substantiation of the results.

Triggering process of drought-induced subsidence
Urban soft-soils are observed to swell and compact seasonally. The extent of soil compaction during dry periods thereby increases for more severe droughts, whereas the extent of swells during wet periods remains similar for varying degree of wetness. An extreme drought thereby results in a net subsidence. This is expected to be caused by a groundwater level drop, which increases the soil's effective stresses and the possibility of degradation of organic materials. The influence of the soil moisture content depletion on subsidence in the unsaturated zone in soft-soil urban areas is nihil, due to the presence of barely compressible (sand) covers. The exact processes are however not understood yet.

Influence of local characteristics
Soil structure
Soils with larger compressible layers are observed to result in slightly larger surface level movements, although no difference in net irreversible subsidence in 2018 is found. The cover thickness is expected to influence what subsidence types are triggered (clinch, shrinkage, peat oxidation). Moreover, the peaty soil in Kampen is noticed to swell (absolutely) in wet periods. There is no explanation found for this observation yet.

Pavement type
Unpaved surfaces in both areas are observed to result in larger relative surface level movements than (open) paved surfaces, although it is not found to result in a larger net drought-induced subsidence in 2018. This conclusion is however merely indicative due to limitations of the InSAR data upon unpaved terrain.

Vegetation
Areas with a higher vegetation percentage are observed to result in a larger seasonal surface level fluctuation than less vegetated areas. Areas with a higher vegetation percentage in dense urban areas might thereby result in a larger net drought-induced subsidence (3 millimeter) than the average found.

Surface water
The larger surface level movement observed near surface waters in both study areas contradicts the expectation that these waters hamper groundwater level variations and hence surface level movements close-by.

Surface waters are therefore assumed, based on literature, to only have influence on groundwater levels and thus drought-induced subsidence at small distances (few meters).

Lag and difference in duration between drought and subsidence
A lag is found between the start of drought and the start of soil compaction, of approximately 100 days. This substantiates assumptions about the presence of lags in academic literature and moreover gives a first insight into its extent. It is however not yet understood what the causes and possible consequences are. Furthermore, the duration of seasonal compaction is found to be approximately 20 days shorter than the duration of the simultaneous drought. This verifies hysteresis between wetting and drying of soils.

Research findings in a broader perspective
In other Dutch soft-soil urban areas a similar drought impact on subsidence rates is expected, since an identical magnitude of the surface level fluctuation is found in distinct locations. No assumptions are however made about drought impacts on soft-soil urban areas abroad, due to lack of knowledge of local scenery's and climate. Although the found singular drought-induced subsidence seems limited with respect to other (artificial) subsidence processes, the seasonal recurrence of (extreme) drought continues to alter surface levels at Dutch soft-soil urban areas (to a greater extent) in coming decades. Not all experts questioned are currently aware of, and hence might underestimate, this long-term reoccurring impact and its consequences. The seasonal (drought-induced) surface level fluctuation might (increasingly) cause crooked buildings; cracks in constructions; faulty (sewer) pipe connections; elevation differences; and more. The seasonal fluctuation should therefore be studied more thoroughly.

Mitigation and adaptation strategies
Mitigation strategies are based on two main principles in order to decrease the (seasonal) fluctuation in effective stresses in soils. Firstly, extensive groundwater level variations can be prevented by water storage and infiltration facilities, reversed drainage, the construction of crawl-space free buildings, or by designing urban areas having vegetation types with a low water usage. Additionally, it is recommended, if soft soil layers are near the surface, to apply a sufficient cover thickness (at raises) which prevents future extensive groundwater levels dropping to these layers, and thereby limits (seasonal) shrinkage and/ or peat oxidation. Secondly, light-weight materials as EPS, Bims, broken Argex, or foam concrete, or self-carrying constructions reduce the top layer's weight and hence the surface level fluctuation.

Principles of the 6M approach (Erkens & Stouthamer, 2020) are suggested to adapt to surface level movements. Spatial and temporal trends, and zones, of vulnerable soft-soil urban areas might be detected by measuring and monitoring surface levels. Drought can be considered in subsidence modelling by applying variable or lower groundwater levels in estimations of effective stresses within consolidation and creep calculations, or by including shrinkage and peat oxidation in the models. Municipalities should include long-term costs in site preparation strategies, possibly comparing it to costs for groundwater nuisance. Moreover, (reoccurring) soil raises might be combined with for example maintenance of sewer systems to reduce costs.

8.2. Recommendations for further research

Based on this research's findings, recommendations on further studies are given. The main recommendations are focused on statistical verification of results presented in this research, and moreover on improvements in measuring and modelling of drought-induced subsidence. Hereafter, recommendations are given on topics to further explore, in order to gain more insights into drought-induced subsidence.

Statistical verification of results
The focus of this research is on qualitative analyses of in-practice data such that significant processes have been disclosed, rather than statistically verifying the results. Similar studies at other distinct research locations, with differing localities (e.g. soil structures; methods of raises; closed-pavement; etc.) are required in order to be able to (statistically) verify the research results of the seasonal surface level fluctuation; the net subsidence; and possible local influences.

Moreover, a larger time interval is required in order to statistically verify that the severe drought in 2018 caused the net subsidence, in comparison to the elastic soil behaviour in other years. Simultaneously, the long-term effects of drought impacts on soils can be studied.

Spatial heterogeneity

Subsidence in urban areas differs spatially on small scale due to the spatial heterogeneity of soils and the complexity of urban (water) systems, and their influence on local groundwater levels and soil moisture content, Since these local differences of groundwater levels and soil moisture content are not examined in this research, this topic requires further study via in-situ measurements. Usage of multiple groundwater wells and InSAR data with a higher resolution results in a more detailed determination of the impact of variations in groundwater levels and soil moisture content on soil processes. The variation in groundwater levels might be even modelled (in 3D) by combining data from the groundwater wells, the subsurface drainage layout, and hydrological variables such as precipitation, (actual) evaporation, seepage, and drainage discharge.

Subsidence mechanisms

Although the clarification of drought-induced subsidence mechanisms is improved by the results presented in this research, the exact share of processes and subsidence mechanisms could not be estimated. Therefore, additional research is needed on the extent of specifically seasonal shrinkage and swell of clay and peat, and on peat oxidation, in soft-soil urban areas. Possible extent of shrinkage in (mixed material) cover layers, and the role of cover thickness at subsidence processes, can be studied by using an extensometer, which includes the unsaturated zone, and combining this weekly gathered data with groundwater levels.

Subsidence measuring/ modelling

Subsidence modelling is prone to spatial inaccuracy, according to the experts questioned in this research. Therefore, the application of lower or varying groundwater levels in consolidation and creep calculations in models might be studied in order to improve model performances. Moreover, it might be possible to create a (conceptual) model with existing equations, which focuses on the surface level fluctuation rather than the average subsidence rates. For example, estimations for (covered) peat oxidation in rural areas (Van den Akker et al., 2007) might be applied in urban areas, but using (sand) covers in the calculation.

A similar study as this one can be preformed but using more local InSAR data of surface levels having less noise. This requires specific corrections of the InSAR images for each neighbourhood, and is therefore costly, however municipalities increasingly have this data available. Additionally, the open accessible InSAR data might be compared to other measurement techniques, e.g. an extensometer, to verify its precision and hence better understand the usefulness of the data for scientific means. It might also be worthy to research if current urban infrastructures can be used to integrate modern measurement techniques, e.g. chips continuous monitoring the elevation.

The expectation of future drought impacts on subsidence rates is only based on an estimation of future return periods of extreme droughts. The various KNMI climate change scenarios for weather patterns can be modelled in order to better interpret future changes of drought impacts on subsidence and its consequences. This can be done by for example conceptually modelling future groundwater levels and soil moisture contents using the changing weather patterns. The outcomes can then be used in further subsidence calculations.

The following topics are recommended to further explore, in order to gain more insights into drought-induced subsidence.

Interdependence of local characteristics

The interdependence of local characteristics is not considered in this research, but could be researched by a sensitivity analysis. First, the local spatial differences can be mapped for the individual local characteristics: more CPTs; more details in the pavement map; a higher resolution for vegetation percentages including their type and size; and a better estimated length of influence zones of surface waters. By increasing this precision but also amount of data (time interval, distinct locations) the sensitivity of local characteristics on the extent of surface level fluctuation can be determined.

A similar research can be conducted, but excluding the (non-overlapping) subsidence data locations, further away than a distance (few meters) of the CPT locations. This reduces the amount of available surface level observations per area, but increases the estimation of the soil structures of the subsidence locations.

Specifically vegetation in urban areas is expected to have a negative impact on (heterogeneous) surface level variations. Although vegetation is included in prior studies on subsidence (de Lange et al., 2009), a thorough study on this topic is lacking. A study can be conducted by measuring the groundwater levels and soil moisture content, and surface level elevations, in the direct surroundings of vegetation, in-situ or in a setup covering single vegetation types.

Temporal trends

By analysing behaviours of cumulative precipitation surplus and surface levels within time intervals (between peaks and valleys) more details on short-term changes can be analyzed. This requires less noisy InSAR data, thus having area-specific corrections. This way more insight could be gained into the lag and difference in duration between drought and the surface level fluctuation. These processes might even be used to minimize surface level fluctuations if it is known whether groundwater levels can be best kept high in the beginning phase of a drought (April in the Netherlands), or in the ending phase (October).

Soil processes

The variation of compression coefficients varying through time is to be analyzed further. This might be done by comparing, within one area, the settlement of places with varying external loads, as is done in the analyzed Kampen area, including variations of loads and subsidence in time.

The cause of the observed net swell of urban peat soils is to be further analyzed, since it is not known if this is caused by atmospheric influences on radar data, or this has other causes. This can be done by comparing InSAR of these locations data with a placed extensometer measuring the elevation in-situ.

Furthermore, the process of the counteracting weight of the unsaturated zone due to changes in water content, possibly hampering the degree of compaction or swell of saturated layers, might be analyzed. This study can be conducted by continuously measuring the groundwater level in combination with the soil moisture in the unsaturated zone and the pressure in the soil (e.g. every 10 centimeters), for which the structure and exact unit weights are known or measured.

Effectiveness of enhanced site preparation strategies

Although most suggested enhanced site preparation strategies already exist, the precise impact of suggested measures on surface level variations requires more research since it is not examined in this study. This can be done by comparing surface level variations in distinct urban areas based upon the usage or absence of measures. Municipalities can be included to monitor effectiveness of measures on long-term by setting up an open database. Thereby drought-induced subsidence can be better anticipated.

Help! Maintenance needed!
Vogelweide, Diemen
February 2021

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A

Cone penetration tests categorization

This appendix consists of a brief introduction into cone penetration tests (CPTs) and the classification of soil types based on CPT results used in this research.

Cone penetration tests
CPTs are one of several in-situ testing methods for soils. CPTs provide fast and continuous profiling of the soil. CPTs are conducted in order to determine the nature and sequence of subsurface/ soil layers, groundwater conditions, and physical and mechanical properties of subsurface/ soil layers (P. Robertson & Cabal (Robertson), 2014). Calculations and designs of (urban) areas are based on CPTs. The accompanying risk and uncertainty of the ground can never fully be eliminated by CPTs (P. Robertson & Cabal (Robertson), 2014).

A general overview of cone penetrometer components is given in Figure A.1. It consists of a cone on end of (series of) rods which are drilled into the ground at constant speed by a machine. Continuous measurements are made of the resistance of cone and friction sleeve of the penetrometer. Additional sensors can be present at penetrometers measuring example given pH, temperature, EC, etc.

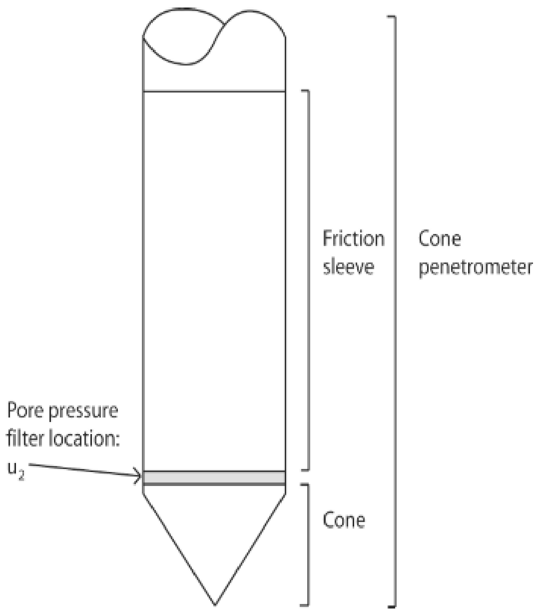

Figure A.1: *Components of cone penetrometer.* Acquired from Robertson (2014).

CPTs can be conducted to depths of over 100 meter in soft soils (P. Robertson & Cabal (Robertson), 2014). The standard rate of penetration is 2 cm per second, giving one measurement per second (so each 2 cm). In Figure

A.2 an example of CPT results is shown for a conducted drill in Diemen. Cone resistance (conusweerstand) is typically high in sand and low in clay or peat. Friction ratio (compared to cone resistance; wrijvingsgetal) is however low in sands and high in clay and peat. CPTs do not result in estimations of physical characteristics (for example grain size distribution) but rather mechanical characteristics (stiffness, compressibility). This is also called the Soil Behaviour Type (SBT).

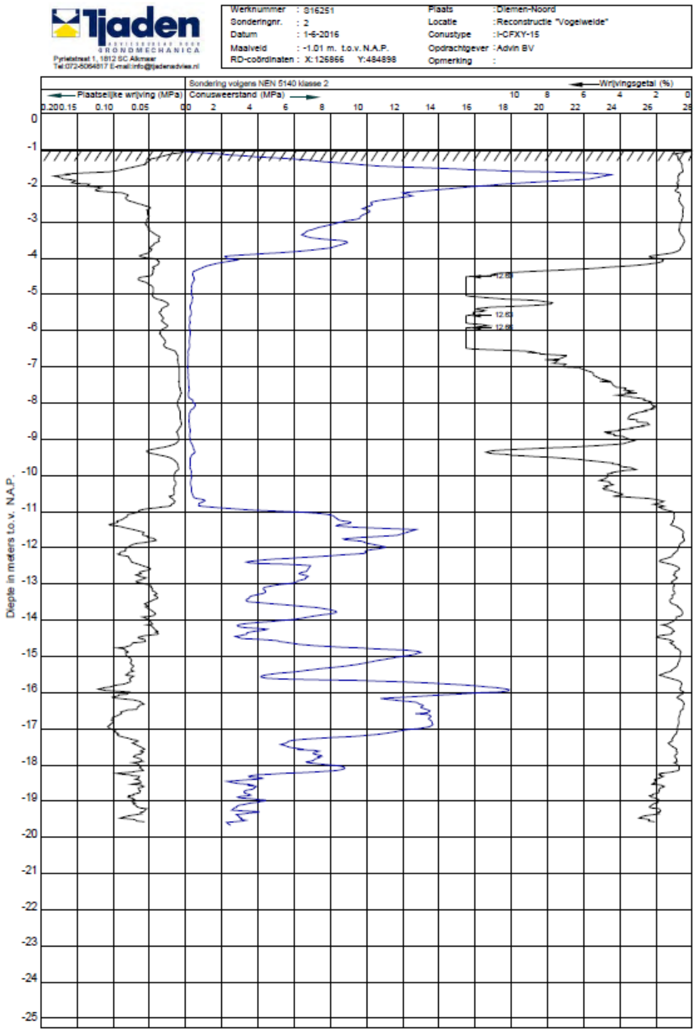

Figure A.2: *Cone penetration test results on paper in Vogelweide, Diemen.* Acquired from Te Groen (2016).

Categorization

The categorization of soil types based on cone penetration test results is based on Robertson & Cabal (Robertson) (2014). Figure A.3 shows the various soil behaviour types distinguished. As shown the soil types are not categorized as sand, clay and peat. Therefore, a simplification of the categorization is required.

Zone	Soil Behavior Type
1	Sensitive, fine grained
2	Organic soils - clay
3	Clay – silty clay to clay
4	Silt mixtures – clayey silt to silty clay
5	Sand mixtures – silty sand to sandy silt
6	Sands – clean sand to silty sand
7	Gravelly sand to dense sand
8	Very stiff sand to clayey sand*
9	Very stiff fine grained*

** Heavily overconsolidated or cemented*

Figure A.3: *Soil Behaviour Types.* Acquired from Robertson & Cabal (2014).

Figure A.4 shows the simplification of the categorization of soil types based on cone penetration test results. The area which is not classified is a combination of cone resistance and friction ratio which is not found in the study areas. The ranges of cone resistance and friction ratio for different soil types is based on existing tables of soil characteristics (Blok, 2013).

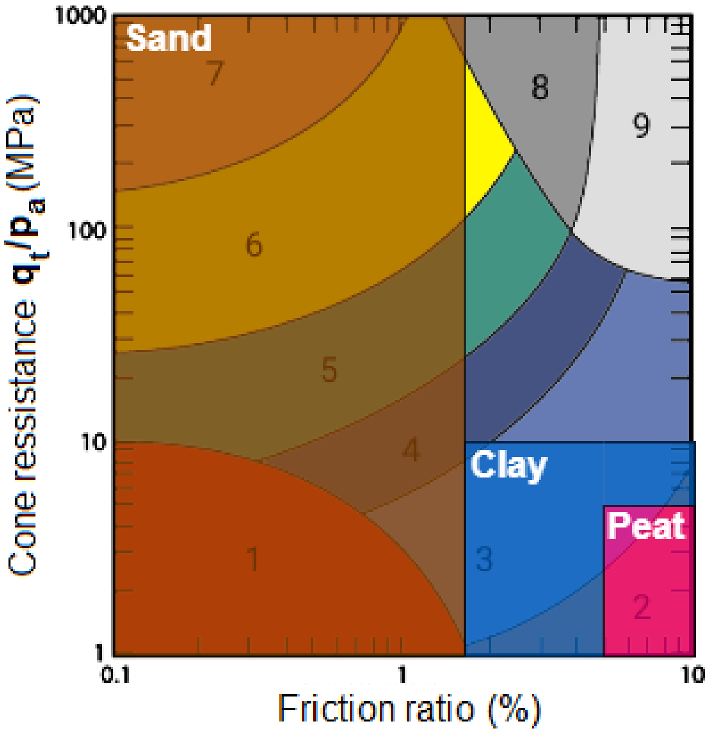

Figure A.4: *Simplification of Robertson's (2014) classification of soil types based on cone penetration test results.* Reprocessed from Robertson (2014).

The resulting ranges of cone resistance and friction ratio are shown below in Table A.1.

Table A.1: *Full soil type classification used in this research based on (Blok, 2013).*

Soil type classification	**Cone resistance** *Low value*	*High value*	**Friction ratio** *Low value*	*High value*
Sand, course	0	1000	0	0.6
Sand	0	1000	0.6	0.9
Sand, silty	0	1000	0.9	1.2
Sand, clayey	0	1000	1.2	2
Clay, solid	0	10	2	3.5
Clay, moderate	2	4	3.5	5
Clay, limp	0	2	3.5	5
Clay, peaty	4	6	5	10
Peat	0	4	5	10

Further distinction of specific sand, clay or peat types is not needed since compressiblity calculations are only used roughly. Moreover a further distinction is not needed for the given suggestions on site preparation strategies (Van de Ven et al., 2009). Therefore, a further simplification of the table above is made for this research. The final produced ranges of sand, clay and peat for cone resistance and friction ratio are shown in A.2.

Table A.2: *Simplification of full soil type classification used in this research.*

Soil type classification	**Cone resistance** *Low value*	*High value*	**Friction ratio** *Low value*	*High value*
Sand	0	1000	0	2
Clay	0	10	2	5
Peat	0	4	5	10

B

InSAR background information

This appendix covers information of the satellite data used in the research, provided by bodemdalingskaart.nl, an initiative of Nederlands Centrum voor Geodesie en Geo-Informatica in collaboration with several other Dutch companies, universities and institutes (Bodemdalingskaart.nl, 2020). One of the companies, SkyGeo, processes the raw satellite data (InSAR) acquired from NASA. Figure B.1 shows an overview of the dataset for the entire Netherlands.

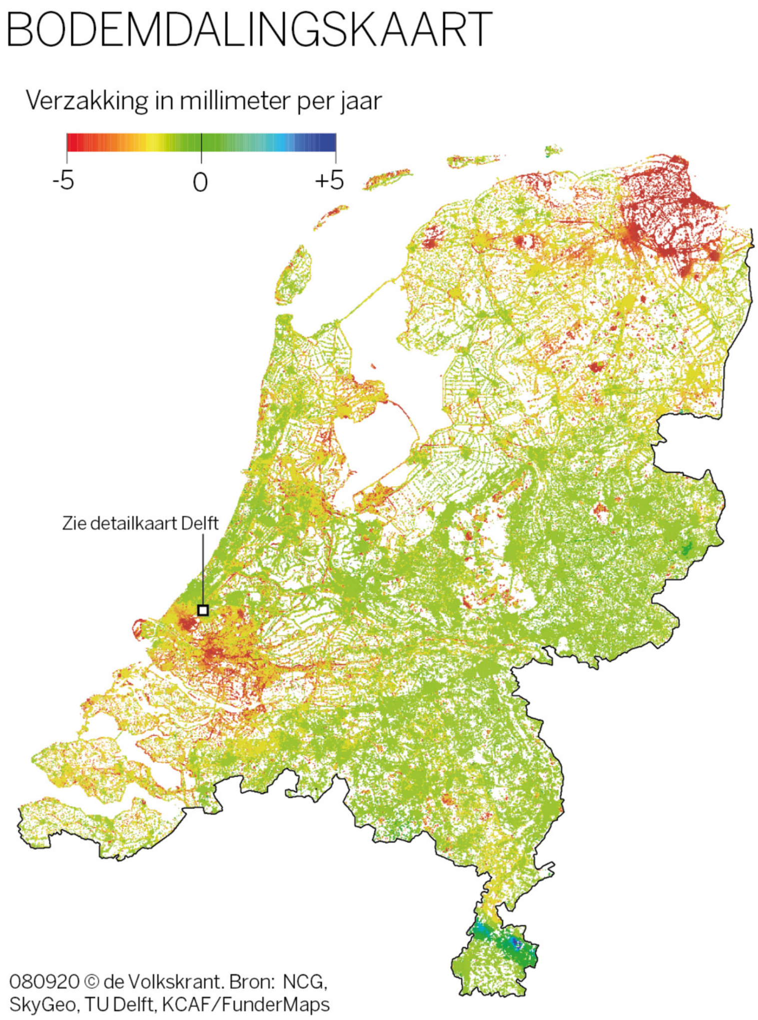

Figure B.1: *Map of subsidence measurements from InSAR satellite data in the Netherlands.* Acquired from De Volkskrant on 11-09-2020 (Tieleman, 2020).

The explanation of this processing below is provided by Sataloff et al. (n.d.).

InSAR radar signals

InSAR is an abbreviation for Interferometric Synthetic Aperture Radar. It is a satellite which consists of a device which measures changes in the elevation of surface levels by measuring wave length and amplitude sending and reflecting from earth's surface by a radar emitter. In case the earth's surface subsides the radar signal has to travel a longer distance through which its wave length incoming is changed in comparison to earlier measurements, shown in Figure B.2. The phase difference (extra bit of wave length) thus describes the extent of subsidence of surface levels. A full wave cycle difference between two measurements results in a difference in surface level elevation of few centimeters, through which the level of detail is very precisely, in order of millimeters.

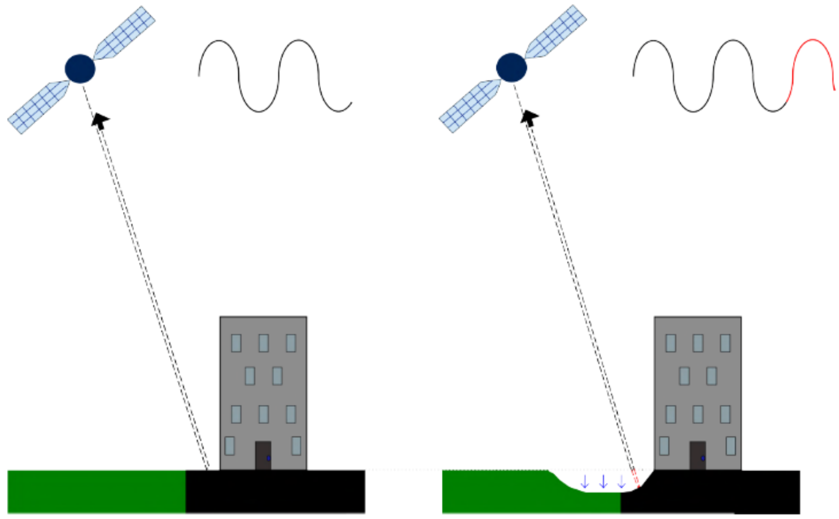

Figure B.2: *InSAR radar signals detecting subsidence.* Acquired from Sataloff et al. (n.d.).

As explained InSAR is used to determine phase differences between two measurements. Thereby the satellite measures relative surface level movement, without measuring the exact height of the earth's surfaces. Several characteristics of InSAR and required corrections from raw satellite data to surface level differences are explained below.

Persistant and Distributed Scatterers

Firstly the difference between Persistent Scatterers (PS) and Distributed Scatterers (DS) should be elaborated. The InSAR satellite measures with a spatial resolution, where each scanned area (pixel) may have multiple reflection points - also called scatterers. In case one scatterer reflects much stronger than the others (PS) the weaker scatterers can be considered negligible for the measurements, giving a high signal to noise ratio. In case all of the scatters in the pixel give a weaker reflection (DS), neighbouring pixels with similar reflection characteristics are searched by an algorithm in order to check the trustworthiness of the scatterers. The data used in this research consists mainly of Persistent Scatterers since it measures urban areas (man-made solid structures). Near vegetation areas the data is mainly DS.

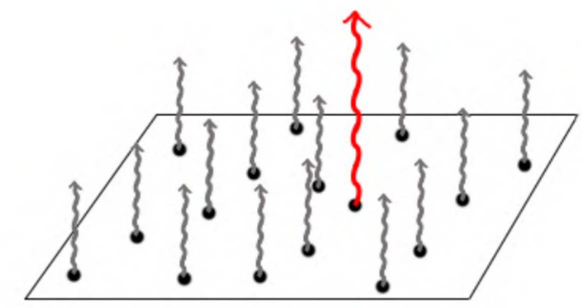

Figure B.3: *Persistant Scatterers.*Acquired from Sataloff et al. (n.d.).

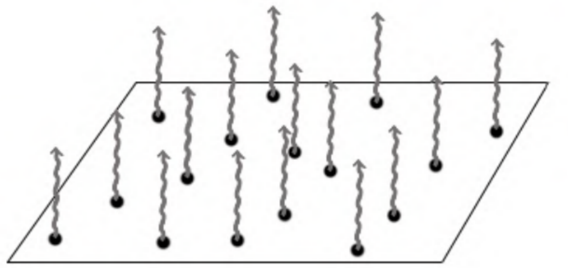

Figure B.4: *Distributed Scatterers.* Acquired from Sataloff et al. (n.d.).

Horizontal/vertical displacements
Satellites observe the earth's surface under an angle. Therefore they measure not only vertical displacement, but also horizontal. It results therefore of slightly odd measurements. This is accounted for in calculations of surface level movements. In case radar signals of two satellites orbiting the earth differently are combined a better estimation of horizontal and vertical components of displacement can be made. The data used in this research solely consists of vertical displacements since infrastructures like streets have almost zero horizontal displacements. Horizontal variations are therefore ignored.

Consistent reflecting objects
As shown in Figure B.5 not all radar signals are reflected properly to the satellite. The best reflecting surfaces are solid objects like buildings or infrastructure. This makes InSAR very useful for urban areas. Surface water might act as a mirror through which almost no signal is reflected back to the satellite. InSAR uses short wavelengths to obtain high point densities on infrastructures. Furthermore, objects should be consistent in order to have its location recognisable. Solid objects (coherent reflectors) work very well with radar signals, but example given vegetation changes through seasons and is quicker removed by the algorithm. The radar signal however might sometimes penetrate through vegetation and measure the bare soil.

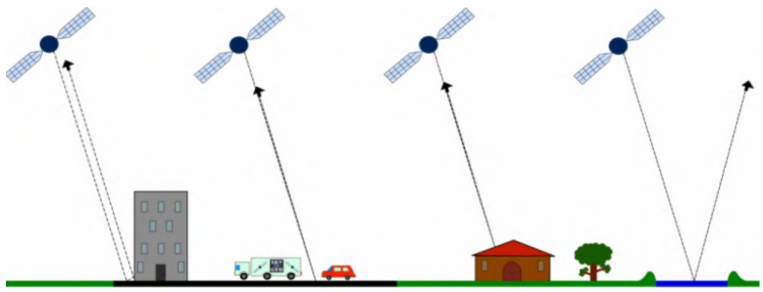

Figure B.5: *Radar reflections on the earth's surface.* Acquired from Sataloff et al. (n.d.).

Resolution
As already explained the satellite radar measures the earth's surface with a spatial resolution. Per scanned area only one measurement (likewise camera's) can be obtained. If these areas are smaller, giving a higher resolution, more measurements can be obtained from the earth's surface. Distinction is made between standard and high resolution mainly based on the type of satellite. The high resolution images have the advantage to have less noise, a better accuracy in displacement and location, and more measurement points.

Point location (X,Y,Z)
Satellites obtain one measurement per cell (resolution) but cannot therefore know exactly the location of the dominant reflection in the cell. The precision of the reflection location depends on the resolution of the satellite, as shown in Table B.1.

Table B.1: *Position precision of subsidence data after corrections.* Reprocessed from Sataloff et al. (n.d.).

	X,Y	**Z**
Standard resolution	2-3m	2-2.5m
High resolution	1-2m	1-1.5m

Measurement precision
Measurements are prone to precision and reliability. The table above shows the precision on location estimation. Table B.2 shows the precision per individual measurement (in time and location) and the overall displacement velocity per location. The Point Quality derived by SkyGeo as indication of the quality of the unwrapping (explained below) per measurement point is not taken into account at the research since different steps to encounter the noise are taken (see Chapter 3).

Table B.2: *Precision in measurements and according displacement velocity.* Reprocessed from Sataloff et al. (n.d.).

	Individual measurement precision	**Displacement velocity precision**
Standard resolution	6-8mm	1-2mm/year
High resolution	2-3mm	<1mm/year

Unwrapping
The measured phase difference in space results in a so-called interferogram, where for a larger area of thousands of pixels the phase differences are displayed. The derivation of the displacement from the interferogram is called unwrapping. Correlations in time and/ or space are used to 'unwrap' measurements. Unwrapping is executed correctly by SkyGeo 99% of the time.

Atmospheric conditions
Several corrections are to be made to account for atmospheric conditions affecting radar signals (noise). The disturbances of the radar signal are due to atmospheric humidity, pressure and temperature differences. The time of the day a measurement is made influences the radar signal due to heat and water vapor being produced by the sun. The atmosphere is however not correlated in time due to varying weather conditions (e.g. thunder storms), but the displacement of surface levels is (Sataloff et al., n.d.). Based on this principle the atmospheric influences on surface levels can be separated.

The atmospheric conditions have a spatial heterogeneity, which might affect the signal greatly over larger areas. The variation in atmospheric conditions for each observation location is therefore estimated with a model of SkyGeo. This model uses the Kriging method (spatial interpolation) for the estimations, in combination with several high-quality calibration points with a regular displacement pattern, in order to create an atmosphere map over the area (in time). The accuracy of the estimations increases by a decrease in the area for where corrections are to be made. The corrections for atmospheric conditions of a neighbourhood or city can be made more precise than the corrections for an entire country. Since the atmospheric conditions are to be estimated by a model, the inaccuracy influences the accuracy of the surface level calculations, but is not the leading factor for seasonal displacement of surface levels.

The quality of the measurement point is given by a 'Point Quality'. This indication of noise, induced by atmospheric conditions and the satellite resolution, ranges from 0 (lots of noise) to 1 (nihil noise). A minimal quality cut-off is applied by SkyGeo before delivering the dataset (Sataloff et al., n.d.). The points quality is derived by comparing the calculations to the estimated surface level movement of a model, which might be for example linear, quadratic, or seasonal (sinusoidal). However, if a wrongly model is used for comparison, the point quality can be reduced.

Data used
In this research the satellite Sentinel-1 is used for collection of surface level movements. In this research descending satellites are used since these measure the earth's surface in the Netherlands at 06:00, so before daily evaporation has influence. This satellite is working since 2014. It has a repeat cycle of 12 days. The resolution is standard for which specifications of precision in measurement and point location can be found in the

given tables above. The satellite data is openly accessible by visiting bodemdalingskaart.nl, an initiative of Nederlands Centrum voor Geodesie en Geo-Informatica, in collaboration with several other Dutch companies, universities and institutes (e.g. TU Delft and SkyGeo) (Bodemdalingskaart.nl, 2020).

The data used is converted by means of a simple moving average to reduce the influence of possible noise. This is explained in appendix C. Furthermore, buildings are removed from the dataset before analyzing the data. The observation locations on buildings are located by means of their spatial overlap with a building in the open TOP10NL maps of PDOK (n.d.). It is chosen not to use the point height and DEM height of the observation locations since it has similar/ larger uncertainty in their elevation precision. The Point Quality of the observations in both locations of the research varies between 0.6 (fine quality) and 0.99 (very good quality).

C

Consecutive data conversion steps

This appendix gives a detailed overview of consecutive data conversion of subsidence, cumulative precipitation surplus, and groundwater data into useful parameters for the research's analyses. Furthermore, the temporal transformation of the data is also covered.

C.1. Subsidence data conversion

Subsidence data consists of time series of relative changes in surface level for many locations in an area, as observed by a satellite. Subsidence data is acquired from the initiative bodemdalingskaart.nl (Bodemdalingskaart.nl, 2020). The raw satellite data (InSAR) is processed by one of the accompanying companies (SkyGeo) by means of corrections to relative changes in surface levels. These acquired time series need several conversion steps in order to analyze them. An overview is given in Figure C.1

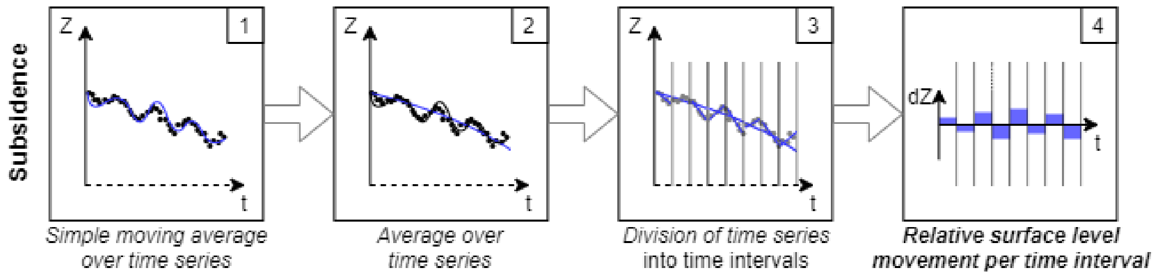

Figure C.1: *Conversion of subsidence time series to relative surface level movements per time interval.*

C.1.1. Step 1: Simple moving average

Since the surface level data from satellites is prone to noise (atmospheric conditions, Appendix B), firstly a Simple Moving Average (SMA) is calculated over the time series. The SMA calculates for each observation point the average of the observations for a certain window around this point (two-sided, centered) as shown in equation C.1. Since not every day an observation is made, the observation number x is given for time t during the entire time series period: at start x=1 on t=0, but x=2 is on t=11 (approximately 11 days frequency of satellite).

$$SMA(x) = \frac{\sum_{j=x-w/2}^{x+w/2} (y_j)}{w} \tag{C.1}$$

Where:

SMA(x)	Simple Moving Average calculated at x [mm]
y_j	Observation at point j within window w [mm]
w	Window size of SMA [-]
x	Observation number at time t [-]

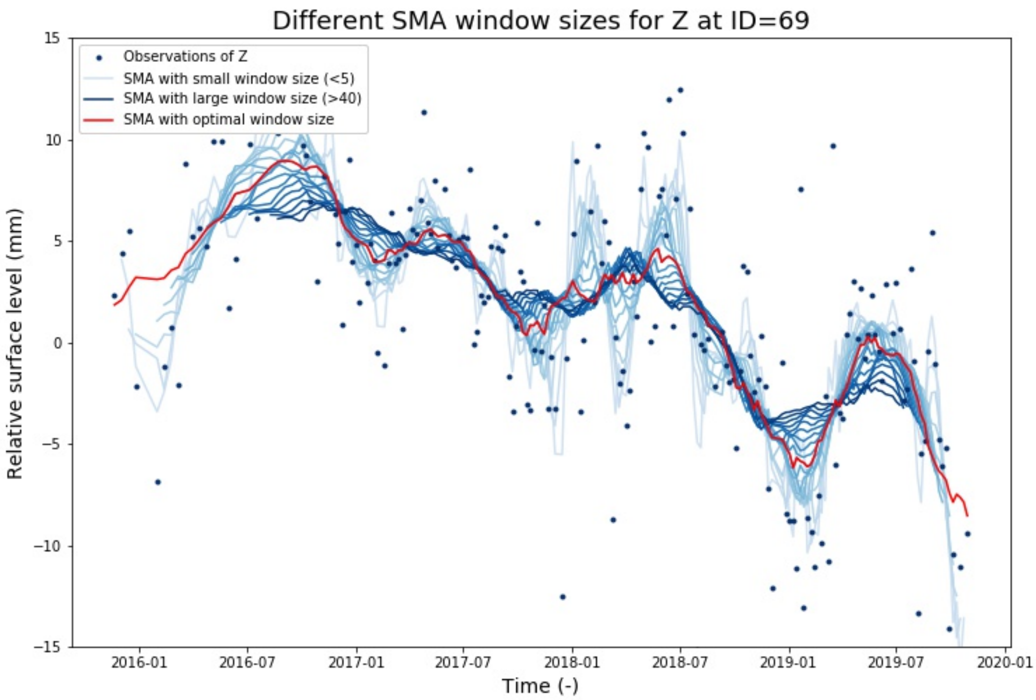

Figure C.2: *Surface level observations, considered and optimized simple moving averages at one location in Vogelweide, Diemen.* The simple moving average is optimized to have a window of 21 days (10 at both sides).

As explained the SMA value depends on the window size used in the calculations. Various window sizes are considered in the study where-after an optimal window size is chosen. Figure C.2 shows an example where it becomes clear that for higher window sizes the SMA results in a smoother line with less extremes. The optimal window size is calculated by minimizing the Mean Absolute Difference (MAD) between the SMA calculations in the entire time series and the observations of the surface level. The MAD is calculated by:

$$MAD_w = \frac{\sum_{x=1}^{N} |Z(x) - SMA(x)|}{N} \tag{C.2}$$

Where:
- MAD$_w$ Mean absolute difference for SMA window size w [mm]
- Z (x) Relative surface level observation by satellite at observation x [mm]
- N Amount of observations in the time series [-]

So that the optimized SMA with optimal window size is showed in Figure C.3 and calculated to be:

$$SMA_{opt} = min(MAD_{w_1}, MAD_{w_2}, ..., MAD_{w_X}) \tag{C.3}$$

Where:
- SMA$_{opt}$ Optimalized SMA [-]
- X Amount of window sizes considered [-]

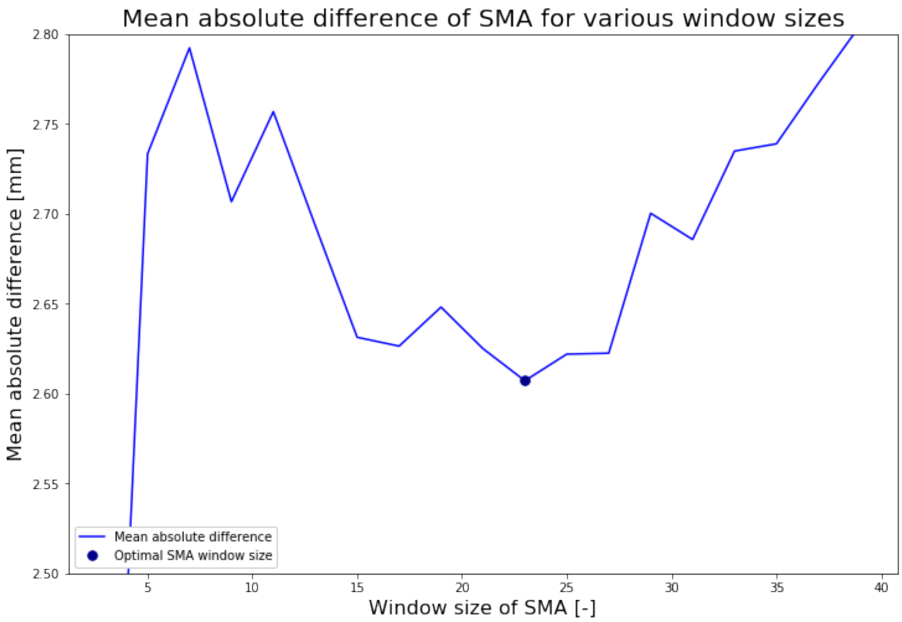

Figure C.3: *Example of SMA with optimized window size of 21.*

C.1.2. Step 2: Average over time series

The second step is the calculation of average subsidence rates for the individual time series. Since subsidence is not only induced by drought (but more by e.g. external loads) it is important to counter the average subsidence in the calculations. This way the analysis can be conducted on variations of subsidence and not on the average subsidence itself. The various surface levels data are estimated to change linear trough the time series since it has only a length of 4 years. Equations C.4 (linear estimation) and C.5 (regression of data) show the two steps needed to calculate the average subsidence.

$$y = A \cdot x + B \tag{C.4}$$

The least squares regression fit calculates for which A and B of formula C.4 the sum of distances from the observations in the time series to the accompanying line y is the smallest. In other words:

$$fit(A\&B) : min \sum_{x=1}^{N} \left(\frac{Z(x) - y(x)}{\sigma_x} \right)^2 \tag{C.5}$$

Where:

Z (x)	Relative surface level observation by satellite at observation x [mm]
y(x)	Calculated value of estimated regression line at x [mm]
σ_x	Standard error of the estimated regression [mm]
N	Amount of observations in the time series [-]

The standard error σ_x is then calculated by:

$$\sigma_x = \sqrt{\frac{\sum \left(y(x) - \overline{Z} \right)^2}{N}} \tag{C.6}$$

Where:

$\overline{Z}$	Mean surface level over time series

C.1.3. Step 3: Time intervals

In the third step time series are split in sub-periods based on peaks (start of drought) and valleys (end of drought) of the simple moving average shown in Figure C.4. This way the surface level data is divided into intensified subsidence: compaction (red line going down faster) and less subsidence: swell (red line going down slower, or rising). The peaks and valleys are calculated by maximizing the absolute distance between the average subsidence line and SMA line. This is done by first splitting the time series into smaller periods where the SMA is either larger or smaller than the average. This is done by minimizing the results of SMA value minus value of average in the graph (approximate intersections).

$$I_i(x) = min\big(SMA(x) - y(x)\big) \tag{C.7}$$

Where:

$I_i(x)$ Intersection i at x splitting the time series into negative or positive results of SMA(x) - y(x) [-]
y(X) Value of average subsidence rate at observation x [mm]

Next, over these smaller intervals the absolute maximum value of difference between SMA and average of subsidence is searched giving either a peak or valley.

$$P_i(x) = max_{I_i(x),I_{i+1}(x)}\,(abs(SMA(x) - Z(x))) \tag{C.8}$$

Where:

$P_i(x)$ Observation number x of peak or valley i in the time series
$max_{I_i(x),I_{i+1}(x)}$ Observation number x with maximum over part of time series between intersections i and i+1 []

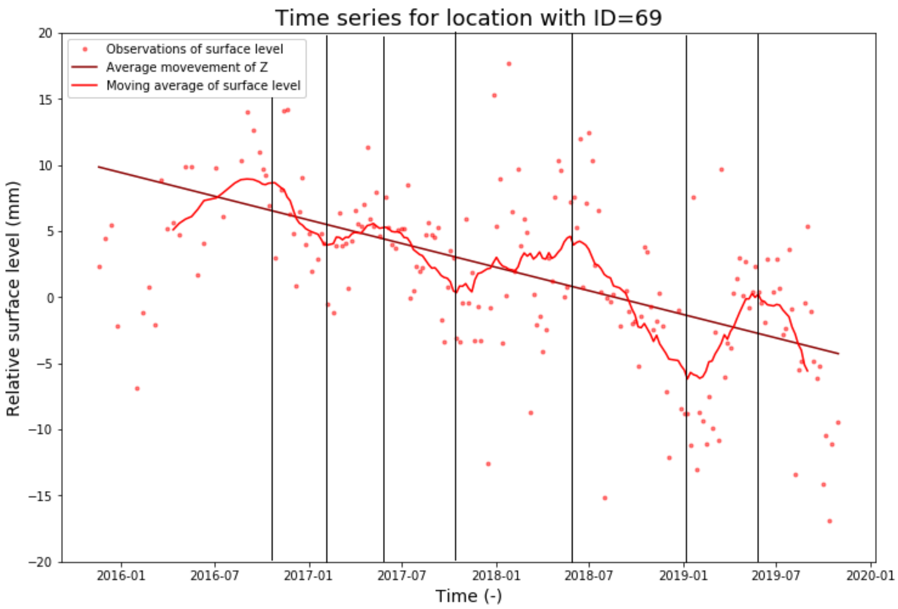

Figure C.4: *Example of average subsidence rate together with peaks and valleys of SMA.*

It is important to say that in case the SMA gives many peaks there can be a minimum distance installed between the intervals, of example given 5 observations (approximately 60 days). The amount of periods of compaction (intensified subsidence) and swell should be the same as amount of wet/dry periods: seasonally (dry, summer; wet, winter). An optimization therefore in the SMA window should be found.

C.1.4. Step 4: Calculate relative surface level movements

Last step is to calculate the relative surface level movement per time interval. This is the difference in average surface level movement in a period and SMA surface level movement in a period. Firstly the change in average subsidence over a certain period is expressed as:

$$\Delta y_i = y(P_i(x)) - y(P_{i+1}(x)) \tag{C.9}$$

Where:

Δy_i	Change in average subsidence over period i [mm]
$y(P_i(x))$	Value of average subsidence at peak or valley i (left value) [mm]
$y(P_{i+1}(x))$	Value of average subsidence at peak or valley i+1 (right value) [mm]

Next step is to calculate the changes of the SMA with computed optimal window size over the periods. This is done same-like the change in average subsidence:

$$\Delta SMA_{opt,i} = SMA_{opt}(P_i(x)) - SMA_{opt}(P_{i+1}(x)) \tag{C.10}$$

Where:

$\Delta SMA_{opt,i}$	Change in optimal SMA over i [mm]
$SMA_{opt}(P_i(x))$	Value of optimal SMA at point peak or valley i [mm]
$SMA_{opt}(P_{i+1}(x))$	Value of optimal SMA at point peak or valley i+1 [mm]

Lastly the relative surface level movement for each period is calculated. This is calculated as the difference between the change in average subsidence and absolute change of the surface level over a period:

$$f_i = \Delta SMA_{opt,i} - \Delta y_i \tag{C.11}$$

Where:

f_i Relative surface level movement over period i [mm]

The relative surface level movement illustrates the extent of extra or less subsidence for a certain period compared to the average subsidence.

C.2. Cumulative precipitation surplus

KNMI defines a drought by cumulative potential precipitation deficits of areas. To be able to interpret the extent of drought or wetness of time intervals first a few adjustments at this calculation method are required. An overview is given in Table C.1, followed by a more detailed description.

Table C.1: *The differences between calculation steps of KNMI and this research.* The Urban Water balance Model is a product of Dutch company Deltares (Brolsma & Vergroesen, 2020).

KNMI calculation	**Research calculation**
Usage of potential evaporation data via Makkink method	Usage of actual evaporation data via Urban Water balance Model
Cumulative precipitation deficit	Cumulative precipitation surplus
Fixed time intervals of summer & winter half years	Time intervals based on precipitation surplus

The main difference with KNMI calculations is usage of actual evaporation instead of potential evaporation. The actual evaporation improves process estimations since it is more specified to local context. This modification via Urban Water balance Model (Brolsma & Vergroesen, 2020) is given in Appendix D. Furthermore, the terminology *cumulative precipitation surplus* is used instead of *cumulative precipitation deficit* since this research focuses on (differences between) both dry and wet periods. Lastly, fixed time intervals of KNMI do not exactly overlap drought time intervals and therefore time intervals based on peaks and valleys (maximum and minimum values) of cumulative precipitation surplus are used. The conversion to cumulative precipitation surplus is shown in Figure C.5.

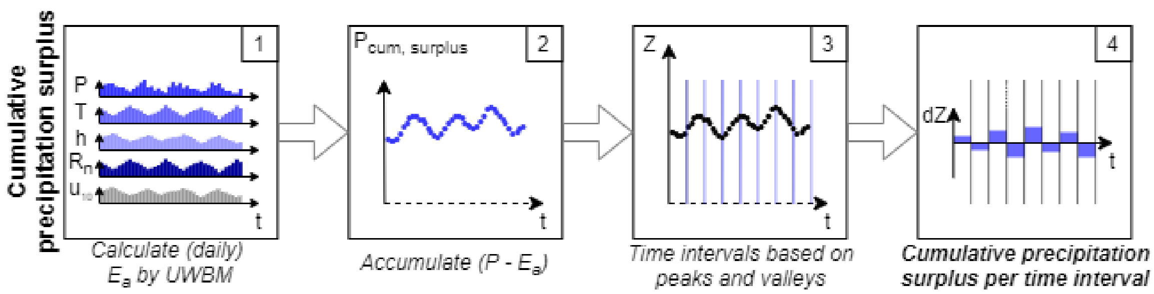

Figure C.5: *Conversion of raw precipitation P & variables for open water evaporation data (temperature T, relative humidity h, net radiation Rn, wind speed at 10 meters height u10) via Urban Water balance Model (Brolsma & Vergroesen, 2020) (UWBM) to cumulative precipitation surplus data.*

C.2.1. Step 1: Urban Water balance Model

The Urban Water balance Model requires precipitation, open water evaporation, and potential reference crop evapotranspiration data in order to calculate non-intercepted precipitation and actual evaporation and hence cumulative precipitation surplus. Open water evaporation is calculated via Penman (Schuurmans & Droogers, 2010) by acquired temperature, relative humidity, net radiation, and wind speed time series from an open database of weather stations data of KNMI (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a). Potential reference crop evapotranspiration is estimated to be approximately 0.8982· Penman Evaporation (Brolsma & Vergroesen, 2020). Precipitation data is directly acquired from aforementioned KNMI database. The input and process of the Urban Water balance Model is explained in Appendix D.

C.2.2. Step 2: Calculate cumulative precipitation surplus

The daily cumulative precipitation surplus data is calculated by subtraction of actual evaporation data (UWBM) from precipitation data per time step (day). Since the precipitation and actual evaporation data is computed daily the equation below consists of t (days) rather than x (observation numbers). The cumulative outcome of the precipitation surplus over the time series period is therefore given by:

$$P_{cum,sur}(t) = \sum_{i=0}^{t} (P(i) - E_a(i)) \tag{C.12}$$

Where:

$P_{cum,sur}(t)$	Cumulative precipitation surplus at time t [mm]
P(i)	Precipitation at i [mm]
$E_a(i)$	Actual evaporation as assessed by Urban Water balance Model at i [mm]
i	Day of observation [d]
t	Day of interest/ calculation [d]

For the entire time series t is equal to N, the amount of days in the time series. In case the cumulative precipitation surplus of day B is bigger than earlier day A the in-between period was 'wet' (more precipitation than evaporation), while other way around it was 'dry' - and if this is significant in days or extent it is considered a drought.

C.2.3. Step 3: Time intervals

The third step is the division of entire time series into periods. This is not based on the division of summer and winter half years of the KNMI, but rather on the peaks and valleys of cumulative precipitation surplus. Hence, the boundaries of the periods align better to these peaks and valleys, as is shown in Figure C.6.

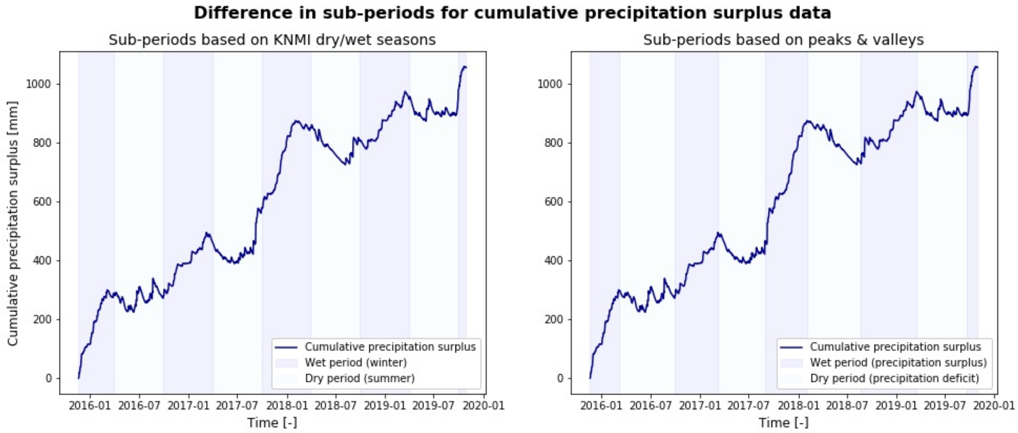

Figure C.6: *Example of difference in periods for KNMI computation and this research computation.*

In this research the places (days) of peaks and valleys are computed by hand since only 2 cumulative precipitation surplus time series are calculated. It can however also be done by calculating the next peak or valley after prior opposite valley or peak. This is for example done for subsidence data (Section C.1.3)

C.2.4. Step 4: Calculate extent of drought or wetness per time interval

The change of cumulative precipitation surplus per period gives an extent of drought or wetness of the period. This is calculated by:

$$\Delta P_{cum,sur,j} = P_{cum,sur}(P_i(t)) - P_{cum,sur}(P_{i+1}(t)) \tag{C.13}$$

Where:

$\Delta P_{cum,sur,j}$	Change in cumulative precipitation surplus over period j [mm]
$P_{cum,sur}(t)$	Cumulative precipitation surplus at day t [mm]
$P_i(t)$	Right boundary (peak or valley) of period j [d]
$P_{i+1}(t)$	Left boundary (peak or valley) of period j [d]
j	Sub-period of time series [-]

If cumulative precipitation surplus is calculated to be positive it indicates a wet period. If cumulative precipitation surplus is calculated to be negative it indicates a dry period (drought).

C.3. Groundwater regime

The conversion of groundwater level measurements into a representative groundwater level is done by taking the median for every observation time step. The median is expressed by the value of the middle value in the *ranked list* (from lowest to highest) of all measurements for a time step:

$$M(t) = v_{mid}(t) \tag{C.14}$$

Where:

M (t)	Median value of measurements at time t
$v_{mid}(t)$	Value at position $mid(t)$ at time t

Wherein for odd number of measurements:

$$mid(t) = \left(\frac{n+1}{2}\right) \tag{C.15}$$

And for even number of measurements:

$$mid(t) = \frac{\left(\frac{n+1}{2} + \frac{n}{2}\right)}{2} \tag{C.16}$$

Where:

mid (t)	Position of median in ranked list of measurement values
n	Number of different measurement values at time t

C.4. Temporal transormation of data

C.4.1. Lag of subsidence

An important aspect of the behaviour of surface levels with respect to cumulative precipitation surplus is that it is a slower process, which might cause delay (lag). In other to counter this, the possible lag should be calculated and accounted for in the database.

The possible lag is calculated by calculating the difference in days between the peaks (not valleys!) of the cumulative precipitation surplus (start of dry season) and peaks (not valleys!) of surface level (start of intensified subsidence period) in the time series. As explained in earlier steps the amount of peaks in the SMA data should therefore be equal to the amount of peaks in cumulative precipitation surplus data.

$$L_i = P_{i,SMA}(t) - P_{i,sur}(t) \tag{C.17}$$

Where:

L_i	Lag i between start of intensified subsidence and start of drought (negative cumulative precipitation surplus) [d]
$P_{i,SMA}(t)$	Time step (day) of peak i of simple moving average of subsidence data
$P_{i,sur}(t)$	Time step (day) of peak i of cumulative precipitation surplus data

The lag is then expressed as the average of the individual differences in days for a given point:

$$\overline{L} = \frac{\sum_{P_i(t)=1}^{P_{tot}} (P_{i,SMA}(t) - P_{i,sur}(t))}{P_{tot}} \tag{C.18}$$

Where:

$\overline{L}$	Lag between start of intensified subsidence and start of drought (negative cumulative precipitation surplus) [d]
$P_{i,SMA}(t)$	Time step (day) of peak i of simple moving average of subsidence data
$P_{i,sur}(t)$	Time step (day) of peak i of cumulative precipitation surplus data
P_{tot}	Total amount of peaks in time series [-]

Chosen is not to calculate the difference between the valleys, since the period of subsidence data can be spread out differently than the cumulative precipitation surplus data. Therefore, the valleys are expected to be less comparable. This difference in duration is explained below.

C.4.2. Difference in duration of subsidence and cumulative precipitation surplus

The difference in duration of intensified subsidence period and drought period is calculated since it represents the hysteresis of soil wetting and drying. The difference in duration is calculated by first calculating the period length of drought. This is done by subtracting the time step (day) of a peak (start of drought) from its subsequent valley (end of drought) time step (day):

$$D_{i,sur} = P_{i,sur,valley} - P_{i,sur,peak} \tag{C.19}$$

Where:

$D_{i,sur}$	Duration of drought i in cumulative precipitation surplus time series [d]
$P_{i,sur,peak}$	Time step (day) of peak i of cumulative precipitation surplus time series [d]
$P_{i,sur,valley}$	Time step (day) of subsequent valley i of cumulative precipitation surplus time series [d]

The same is done for simple moving averages of surface level time series:

$$D_{i,SMA} = P_{i,SMA,valley} - P_{i,SMA,peak} \tag{C.20}$$

Where:

$D_{i,SMA}$	Duration of intensified subsidence (compaction) i of SMA in relative surface level time series [d]
$P_{i,SMA,peak}$	Time step (day) of peak i of SMA in relative surface level time series [d]
$P_{i,SMA,valley}$	Time step (day) of subsequent valley i of SMA in relative surface level time series [d]

The difference in duration is then calculated by subtracting the duration of drought from intensified subsidence:

$$D_i = D_{i,SMA} - D_{i,sur} \tag{C.21}$$

Where:

D_i Duration difference of drought and intensified subsidence (compaction) [d]

A negative difference in duration indicates a faster shrinking process than swelling (hysteresis), wherein the duration of a drought is accounted for.

C.5. Overview of converted subsidence data

Figure C.7 shows an overview of subsidence and cumulative precipitation surplus data which can be compared. It shows the time intervals of cumulative precipitation surplus, the computed average subsidence and average lag of subsidence.

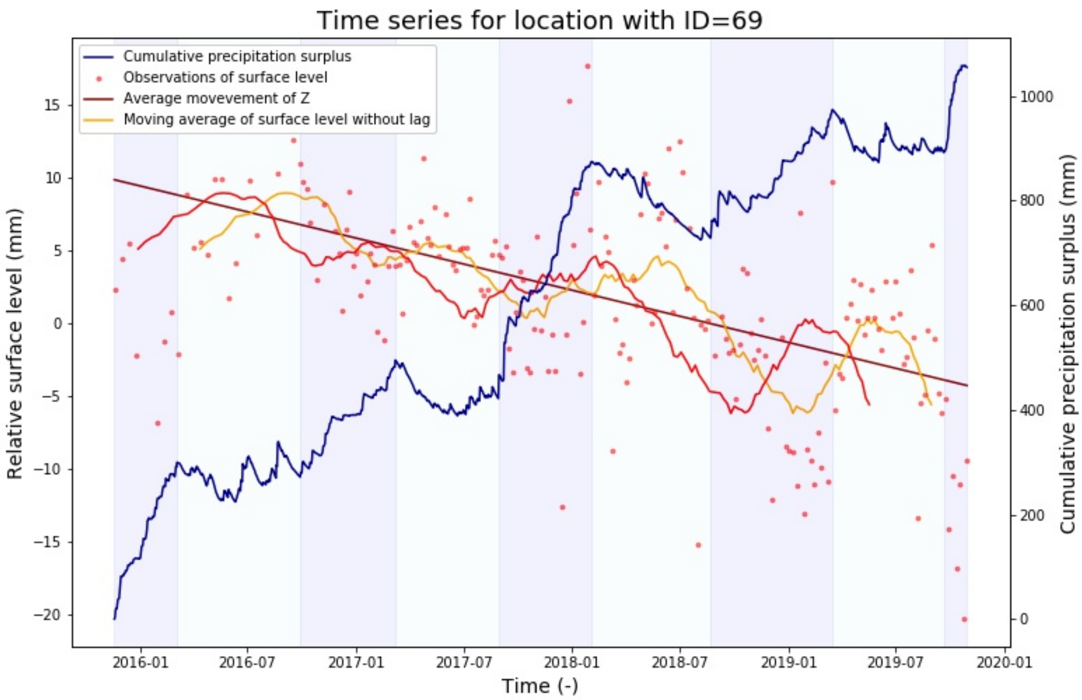

Figure C.7: *Example overview of converted data of subsidence and cumulative precipitation surplus.*

D

Urban Water balance Model - input

This appendix describes the general assumptions and usage of the Urban Water balance Model in the research. This model is made by Deltares (2020) and can be openly used. The information regarding the UWBM is gathered from the open Publicwiki website (Brolsma & Vergroesen, 2020). It is recommended that, in case one wants to use the Urban Water balance Model, this Publicwiki reference is to be used rather than this appendix. Experts' opinions can also be conducted (within Deltares).

D.1. General description

The UWBM is a lumped conceptual model which describes all urban water flows and associated water resources, as shown in Figure D.1. Water exchanges with atmosphere, deep groundwater, water from other urban areas (outside) and Wastewater Treatment Plants are included. The objective of the model is to determine return periods of runoff events for large time series (>30years). The UWBM includes initial conditions (memory of last storms and changes by e.g. evaporation in-between) whereas other models do not include these. The model takes much less time to build (for an urban area) and to process, however few assumptions and simplifications are made.

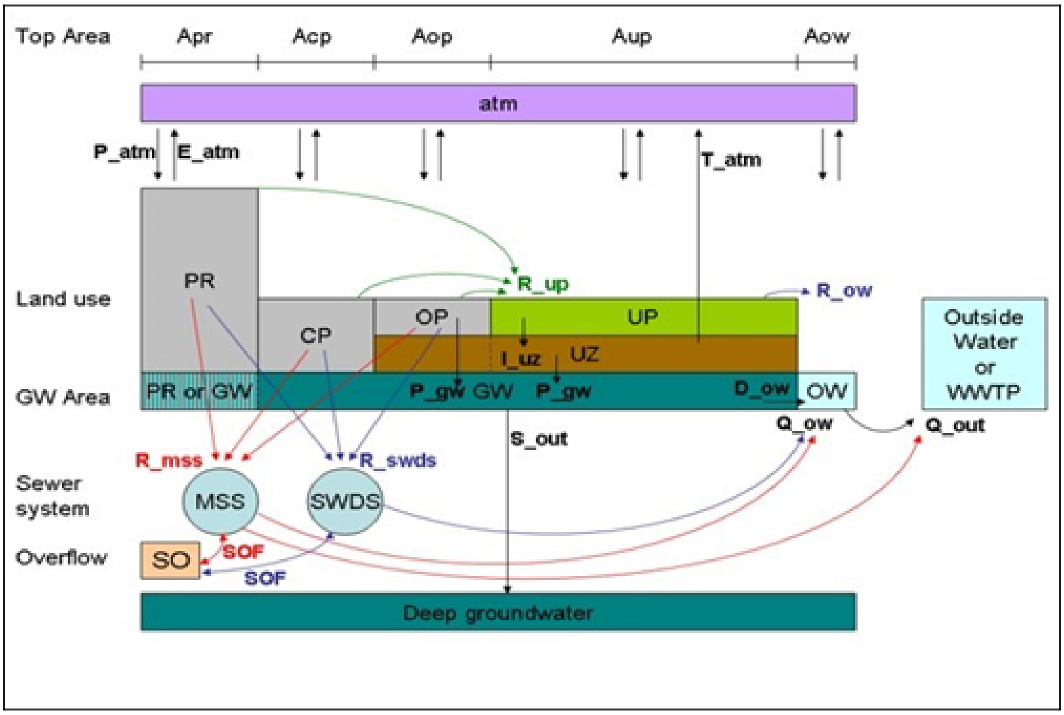

Figure D.1: *General overview of Urban Water balance Model working.* Acquired from Brolsma & Vergroesen (2020).

D.2. General assumptions

Some general assumptions are discussed below which have direct (large) influence on this research's calculations. Other assumptions are given in the Publicwiki.

- Only rainfall is considered as precipitation.
- Precipitation is intercepted by a surface layer. For paved areas first evaporation occurs, after which for open paved areas infiltration starts in that time step. Evaporation rates are limited by potential open water evaporation. Infiltration is limited by the infiltration capacity of open paved area. In unpaved areas evaporation and infiltration occurs simultaneously.
- Runoff from paved areas runs directly into the sewer system, unless paved areas are disconnected. Then runoff flows to unpaved areas.
- Internal routing is irrelevant for the model: there is no travel time of water included (all in 1 time step). Therefore the model is only applicable at small neighbourhoods.
- Water flows from and to reservoirs are limited by 3 aspects: water availability to flow; storage availability to flow to; and transport capacity to flow.

D.3. Model components

The major model components are briefly covered in this section. In the section below some of the components are discussed in more detail.

D.3.1. Surface areas

- Paved roof.
  PR (e.g. buildings).
- Closed paved.
  CP (e.g. asphalt).
- Open paved.
  OP (e.g. bricks).
- Unpaved.
  UP (vegetated or bare soil).
- Open water.
  OW (surface water).

D.3.2. Soil & subsurface components

- Unsaturated zone.
  Is only considered relevant under unpaved since PR and CP route water to the sewer system; OP infiltration percolates directly to groundwater.
- Shallow groundwater.
  Groundwater level is irrelevant under OW and PR although a percentage of OW and PR above phreatic level is included
- Sewer system.
  Both mixed sewer system and storm water drainage systems are incorporated in the UWBM.

D.3.3. Model boundaries

- Atmosphere.
  Rainfall and potential evaporation are the main forces of the model. Other atmospheric conditions are incorporated to determine actual evaporation and transpiration at unsaturated zone.
- Deep groundwater.
  Is considered as a constant flux (seepage or leakage) from other areas.
- Outside water & WWTP.
  Excess open water is discharged to outside water, if open water gets below its target water is supplied from outside water. The mixed sewer system directs incoming water to the WWTP while a storm water drainage system directs water to open waters.

D.4. Pavement types

The general working of closed paved (CP), open paved (OP) and unpaved (UP) pavement types is explained in this section. The types are schemetically shown in the figures below, which are also found in the Publicwiki.

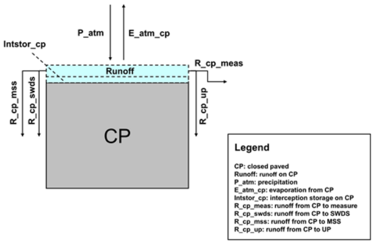

Figure D.2: *UWBM closed paved.*

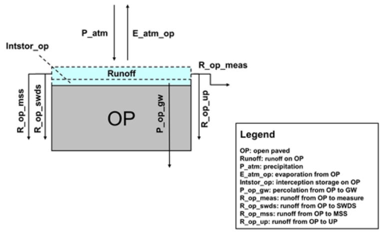

Figure D.3: *UWBM open paved.*

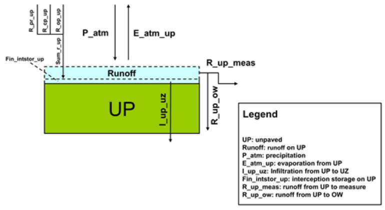

Figure D.4: *UWBM unpaved.*

D.4.1. Closed paved (CP)

Closed paved surface type is (almost) similar to paved roof, therefore only closed paved is discussed. On CP only limited amount of precipitation is intercepted by surface ponding, which is evaporated in later steps. Excessive precipitation flows to the sewer system, exceptionally if closed paved areas are disconnected from the sewer. Then it flows to unpaved areas. The amount of excessive precipitation depends on the interception storage of closed paved areas, which is generally very small.

D.4.2. Open paved (OP)

At open paved water is able to flow through the pavement, generating an extra water flux of infiltration to groundwater. This flux is limited by infiltration capacity as well as the interception storage of open paved areas. Excess water from this storage (can only be emptied fully by evaporation!) infiltrates to groundwater first. In case this infiltration capacity is exceeded water flows to the sewer system or, in case the area is disconnected, to unpaved areas. There is no vegetation at open paved areas (and hence no transpiration). Therefore infiltrated water is directly percolated to groundwater.

D.4.3. Unpaved (UP)

Unpaved areas have no paved surface but houses vegetation. The type of vegetation is defined in the model by crop type. Excess water from interception storage mainly infiltrates into the unsaturated zone and afterwards percolates to groundwater (and is drained). Simulteneously water is evaporated and infiltrated from interception storage. In case the interception storage and infiltration capacity is exceeded the excess water flows to open (surface) water. Some extra assumptions are made:

- Disconnected runoff water from paved areas is equally spread over unpaved areas and is thus added to precipitation water to be infiltrated, evaporated or routed to open surface water.
- Interception capacity from vegetation is not separately defined. Moreover, transpiration from vegetation is covered in the unsaturated zone balance (see section below).
- Evaporation and infiltration of water will simultaneously occur as long as water is available in the interception storage.
- Infiltration is limited by actual infiltration capacity and available storage in unsaturated zone, which is moreover changed by percolation to groundwater. Evaporation is limited by potential open water evaporation.
- A time factor is defined to determine the time water is remaining on the surface level. Water evaporation is multiplied by this time factor to calculate actual evaporation; actual infiltration capacity is multiplied by this time factor to calculate actual infiltration.
- If no open water is available the excessive water will stay on the unpaved area. However, it is advised to have at least a fraction of open water in the model for this reason.

D.5. Soil moisture content

This section covers the soil moisture content calculations and assumptions. Unsaturated zones are assumed to be only located below unpaved areas since other surface areas discharge via open water, sewer system or unpaved areas. The inflow of unsaturated zone is considered to be infiltrated water. The outflow of water is considered to be transpiration via vegetation and percolation to groundwater, as shown in Figure D.5.

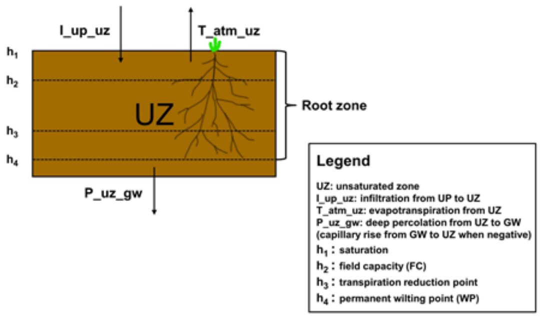

Figure D.5: *UWBM unsaturated zone description.* Acquired from Brolsma & Vergroesen (2020).

Within the unsaturated zone a root zone is defined as the depth until plant roots uptake water for transpiration. In this zone the water content therefore fluctuates. The inflow of water into the root zone is infiltration of precipitation and capillary rise from deeper unsaturated zone (groundwater). Soil evaporation, transpiration and percolation removes water from the root zone causing a depletion. Evapo(transpi-)ration is calcualted by Penman-Monteith (reference crop evaporation) and a so-called transpiration reduction coefficient (water stress factor) which is conceptualized in Figure D.6.

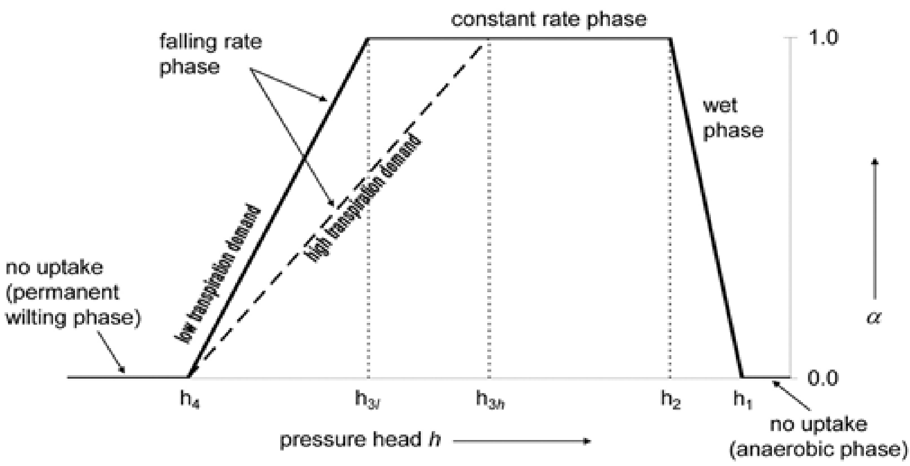

Figure D.6: *Transpiration reduction coefficient in UWBM in relation to root zone water potential.* Acquired from Brolsma & Vergroesen (2020).

In case water is added to the root zone a so-called fiel capacity (h1) can be reached. This is the amount of water that a well-drained soil can hold against gravity. If more water is present it will percolate to groundwater. If water is subtracted from the root zone it can reach the wilting point (h4). This is the amount of water in the soil when crops no longer can extract remaining water since the force between remaining water and soil particles is greater than the uptake force of present vegetation. Some extra assumptions are made:

- Evaporation of soil and transpiration via plant roots occur simultaneously and are therefore not differentiated in the model.

- Reference crop evapotranspiration takes the reference crop grass (height = 0.12m, surface resistance = 70 s/m, albedo = 0.23) to calculate evapotranspiration.
- Makkink evaporation is considered $0.8982 \cdot Penmanevaporation$.
- Actual crop evapotranspiration is calculated to be combination of crop factor (1 for hypothetical grass reference crop), reference crop evapotranspiration, and water stress factor α.
- Percolation to groundwater is limited by saturated soil conductivity.

D.6. Groundwater

Groundwater is modelled as unconfined aquifer. Input of groundwater reservoir is percolation from open paved (directly) and unpaved (unsaturated zone). Outflow (or if negative inflow) consists of seepage/ leakage to other areas and drainage and moreover the in flowing water of open water bodies situated above groundwater levels. The extent of fluxes is based upon the hydraulic head differences between present open water bodies and groundwater levels. The flux might reduced in time in case open water bodies are not recharged by precipitation or outside water and thus decrease in water level elevation and hence hydraulic head. Groundwater is not further explained in this appendix.

D.7. Model input

Briefly the steps taken to use the model are explained. In case the model is to be used a better reference is to use Publicwiki (Brolsma & Vergroesen, 2020) to construct and run the model. Only 3 time series are needed to run the model: precipitation; potential open water evaporation (e.g. Penman); potential reference crop evapotranspiration (e.g. Makkink).

D.7.1. KNMI input file

Firstly a file from KNMI databases is downloaded (Koninklijk Nederlands Meteorologisch Instituut, n.d.-a) which consists of precipitation, wind speed, temperature, radiation and relative humidity. An example file is showed in Figure D.7. Both hourly as daily data can be used in the research resulting in same-like output (soil moisture content).

```
# BRON: KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT (KNMI)
# Opmerking: door stationsverplaatsingen en veranderingen in waarneemmethodieken zijn deze tijdreeksen van dagwaarden mogelijk inhomogeen! Dat betekent dat deze reeks van gemeten waarden niet geschikt is voor trendanalyse. Voor studies naar klimaatverandering verwijzen we naar de gehomogeniseerde reeks maandtemperaturen van De Bilt <http://www.knmi.nl/kennis-en-datacentrum/achtergrond/gehomogeniseerde-reeks-maandtemperaturen-de-bilt> of de Centraal Nederland Temperatuur <http://www.knmi.nl/kennis-en-datacentrum/achtergrond/centraal-nederland-temperatuur-cnt>.
#
#
# STN      LON(east)   LAT(north)     ALT(m)  NAME
# 240:         4.790       52.318      -3.30  SCHIPHOL
#
"# YYYYMMDD = Datum (YYYY=jaar MM=maand DD=dag); "
"# FG       = Etmaalgemiddelde windsnelheid (in 0.1 m/s); "
"# TG       = Etmaalgemiddelde temperatuur (in 0.1 graden Celsius); "
"# Q        = Globale straling (in J/cm2); "
"# RH       = Etmaalsom van de neerslag (in 0.1 mm) (-1 voor <0.05 mm); "
"# UG       = Etmaalgemiddelde relatieve vochtigheid (in procenten); "
#
STN,YYYYMMDD,   FG,   TG,    Q,   RH,   UG
#
  240,20151119,   96,  113,  154,   28,   78
```

Figure D.7: *Example of input file for Diemen location as downloaded from KNMI.*

D.7.2. Penman equation

The input from KNMI database is transformed by Penman equation to have potential reference crop evapotranspiration used as input. The Penman formula is given below and can be calculated by only using the KNMI data showed in Figure D.7.

$$E_0 = \frac{\frac{s \cdot R_n}{\rho \cdot \lambda} + \frac{c_p \cdot \rho_a}{\rho \cdot \lambda} \cdot \frac{e_s - e_a}{r_a}}{s + \gamma} \tag{D.1}$$

Where:

- λ Latent heat of evaporation = $2.45 \cdot 10^6 [J \cdot Kg^{-1}]$
- c_p Specific heat = 1004 [J $\cdot Kg^{-1} \cdot K$]
- ρ_a Mean dry air density = 1.205 [Kg $\cdot m^{-3}$]
- ρ Mean density of water = 1000 [Kg $\cdot m^{-3}$]
- γ Psychrometric constant = 0.066 [kPa $\cdot C^{-1}$]
- r_a Air resistance at 2 meters height = $245/(0.54 \cdot u_2 + 0.5)[s/m]$
- u_2 **Wind speed** at 2 meters height [m $\cdot s^{-1}$]
- e_s Saturated vapor pressure = $0.61 \cdot exp(19.9 \cdot T/(273+T))[kPa]$
- T **Temperature** [C]
- s Slope of vapor pressure curve = $(5430 \cdot e_s)/(273+T^2)[kPa \cdot C^{-1}]$
- e_a Actual vapor pressure = $e_s \cdot h[kPa]$
- h **Relative humidity** [%]
- R_n **Net radiation** [J * m^{-2}]

Since Makkink is considered by a factor 0.8982 times Penman only this formula and KNMI data is needed to form all 3 time series. The precipitation time series from KNMI is not further modified. Now only the parameters describing the urban area characteristics are needed.

D.7.3. Soil structure & crop type input parameters

Below a list is given of soil structures and crop types to choose from as input parameters for the urban area. This research used for both areas soil structure type 5 (peat area with sand cover placed on sand) and crop type 1 (grass). Soil structure type 5 is used in Diemen since the deeper clay layer is of less influence on the changes in the unsaturated zone and hence there is only a peat layer between the sand cover and the deeper sand layer (above the clay layer). This is only an estimation of the areal characteristics and is therefore prone to (large) errors. However, soil moisture is only analyzed qualitatively on its difference between various summers.

Table D.1: *List of different soil structure and crop types to be used as input in UWBM.*

Type number	Soil structure	Crop
1	Veengrond met veraarde bovengrond	Gras
2	Veengrond met veraarde bovengrond, zand	Maïs
3	Veengrond met kleidek	Aardappelen
4	Veengrond met kleidek op zand	Suikerbieten
5	Veengrond met zanddek op zand	Graan
6	Veengrond op ongerijpte klei	Diversen
7	Stuifzand	Niet-bouwland
8	Podzol (Leemarm, fijn zand)	Broeikas
9	Podzol (zwak lemig, fijn zand)	Boomgaard
10	Podzol (zwak lemig, fijn zand op grof zand)	Bolgewassen
11	Podzol (lemig keileem)	Gebladerd bos
12	Enkeerd (zwak lemig, fijn zand)	Dennenbos
13	Beekeerd (lemig fijn zand)	Natuur
14	Podzol (grof zand)	Braak
15	Zavel	Groenten
16	Lichte klei	Bloemen
17	Zware klei	
18	Klei op veen	
19	Klei op zand	
20	Klei op grof zand	
21	Leem	

D.7.4. Diemen & Kampen parameters

The table below shows the parameters used as input, next to the time series, to construct the soil moisture content used in analyses. Some parameters (infiltration capacity, storage capacity, seepage, flow resistance, drainage resistance) were standardized in provided Urban Water balance Model. Groundwater levels are stated positive but are given as depth with respect to NAP.

Table D.2: *Input parameters for UWBM in Diemen and Kampen.*

Parameter	Diemen	Kampen
ID type	1	1
Title	DIEMEN	KAMPEN
Total area	147846.76	189191
Fraction roofs	0.1984041	0.192
Fraction closed-paved	0	0
Fraction open-paved	0.472709	0.436
Fraction unpaved	0.2801299	0.351
Fraction open water	0.048757	0.021
Soil type	5	5
Crop type	1	1
Infiltration capacity unpaved	480	480
Infiltration capacity open-paved	10.9	10.9
Storage capacity open water	1030	1030
Starting groundwater level	1.8	1.5
Downward seepage	0	0
Vertical flow resistance from shallow to deep groundwater	1000	1000
Drainage resistance from groundwater to open water	50	50

The output of the model consists of many parameters and variables. In this research only the soil moisture content variations through time is used for the analyses. Figure D.8 shows an example of the time series generated by the Urban Water balance Model. No further modifications from the model output is done.

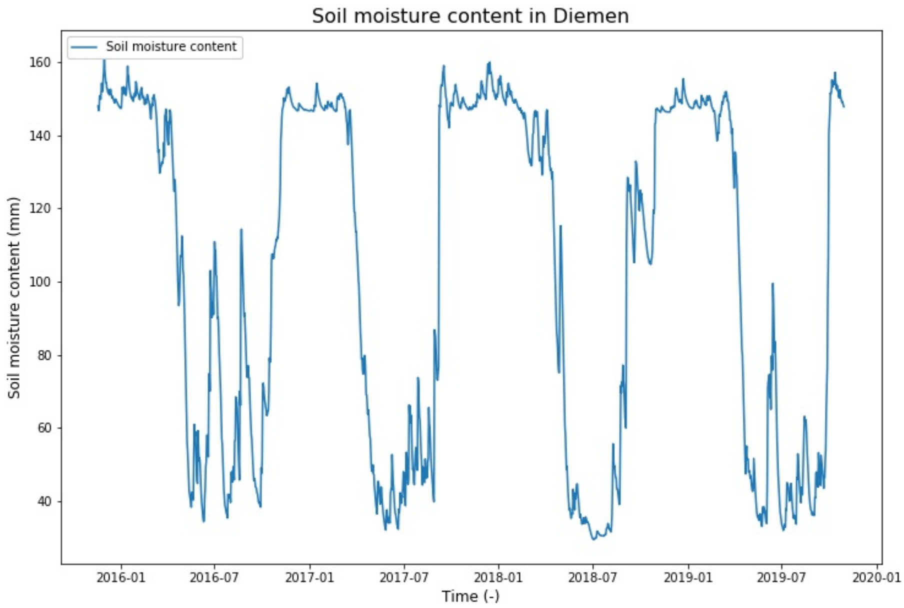

Figure D.8: *Soil moisture content in Vogelweide, Diemen as assessed with the Urban Water balance Model of Deltares.*

E

Questionnaire - drought & site preparation strategies

The expert questionnaire is made in the Dutch language since all experts are Dutch and might therefore find it easier and more comfortable to fill in the questionnaire. The questionnaire consists of following subjects:

- Current problems at estimating/modeling subsidence.
- Soil raising methods.
- Acceleration of consolidation process.
- Drainage and dewatering.
- Reasons to change site preparations.
- Possible solutions.

The objective of the questionnaire is to get overview of current subsidence problems; to estimate the severeness of drought-induced subsidence in-practice, and to see if suggested measures are feasible.

The persons who filled in the questionnaire have following expertise:

Expert 1: Urban development: preparing construction sites

Expert 2: Urban development: chain cooperation and contract management

Expert 3: Urban development: design advice and realisation

Expert 4: Hydraulic and geotechnical engineering

Expert 5: Transport, roads and infrastructure

Expert 6: Urban development: climate adaptation geohydrology

VRAGENLIJST BOUWRIJP MAKEN: BODEMDALING & DROOGTE

Onderwerp	Vragenlijst bouwrijp maken: bodemdaling & droogtes
Project	Afstudeeropdracht TU Delft - Witteveen+Bos: ***Determining drought-induced subsidence in urban areas*** *- A modest in-practice analysis of drought impacts on subsidence in two Dutch soft-soil cities*
Datum	3 maart 2021
Auteur(s)	AJJ (Sander) Geertzen

Doel
Dit document bevat een vragenlijst gericht aan experts op het gebied van het bouwrijp maken van ontwikkelingsgebieden. Het doel van deze vragenlijst is om te toetsen of er urgentie bestaat en mogelijkheden zijn om beslissingen omtrent het bouwrijp maken van gebieden te veranderen als reactie op de bevindingen uit het onderzoek (relatie droogte-bodemdaling). Onderliggend doel is om droogte-gerelateerde bodemdaling te bepalen en uiteindelijk te minimaliseren. Deze vragenlijst staat in kader van het (afstudeer-) onderzoek vanuit de TU Delft (Departement Water Resources Management), in samenwerking met Witteveen+Bos.

Inleiding
Bodemdaling in stedelijk gebied in Nederland is een bekend fenomeen. Ondanks dat bodemdaling in woonwijken steeds beter berekend en gemodelleerd kan worden zijn er veel locaties waar er méér bodemdaling optreedt dan verwacht. Dit tezamen met de ruimtelijke variabiliteit in bodemdaling zorgt voor veel kosten door een hoge(re) onderhoudsfrequentie en schade aan infrastructuur.

Afgelopen jaren kenden (zeer) droge zomers, wat potentieel leidde tot problemen in stedelijke gebieden: schade aan groen, een verminderde waterkwaliteit, rot aan houten paalfunderingen, hittestress, maar ook ongelijke zettingen. Volgens de klimaatscenario's van de KNMI is het reëel dat de komende decennia zomers vaker en intenser droog worden. Zo zal een droogte als in 2018 een herhalingstijd kunnen krijgen van 10 jaar (nu 30 jaar).

Het huidige tekort aan woningen leidt tot een groei van het aantal nieuwbouwlocaties in de komende (tientallen) jaren. Deze nieuwbouwprojecten dienen klimaat-adaptief te worden gebouwd. Hierbij kan er gekeken worden naar een aantal klimaat-thema's: overstroming, wateroverlast, biodiversiteit, hittestress, droogte en bodemdaling. Om eerdergenoemde toekomstige onderhouds- en schadeposten te minimaliseren kan wellicht tijdens het ontwerpen van de waterhuishouding beter rekening worden gehouden met de invloed van droogte op de bodemdaling.

Onderzoek
In het (afstudeer-) onderzoek staat de relatie tussen droogte en bodemdaling centraal.
De vragen welke gepoogd worden te beantwoorden zijn:
1. Op welke wijze en in hoeverre heeft droogte invloed op bodemdaling?
2. In hoeverre hebben omgevingskarakteristieken (bodemopbouw, begroeiing, oppervlaktewater) invloed op de relatie tussen droogte en bodemdaling?
3. Welke beslissingen omtrent het bouwrijp maken van gebieden kunnen genomen worden om droogte-gerelateerde bodemdaling te minimaliseren?

Droogte en bodemdaling: onderzoeksresultaten
In het onderzoek is voor een wijk in Diemen de data van bodemdaling (satelliet, SkyGeo) uitgezet tegen meteorologische gegevens van KNMI. Vervolgens is voor een wijk in IJsselmuiden (Kampen) een casestudy gedaan om de resultaten te vergelijken. Hieruit komt naar voren dat zéér droge zomers als 2018 kunnen leiden tot extra bodemdaling van ~1.5mm. Een eerder onderzoek (Aveco de Bondt, 2020: Den Haag) concludeert hetzelfde.

Oorzaak van de bodemdaling is allereerst het uitzakken van de grondwaterstand, wat leidt tot klink (en eventueel veenoxidatie) van slappe lagen in de bodem (klei, veen). Belangrijk hierbij is de dikte van de aangelegde zandlaag (netto ophoging): indien de grondwaterstand onder deze zandlaag reikt kan dit zorgen voor verergering van bodemdaling (oxidatie, krimp). Daarnaast zorgt verdamping voor het droger worden van de onverzadigde zone, wat leidt tot krimp van deze zone.

Plekken waar veel begroeiing (bomen, struiken) aanwezig is, zakken meer uit in droge periodes. Bomen- en planten verbruiken veel van het aanwezige water in de bodem via hun wortels voor evaporatie. Deze extra uitzakking hoeft niet altijd te leiden tot meer bodemdaling: plekken met veel begroeiing laten ook een groter terugverend effect zien in nattere periodes. De verwachting is desondanks dat een combinatie van drainage en grote planten extra verschilzettingen oplevert. Oppervlakte water heeft enkel zeer lokaal (orde grootte van enkele meters) effect op de grondwaterstand en dus de bodemdaling.

De vervolgvraag welke hierbij gesteld kan worden is of droogte-gerelateerde bodemdaling kan worden geminimaliseerd, en of dit uit oogpunt van consequenties en financiën noodzakelijk is? Om deze vragen te beantwoorden is expertise nodig uit de praktijk, wat resulteert in deze vragenlijst.

Alvast bedankt voor het invullen. Voor vragen/opmerkingen of het terugsturen van de ingevulde vragenlijst kunt u terecht bij: sander.geertzen@witteveenbos.com of: 06-15 46 49 93.

Met vriendelijke groet,
Sander Geertzen

A. Huidige problematiek bodemdaling

A1. Hoe vaak (schatting van percentage projecten) komen berekeningen/modellen voor zettingen overeen met de daadwerkelijke opgetreden gemiddelde zettingen in de praktijk?

20% komt overeen. 70% van de projecten zijn de zettingen minder dan berekend. Wordt vaak uitgegaan van de slechte sondering, hoogste dikte van de zettingsgevoelig lagen en parameters uit de literatuur. De werkelijkheid is vaak beter. 10% meer zetting dan berekend.
Mijn ervaring is dat het over het algemeen goed overeenkomt, 90%. Grote verschillen kunnen ontstaan bij dempingen van voormalige watergangen en bij kunstwerken. Ook is een goed grondonderzoek cruciaal.
Geen inzicht in helaas.
0% Toelichting: zettingen die buiten worden gemeten verschillen altijd met het model. In het beste geval kom je goed in de buurt. Het hangt ook sterk af hoe een ontwerp wordt ingestoken: wil je zettingen forceren of juist minimaliseren? Dat er verschillen zijn hoeft niet erg te zijn, als je hier in ontwerp en monitoring maar verstandig mee omgaat.
Bijna nooit ik schat in 20% dit is sterk afhankelijk van het hoeveel onderzoek van te voren wordt gedaan naar de grondparameters.
Je hoort het vaak alleen wanneer er positieve of negatieve afwijkingen zijn. Wanneer het min of meer klopt, hoor je niets. Ik denk dat 2/3 tot 3/4 van de berekeningen een goede indicatie geeft. Ook minder zettingen dan verwacht kunnen een probleem geven. De ophooglaag met zand wordt dunner waardoor drainage niet goed gaat functioneren

A2. Kunt u een schatting maken in hoeverre de bodem gemiddeld/ maximaal bij onderschattingen extra daalt? Voorbeelden zijn: 1mm/y, 5mm/y, 10mm/y.

Een extra 30cm in 30 jaar
5 mm/y in de eerste jaren
Nee
Nee, dat kan ik niet zeggen. Meestal overschatten wij de zettingen iets omdat dat de veilige benadering is voor het ontwerp, of omdat we zettingsparameters aanhouden uit literatuur, of omdat zettingsparameters zijn bepaald op slechtste stukje grond (in werkelijkheid is het gemiddeld dan wat beter).
Ik denk dat delen waar meer zetting optreedt dan gedacht meestal niet de gebieden zijn die bouwrijp worden gemaakt of worden voorbelast, maar gebieden die dat niet zijn.
Nee, mijn ervaring is dat ten opzichte van de berekeningen de bodem meestal minder daald.
In mm per jaar weet ik het niet. Het gaat er dan vaak om dat ze na 3 of 5 jaar constateren dat er meer zettingen zijn dan verwacht (of juist minder). De afwijkingen liggen in de orde van 5 of 10 cm in een periode van 3 of 5 jaar.

A3. Is de onderschatting/ afwijking verschillend voor verschillende bodemtypen (*Voornamelijk* klei, *voornamelijk* veen, *wellicht* zand)?

Voornamelijk veen
Klei consolideert veel langzamer dan veen.
-
Veen is van deze grondsoorten het meest zettingsgevoelig en daarmee ook meest vatbaar voor afwijkingen. Door de structuur van het materiaal zit er ook meer verschil tussen de ene locatie en de andere. Bij klei is dat vaak meer uniform. In zand verwacht je nauwelijks zettingen.
Ja, in veen en klei gebieden zijn deze afwijkingen groter dan in zandgebieden
Dit speelt vooral bij veen bodems. Bij zand, maar ook pure klei zijn de zettingen toch al beperkt.

A4. Hoe vaak (schatting van percentage projecten) worden de opgetreden zettingen na de aanlegfase gemonitord en geëvalueerd?

0%

Het blijft een voorspelling, die met meetdata wordt onderbouwd. In de praktijk stopt vaak de monitoring na 1 of 2 jaar. Dan zijn er vaak al veel andere activiteiten geweest die effect hadden op de zetting (bijv. tijdelijke depots, bemaling), dat de data niet meer bruikbaar zijn.

Niet

Heel weinig, meestal wordt alleen tijdens de aanlegfase monitoring uitgevoerd. Soms als er een innovatie wordt toegepast of er ook onderhoud in het contract zit, dan gebeurt dit wel eens. Ik zou zeggen 5%

In mijn ervaring niet, in de bouwrijpmaakfase wordt er gemonitoord en door middel van een fit berekening aangetoond dat aan de restzettingseis wordt voldaan

Wat bedoel je precies? Na het opbrengen wordt in de consolidatie periode het zettingsverloop gemonitoord. Maar wanneer met de inrichting van de wijk wordt gestart, stopt dit.

Mijn indruk is dat er dan nog weinig wordt gemonitoord. 10 of 20%. Er wordt alleen actie ondernomen bij afwijkende waarden

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B. Methoden van ophoging
Onderscheid wordt gemaakt tussen integrale ophoging (gehele gebied ophogen met zand), cunette ophoging (ophogen met zand voor infrastructuur ophogen met grond voor tuin, berm, park) en ophogen via andere manieren (lichte materialen: granulair, EPS, schuimbeton) (constructies: zelfdragend, gewapend op palen).

B1. Hoe vaak (schatting van percentage projecten) wordt er voor een andere methode gekozen dan de keuze voor integrale ophoging? Welke methode(s) zijn dit?

Integraal: 10%
Cunet methode: 90%
Andere methode bij nieuwbouw bijna 0%.
Hoe vaak, dat weet ik niet. Ik heb altijd integrale ophoging toegepast. Alternatief is partieel ophogen.
Durf hier geen schatting in te maken. Zal ook sterk regionaal afwijken. In het westen zal vaker voor integrale ophoging worden gekozen dan in het oosten van het land.
Ik schat 30%. De meest gebruikte andere methode is cunet oplossing, daarna lichte materialen, daarna constructies.
In mijn ervaring 100%, ik ga eigenlijk altijd uit van cunet ophoging waarbij de kavels met vrijkomende grond uit het gebied worden opgehoogd.
Vaak worden andere methoden gekozen. Zeker wanneer je verder kijkt dan west Nederland. Percentages zou ik zo niet weten maar ik denk dat slechts in 10 of 20% van de gevallen integraal wordt opgehoogd. Dit zijn wel vaak de grote projecten

B2. Zou u een prioritering in de volgende lijst van methode-overwegingen kunnen aanbrengen? Met op nummer 1 de hoogste prioriteit.

- Kosten 1 4 1 1 1 2
- Ervaring van eerdere projecten 2 2 5 3 3 4
- Planning & organisatie 4 6 6 2 6 5
- Zandverbruik* 3 3 - 5 5 6
- Duurzaamheid (excl. Zandverbruik) 5 5 4 6 2 7
- Lokale verschillen in bodemdaling 7 1 2 4 4 3
- Aanwezig groen/landschapskenmerken 6 - 3 7 7 1

*Diverse antwoorden geven een toelichting: zandverbruik is ook gerelateerd aan kosten

B3. Ziet u dezelfde afwijking van bodemdaling (model - werkelijkheid) terugkomen in integrale ophoging en andere methoden? Denk aan zowel gemiddelde bodemdaling als ruimtelijke variabiliteit van bodemdaling.

Meer bij integrale ophoging. Integraal wordt vaak toegepast wanneer veel ophoging nodig is en dus op de slechtste locaties. Dit is misschien de oorzaak.
Kan ik niet beoordelen
Geen kennis van
Dat is heel moeilijk te zeggen omdat binnen project meestal voor een oplossing wordt gekozen, dus dan weet je niet hoe een andere methode had gewerkt op die locatie. Bij integraal ophogen verwacht je natuurlijk minder ruimtelijke variabiliteit
Bodemdaling is een breed aspect en bestaat zoals je aangeeft uit zetting, klink en mogelijk andere oorzaken, bijvoorbeeld gaswinning of zoutwinning. Hier kan ik zo geen oordeel over geven.
Ja maar dat is niet zo vreemd. Alleen bij gebieden die integraal worden opgehoogd is vaak sprake van grote zettingen

B4. In hoeverre wordt er onderscheid gemaakt tussen restzettingseisen van gemeenten voor openbaar/ uitgeefbaar gebied? Komt dit verschil tijdens projecten ter sprake?

In het verleden was de restsettingseis alleen bedoeld voor openbaargebied. Nu vaak ook restzettingseis voor uitgeefbaar gebied

In mijn projecten niet van toepassing

Ja, dit overscheid wordt vaak gemaakt, is ook afhankelijk van het hoog de eis voor openbaar gebied is. Als deze 10 cm in 30 jaar is, wordt vaak voor de uitgeefbare kavels een minder hoge eis gesteld van bijvoorbeeld 20 cm in 30 jaar.

Dit hangt af van OG, we doen hier zelf ook wel voorstellen voor.

Voor het uitgeefbaar gebied worden er geen restzettingseisen gesteld voor het uitgeefbaar gebied wel.

Vaak, ja

C. Consolidatie proces
C1. Heeft u de indruk dat er tijdsdruk is om het consolidatieproces zo snel mogelijk af te ronden?

Altijd
Altijd, maar tegelijkertijd weet iedereen dat het proces goed afgerond moet zijn om problemen te voorkomen.
Vaak wel
Ja
Ja vaak speelt dat wel een rol, immers hoe sneller er kan worden gebouwd hoe beter, dan 9 maanden a 1 jaar wachten tot de grond bouwrijp is betekend dan mogelijk dat de gemeente/ontwikkelaar geld 1 jaar moet voorinvesteren voor er baten komen.
Ja zeker

C2. Zou u eventueel de grond *meer* laten zetten indien hier meer tijd voor wordt vrijgemaakt?

Nee
Nee
Dit is een kosten afweging. Snellere consolidatie vraagt meer ophogen en/of verticale drains. Indien tijd beschikbaar is wil je dit zo optimaal mogelijk doen (kosten maar ook duurzaamheid)
Niet perse, als aan de eis wordt voldaan is het voldoende
Vraag is mij niet helder, in principe wil je de alle grond zoveel mogelijk laten zitten tenzij dit om civieltechnische redenen niet kan.
Nee, maar wel beter monitoren of de grond inderdaad vrijgemaakt kan worden voor woningbouw. Dus meer flexibiliteit (maar ontwikkelaars en kopers van woningen hebben natuurlijk ook redenen omdat niet te willen)

C3. Gebruikt u vaker een tijdelijke overhoogte, verticale drainage, of eventueel IFCO of andere methodes om het consolidatie proces te versnellen?

IFCO nooit. Overhoogte en of zonder verticale drainage heel vaak
Ja
Ja, tijdelijke overhoogte en verticale drains. IFCO (duur) nog nooit toegepast
Ja
Verschilt, dit is altijd een kostenafwegen i.r.t. tot tijd
Vaak een volgorde: eerst overhoogte, wanneer dit te traag gaat vertikale drainage. In de praktijk heb ik geen ervaring met IFCO

C4. Op welke manier wordt momenteel rekening gehouden met autonome bodemdaling (geologische processen, klink/oxidatie/krimp)? Denk aan: hoeveelheid (mm/j), percentage van geheel. Hoe wordt dit berekend/geschat?

Nooit
Er wordt geen rekening mee gehouden.
Volgens mij zelden
Als we niet of weinig ophogen, dan nemen we hiervoor een waarde mee obv literatuur of metingen in de buurt. Als we zettingen berekenen voor grotere ophogingen, dan gaan we er vanuit dat dit met berekende kruip voldoende is afgedekt
Niet in ontwikkelingsgebieden is mijn ervaring, wel bij dijkversterkingen.
Zeer beperkt. Alleen wanneer de situatie daarom vraagt

D. Ontwatering & afwatering

D1. Wordt tijdens het ontwerp van het ontwateringssysteem nagedacht over consequenties van droge periodes (laagste grondwaterstand als aanvulling op hoogste grondwaterstand)?

Nooit
Vast wel, maar ik ben geen ontwerper….
Onvoldoende
Ik maak deze ontwerpen niet, maar we kijken wel vaak naar effecten van lage GWS
Nee
In beperkte mate. Het gaat niet alleen om het ontwateringssysteem maar om de waterhuishouding als geheel.

D2. Hoe vaak (schatting van percentage projecten) wordt er bij nieuwbouwprojecten het bouwen zonder kruipruimtes besproken (en ook toegepast)? Dit omdat bouwen zonder kruipruimtes kan resulteren in een ondiepere ontwatering.

Besproken 25% van de projecten; Gekozen: minder dan 1%
In mijn projecten niet.
80%
Ik kom dit wel tegen, maar bespreek dit zelf niet
Wordt in mijn ervaring vaak vrijgelaten aan de ontwikkelende partij
Wordt vaak besproken maar beperkt toegepast.

E. Reden tot verandering?!

E1. Wat is uw reactie op de orde grootte van droogte-geïnduceerde bodemdaling (in bijv. 2018 ongeveer 1-1.5mm) ten opzichte van de zettingen door methoden als zandophoging?

De onzekerheid in de restzetting is al groter van de extra 1,5mm van één droge zomer. Is dus een lastig onderwerp
Zorgwekkend voor bestaande stedelijke gebieden in laag Nederland.
Uitgaande dat dit een uitschieter is het effect over 30 jaar mijn inziens beperkt.
Ik snap de vraag niet goed, dit zijn toch geen twee methodes die je tegen over elkaar zet?
Verwaarloosbaar voor mijn gevoel.
Eigenlijk niet zo schokkend wanneer je naar 1 jaar kijkt. Maar als het droger wordt en elk jaar 1,5 mm wordt, telt het wel aan

E2. Vindt u dat de droogte-geïnduceerde bodemdaling (in bijv. 2018 ongeveer 1-1.5mm) mee moet worden genomen als losstaand proces in de consolidatieberekening? (In plaats van bijvoorbeeld een inschatting)

Lijkt mij lastig als losstand proces. Wel interessant om te weten is wanneer (onder welke omstandigheden) dit proces kan optreden.
Nee.
Nu nog geen mening over
Hiervoor ken ik het onderzoek niet goed genoeg
Nee, zie mijn vorige antwoord
Wellicht wel. Maar ik denk dat droogte-geïnduceerde bodemdaling vooral voor bestaande inrichting van belang is (stad en landelijke gebied)

E3. Is er volgens u genoeg reden, voortkomend uit de conclusies in dit onderzoek, voor veranderingen in de afwegingen tijdens het bouwrijp maken? Zo ja, welke afwegingen zijn dit en hoe zou u deze veranderen?

1) ophoging minimaliseren (dus drooglegging minimaliseren) (gevolg is wel kruipruimte loos bouwen of acceptatie van water in de kruipruimte)
2) het belang van een ‘steng” restzettingseis van bijvoorbeeld 10cm in 30jaar. Als door droge of autonome zetting na 30jaar de zetting 15cm in 30jaar is geworden heb je nog steeds geen extra beheerkosten. Mijn ervaring is dat bij meer dan 15cm zetting na 30jaar de beheerkosten sterk gaan toenemen.
3) LCA doen om de afweging restzettingseis versus aanleg en beheerkosten
Bij bouwen in polders is voldoende oppervlaktewater met voldoende kwaliteit van groot belang, zowel als berging en als aanvulling.
Vind het interessant, zal me echter eerst meer moeten verdiepen om hier goed antwoord op te kunnen gegeven.
Ik vraag me af of dit echt de keuzes beïnvloedt, er zit altijd een redelijk grote marge om berekende zettingen. Het zal van locatie afhangen of zo’n effect ook echt zorgt voor andere afweging.
Nee, tenzij het veengebieden betreffen
Alleen dit onderzoek niet. Maar ook opgaven als droogte vragen dat water wordt vastgehouden.

F. Mogelijke oplossingen

Mogelijke oplossingen voor het minimaliseren van droogte-gerelateerde bodemdaling kunnen vanuit twee invalshoeken worden bekeken. Enerzijds kan gepoogd worden excessieve grondwateruitzakkingen te voorkomen. Anderzijds kan het gewicht in de toplaag (/ deklaag) worden gereduceerd ofwel het maaiveld worden verlaagd (t.o.v. het vaste waterpeil) om excessieve inklinking in onderliggende slappe lagen te verminderen.

Omgekeerde drainage - drainage waarbij in droge periodes (oppervlakte)water kan worden toegevoerd via het drainage systeem t.b.v. grondwateraanvulling.
F1. Wordt omgekeerde drainage toegepast bij nieuwbouwprojecten? Of zou u dat (vaker) willen gebruiken?

Eigenlijk nog nooit gezien. Willen gebruiken? Misschien wel maar gemeente zetten hier niet te wachten
Nee, maar met een goed doorlatende ophooglaag wordt hetzelfde bereikt.
Vaak doe je dit al onbewust door drainage te koppelen aan het oppervlakte water.
Volgens mij wordt dit niet toegepast. Ik heb er geen ervaring mee, maar ik zie nu geen reden om het toe te passen
Vaak worden drainages al onder de waterstand in het gebied aangelegd daarmee heb je toch deze functie al?
Ik heb het maar 1x gebruikt. Er zitten ook onzekerheden in, bijvoorbeeld verstopping waardoor water niet meer infiltreert

Indien de deklaag (zij het zand of ander materiaal) dik genoeg is zal het grondwaterregime niet kunnen reiken tot slappe lagen. Hierdoor kan eventueel excessievere uitzakking van maaiveld worden voorkomen.
F2. Zou u een minimale dikte van de initiële deklaag kunnen overwegen om droogte-geïnduceerde bodemdaling te voorkomen? Wetende dat dit zich eventueel kan uitten in een hoger maaiveld.

Zou moeten kunnen.
Dit is een mogelijkheid
Voor nu lastig te beantwoorden
Ik denk dat het aanbrengen van een dikkere deklaag alleen maar voor meer zettingen zorgt, zeker als je dit boven huidig maaiveld gaat doen.
Nee, dikke deklaag betekend ook meer zetting/restzetting en extra kosten
Nee, ik denk het niet. Tenzij dit echt nodig is om problemen te voorkomen

Indien het ontwateringsnetwerk compacter wordt gemaakt (kleinere h.o.h. afstand van drainagebuizen), kan het netwerk ondieper worden gelegd. Grondwaterstanden zullen hierdoor hoger kunnen liggen.
F3. Zou u kunnen overwegen om een (dynamisch) systeem van slimme opvang & infiltratie van regenwater te combineren met ondiepere drains in een compacter netwerk ten behoeve van het minimaliseren van (droogte-geïnduceerde) bodemdaling?

Ondiepere drain zijn lastig met kabels en leidingen en wortels van bomen. Voor parken prima maar niet in woonstraten.
Zo min mogelijk drains toepassen, oplossing zoeken in doorlatendheidseisen van ophoog materiaal .
Zeker
Ik ben niet bekend met dit principe van omgekeerde drainage, dus ik kan moeilijk inschatten hoe effectief het is en of ik dit soort systemen zou overwegen.
Drain vragen ook onderhoud daarom zijn gemeenten vaak terughoudend met de aanleg van een drainagesysteem hoe meer drainage hoe meer onderhoudskosten, als de aanvullende kosten opwegen tegen de baten dan is dit een reden om dit te doen
Het heeft niet de voorkeur. Liever iets verder ophogen de grondwaterstand wat meer laten varieren. Drains zijn toch onderhoudsgevoelig en een dicht netwerk draagt niet bij aan het vasthouden van water. Wanneer je bij slimme systemen denkt aan gestuurde systemen, introduceert dat een nieuw risico: wordt hier daadwerkelijke gebruik van gemaakt en wij is verantwoordelijk.

Indien de drainage diepte variabel wordt (door middel van een mechanisch systeem in de overstortput) kan er wellicht in het grondwater een soortgelijk dynamisch systeem ontstaan als de zomer- & winterpeilen in het oppervlaktewater. In de winter zal de ontwerp-grondwaterstand lager zijn dan in de zomer.
F4. Wordt een variabele drainage diepte al overwogen tijdens projecten, of zou u dat willen overwegen om (droogte-geïnduceerde) bodemdaling tegen te gaan?

Standaard oplossingen is ontwateringsdiepte zo hoog mogelijk. Verhogen van de grondwaterstand is nieuw voor iedereen. In één project voorgesteld en toegepast maar blijft de vraag of de gemeente in de toekomst dit nog snapt.
Nee
Waar dat kan koppel is draiange altijd aan het oppervlakte water.
Nee
Wellicht zie bovenstaande opmerking
Alleen incidenteel. Zie reactie op de vorige vraag. Wordt dit in de praktijk wel beheerd?

F5. Is het praktisch haalbaar om te kijken naar het watergebruik van typen bomen/planten om keuzes voor de typen in straten te baseren op het watergebruik, om zo verschilzettingen te voorkomen?

Lijst van bomen hebben die veel vocht kan onttrekken zou vind zijn. Kan je in gevoelig gebied hier naar kijken
Kan, maar dat is een ontwerpopgave waar de urgentie dan ook duidelijk moet zijn.
Weet ik niet
Daar is vast iets voor te bedenken, maar hierbij moet je opletten dat je niet heel nauwkeurig iets gaat uitrekenen voor een proces waar in algemeenheid vrij veel onzekerheid in zit (zettingen = +/- 30%).
Geen idee, lijkt mij erg lastig
Water en bomen moeten wel worden meegenomen in de waterbalans van een wijk. Ik zal ook altijd willen onderzoeken in hoeverre een wijk zelfvoorzienend kan zijn in droge perioden.

F6. Heeft u nog andere oplossingen?

Nee, niet overal antwoord op kunnen geven, vind onderzoek wel zeer interessant
Nee
Werken aan robuuste systemen met weinig zettingen (ook minder onderhoudskosten) en zoveel mogelijk vasthouden van water in de bodem.

Hartelijk bedankt voor het invullen van deze vragenlijst. Het onderzoeksrapport zal naar u worden teruggekoppeld.

Gemiste vragen?
Ben ik een onderwerp vergeten? Heeft u andere opmerkingen? Ik hoor het graag via sander.geertzen@witteveenbos.com of 06-15 46 49 93

F

Analyses in Kampen

This appendix consists of the case study analysis of Kampen. The case study analysis is shortly covered in Chapter 5.

F.1. Influence of drought on subsidence - Kampen

F.1.1. Drought impact on soil processes

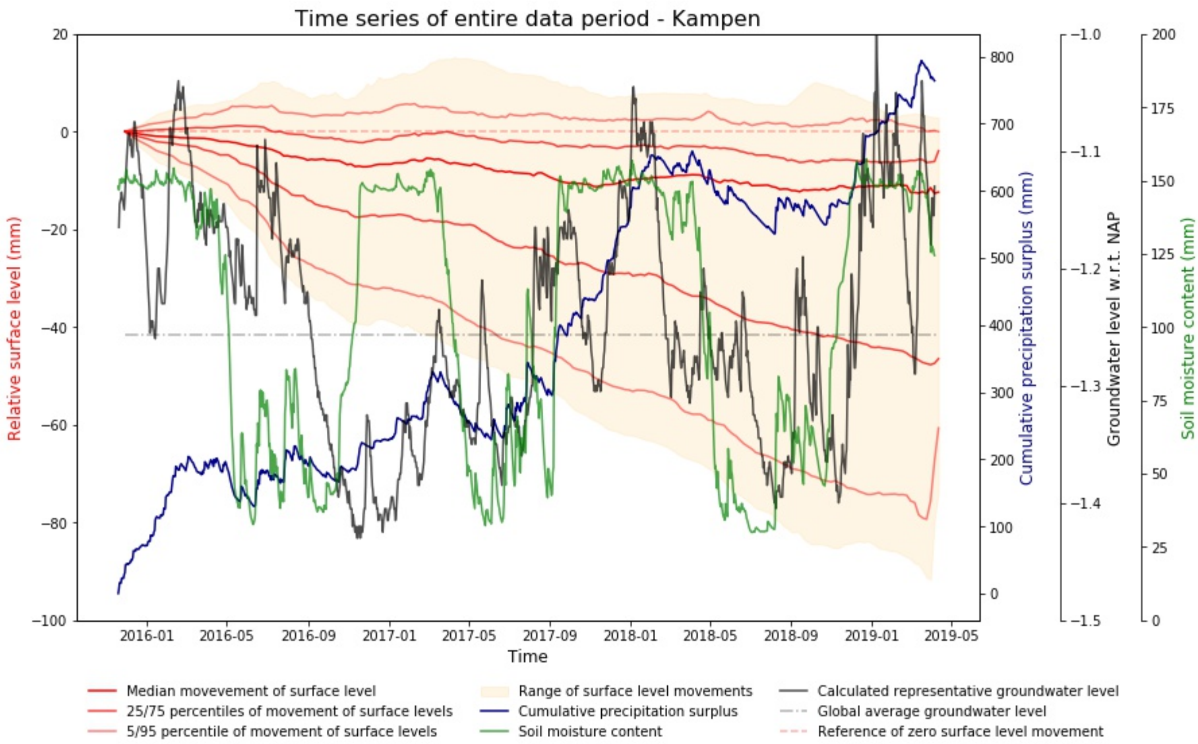

Figure F.1: *Temporal behaviour of surface levels, cumulative precipitation deficit, groundwater level and soil moisture content, Kampen.*

Cumulative precipitation surplus

Figure F.1 shows the calculated cumulative precipitation surplus to have a large difference in winter 2017, indicating a wet winter in comparison to other years. Furthermore, summer 2016 was wet while summer 2018 was extremely dry in comparison to other years.

Groundwater level variations

The average groundwater level during observed period in Kampen is approximately -1.25meter NAP. The groundwater level varies seasonally, having a difference in summers and winters of approximately 20-30 centimeters. The groundwater level however reacts quite fast and ongoing: example given the start of 2018 summer where the groundwater level drops quickly after a few dry days. The groundwater level varied less in 2017.

Soil moisture content depletion

In winters the soil moisture content is almost constant at approximately 150 mm. This is mainly since evaporation is almost not present in these periods and precipitation is abundant. The soil moisture content depletion is largest and longest in summer 2018.

Surface level movement

The compacting and swelling behaviour is seen by the varying median surface level in the Time series plot. The lag between intensified subsidence and drought is seen in the plot, example given in 2018 the peak of median plot is later in time than the peak of cumulative precipitation surplus. The lag and difference in duration of subsidence in comparison to cumulative precipitation surplus is shown in Figure F.2. The range of lag is broad, but has its median on approximately 100 days, while the duration has its median on approximately -30 days, indicating a faster intensified subsidence than the swell afterwards.

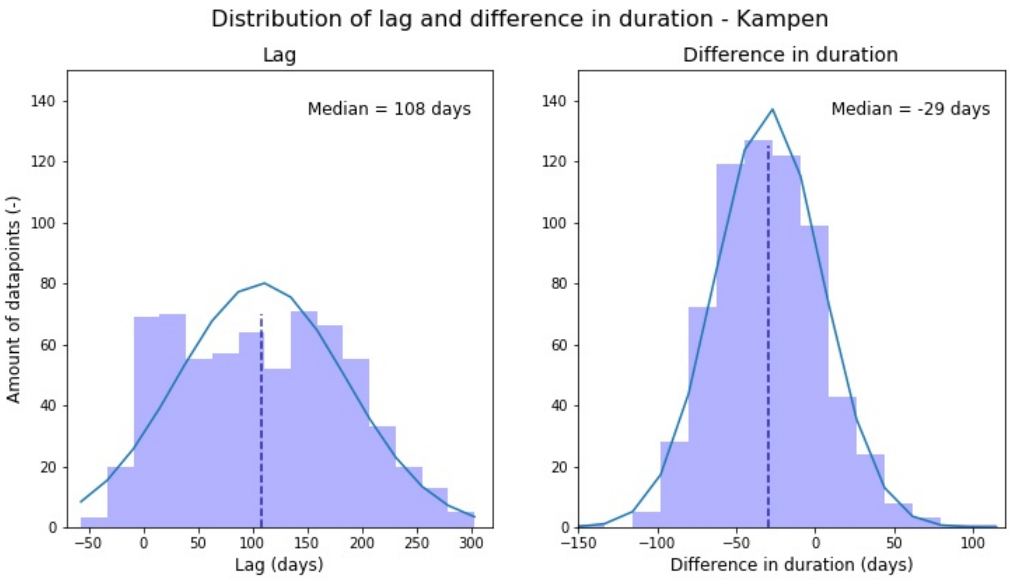

Figure F.2: *Distributions of lag and duration of subsidence, Kampen.* Duration is referred to the difference in duration of drought and intensified subsidence.

The window of minimum and maximum surface level movement is broad: some observation points do not move or even swell through the total period, while others subside almost 25 mm per year. Also the percentile bands show a large difference in subsidence between observation locations. This might be due to recent construction work and soil level raises in the area. The amount of movement at locations is however not influenced by the average subsidence rate, as shown in Figure F.3.

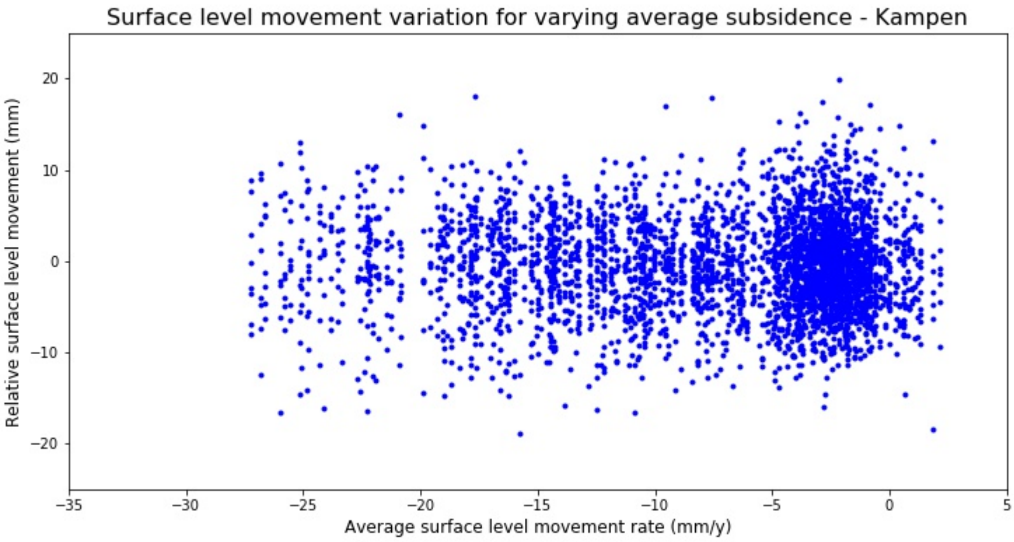

Figure F.3: *Relative surface level movements in several winter and summer periods for varying average surface level movement rates.*

F.1.2. Drought impact on surface level movements

Figure F.4 shows relative surface level movements for certain extent of drought or wetness of periods (cumulative precipitation surpluses). It shows in dry periods subsidence is intensified, while in wet periods subsidence rates are decreased. This might also be a swell of the soil (upwards movement). There is quite a lot variation in relative surface level movements for certain extent of drought (vertical wideness is quite big) indicating the soil moves quite extremely (15mm per halfyear). Since groundwater levels may drop within the peat layers in Kampen other subsidence processes might play a role: shrinkage and peat oxidation. The extent of these processes however cannot be estimated. It is moreover not yet known what the average difference is between dry and wet periods.

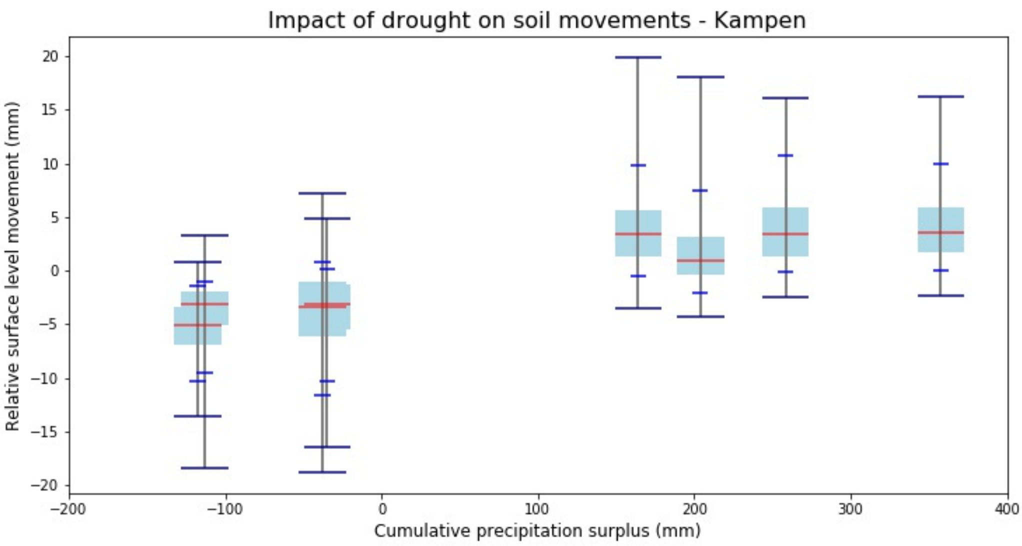

Figure F.4: *Variation in relative surface level movement on extent of cumulative precipitation surplus, Diemen.* The interpretation of the box plot is given in Figure 3.11.

F.1.3. Development of surface level movements

Figure F.5 shows median surface level movements in the years analyzed.

The seasonal fluctuation in relative surface level movement in Kampen is well seen in the figure. It is shown that due to the reoccurring wet and dry periods of the Dutch climate (winters and summers respectively) there is a same-like fluctuation in the relative surface level movements. This sinusoid movement of the soil has an average extent of approximately 4mm (for the median) and hence might have a larger extent for individual surface level locations, as shown by the percentiles. Also it is clear from the percentiles that the amount of observations resulting in opposite movements (for example a swell movement during a drought) is nihil.

The valleys of the graph, indicating intensified subsidence in dry periods, differs per year. 2017 has less movement in its summer, while 2018 has lots more movement than the other years. This might be due to the combination of groundwater level drop and shrinkage, oxidation. The swell in different winters is approximately the same. This causes the intensified subsidence in 2018 to result in 1-2mm irreversible subsidence. The percentile bands are however very wide, indicating a high uncertainty in the analysis.

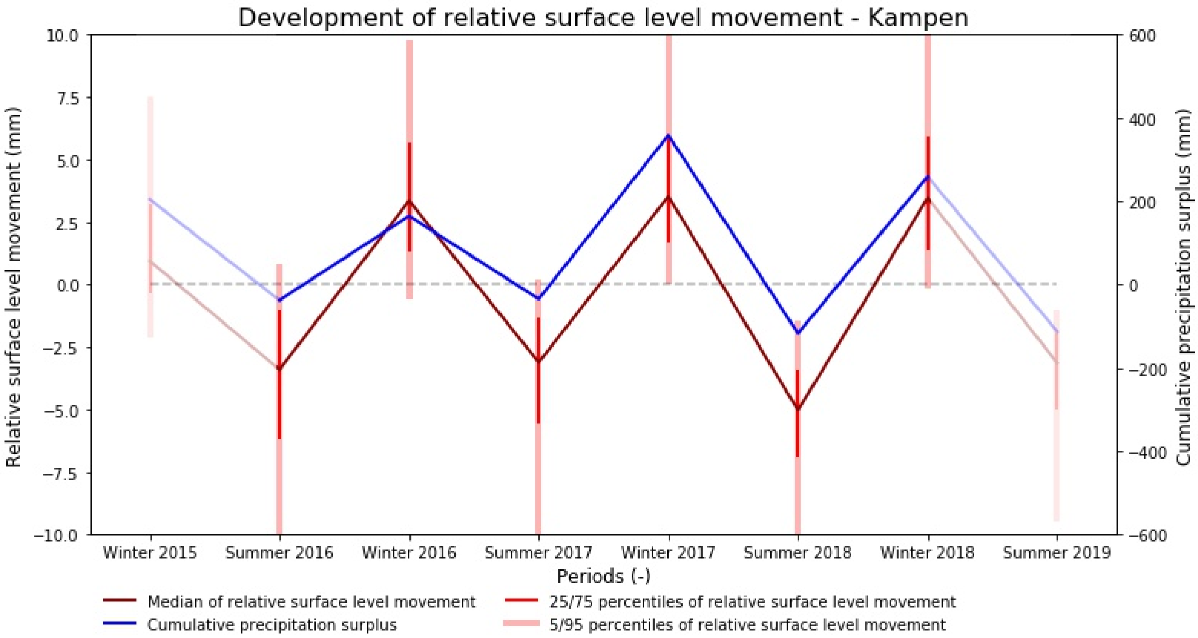

Figure F.5: *Chronological development of relative surface level movement, Kampen.*

F.2. Influence of local characteristics - Kampen

F.2.1. Soil structure

Categorization based on soil structure compressibility illustrates that soils with higher compressibility result in more surface level movement in both dry and wet periods, as shown in Figure F.6. This is expected from theory, however the present highly compressible soils have mainly a peat structure and are therefore not expected to swell extremely. This indicates that either peat layers swell more substantially in wet periods, or sand layers compress and swell more than expected.

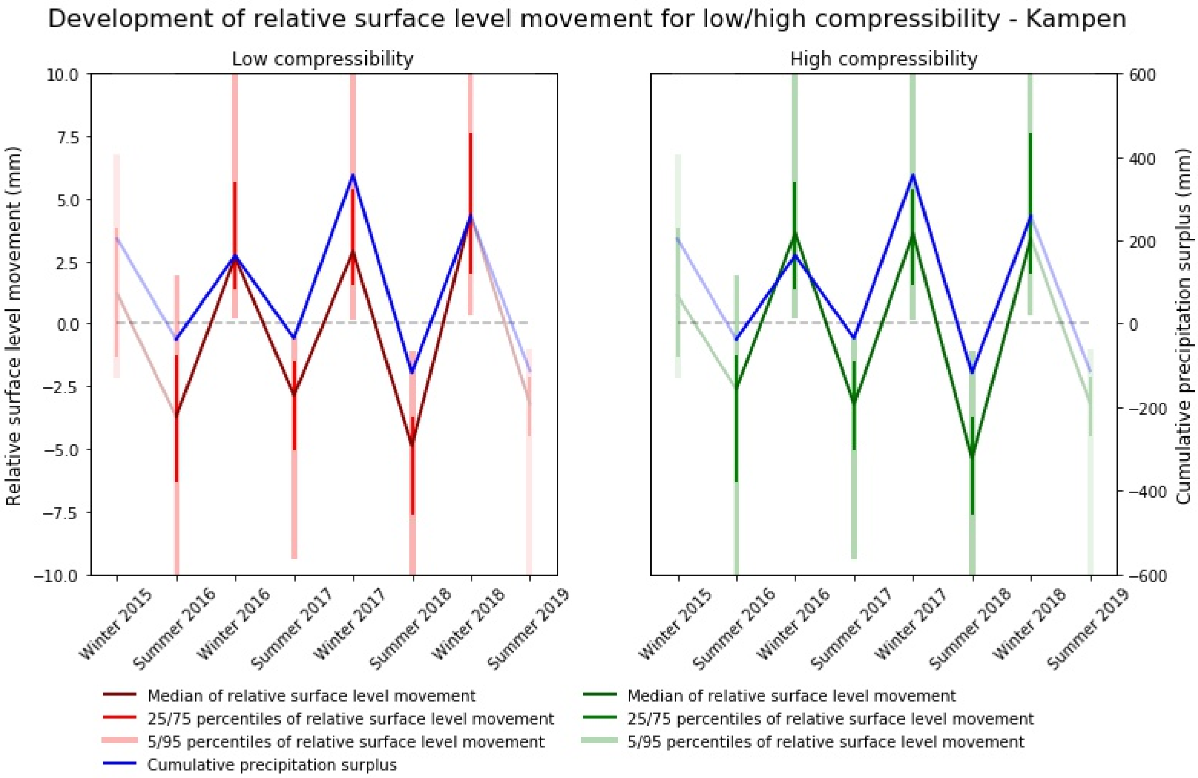

Figure F.6: *Chronological development of relative surface level movement for low and high compressible soils in Kampen.*

F.2.2. Pavement type

Unpaved surfaces in Kampen move minimally in 2017 compared to other years and therefore show a high equivalence with present groundwater variations, as shown in Figure F.7. Paved surfaces however compress and swell more or less to same extent in wet and dry periods. Lack of vegetation and presence of a drainage network might explain more stable surface level movements here.

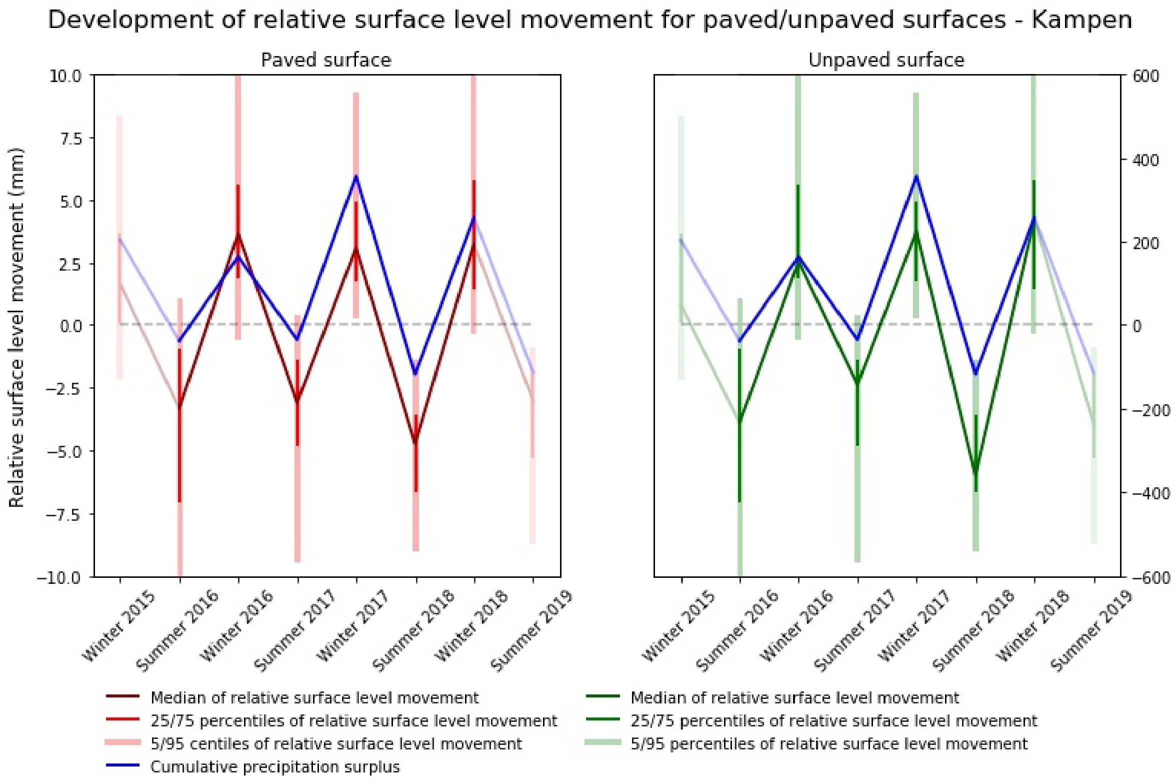

Figure F.7: *Chronological development of relative surface level movement for paved and unpaved surface types in Kampen.*

F.2.3. Vegetation

The difference in slightly and highly vegetated areas in Kampen, shown in Figure F.8, show different extent of compression and swell in summer and winter 2018. Explanation might be that subsidence observation locations and highly vegetated areas in Kampen mainly overlap within urbanized area as shown in Section 4.2. The presence of a drainage system preventing high groundwater levels and thus substantial swells might therefore cause low swell in 2018. This results in more extreme irreversible subsidence due to extreme drought.

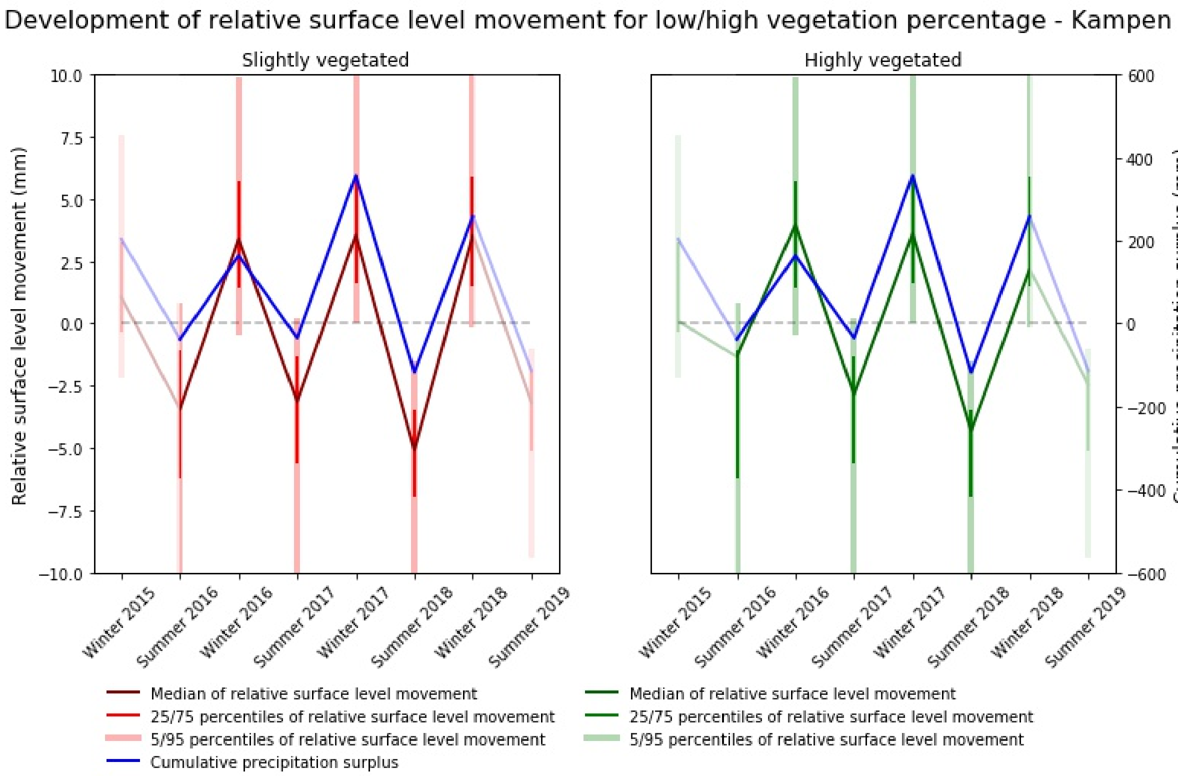

Figure F.8: *Chronological development of relative surface level movement for slightly and highly vegetated areas in Kampen.*

F.2.4. Surface water

Lastly influences of surface waters are analyzed in Kampen in Figure F.9. More extensive surface movements within the influence zone are found which seem equivalence to groundwater levels from observation wells nearby. This contradicts expectations that surface waters do have influence, and suggesting surface waters have influence on groundwater levels in only very limited distance. The large fluctuation in surface levels within influence zones however cannot be explained.

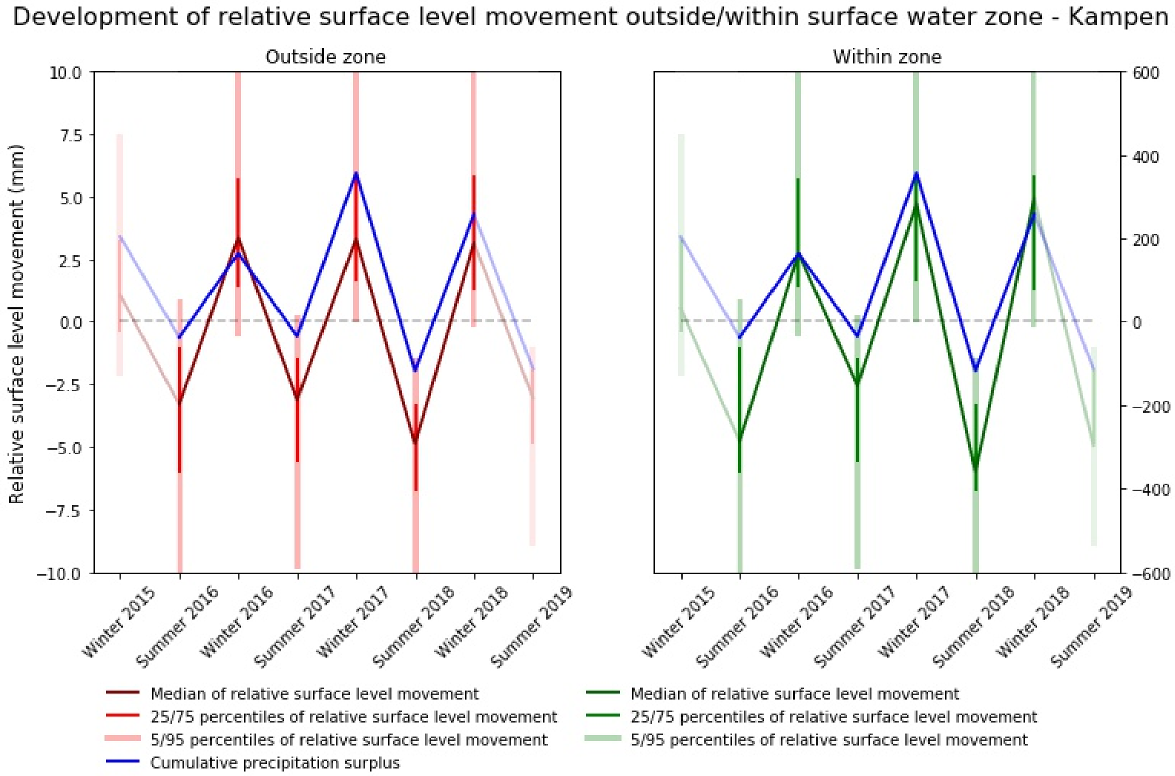

Figure F.9: *Chronological development of relative surface level movement for either being located within or outside influence zones of surface waters in Kampen.*

G
Other analyses

This appendix consists of various overviews and analyses which have been conducted but have not been directly included in the research report. The most analyses have been conducted only of location Diemen since the case study of Kampen only verifies relevant analyses of Diemen which are covered in the report.

G.1. Spatial analyses of surface level movements

Figures G.1 and G.2 show the average subsidence rates and percentiles respectively for given observation points in Diemen. The places with intense subsidence rates are placed in two regions. The first (1) region having high subsidence rates is in the center of the neighbourhood. The compressibility in this region is low, and therefore another reason is to be found for the high subsidence rates. This area however is newly built in 2014 (and thus also raised) and might therefore cause the surface level to subside rather fast (>7mm/y). Approximately 100 meter north-west of this region there is a second zone (2) where subsidence rates are large. It is not exactly known why the subsidence rates might be high, however the compressibility in this area is high.

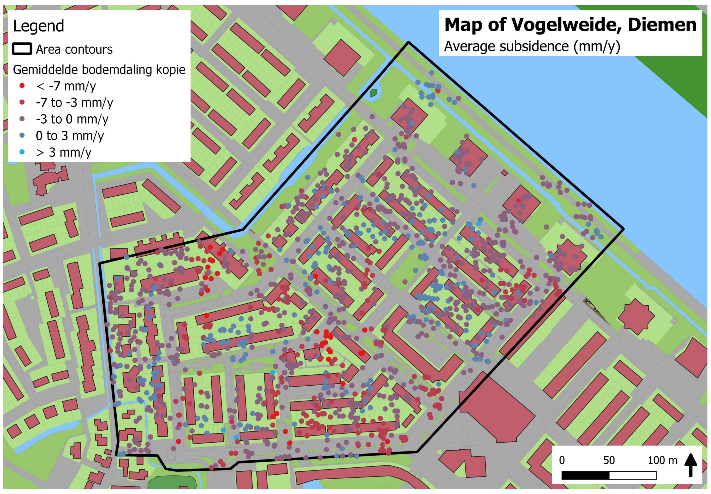

Figure G.1: *Overview of average subsidence rates in Vogelweide, Diemen.*

The region south of latter region discussed above (and west of first region discussed above) (3) has almost no subsidence since it has a low compressibility compared to other regions. Region (4) has a low subsidence rate too, but this cannot be explained by compressibility or other reasons.

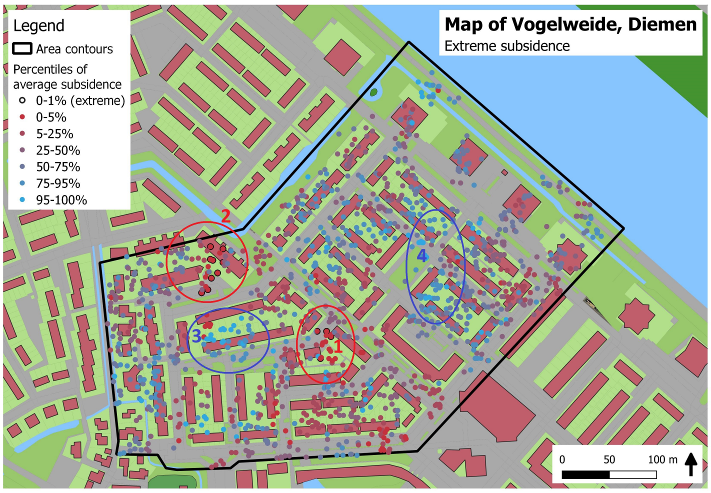

Figure G.2: *Overview percentiles of average subsidence in Vogelweide, Diemen.*

Relative surface level movements

In Figure G.3 the average of relative surface level movements is shown. The absolute movements are considered in the average to cover both swell and compaction movements of the soil. It shows that the two regions with higher average subsidence do have also quite large movements. However, in the other parts of the neighbourhood no such correlation can be found by spatial analysis. Therefore, a further (temporal) analysis is done to estimate the influence of relative surface level movements on the average subsidence in Diemen.

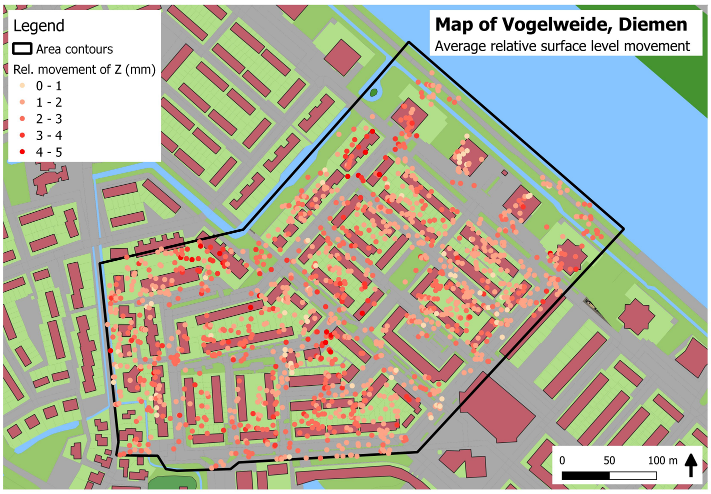

Figure G.3: *Overview of average relative surface level movements in Vogelweide, Diemen.* The average is considered over both positive (swell) and negative (compaction) movements and is therefore given as absolute value.

Figure G.4 shows the comparison of average subsidence rates (given negative) with relative surface level movements (so excluded the average subsidence). It shows that places with larger subsidence rates do not necessarily correlate with relative surface level movements. This does not mean that the soils move less or equally much as points without any subsidence (they can move more) but that relative to its subsidence rate there is no more movement. This indicates that the extent of drought is estimated to be equally for the entire area. This might be explained by the reason that the soil structure is approximately the same for the area and soft soil layers are still large enough to be induced by drought.

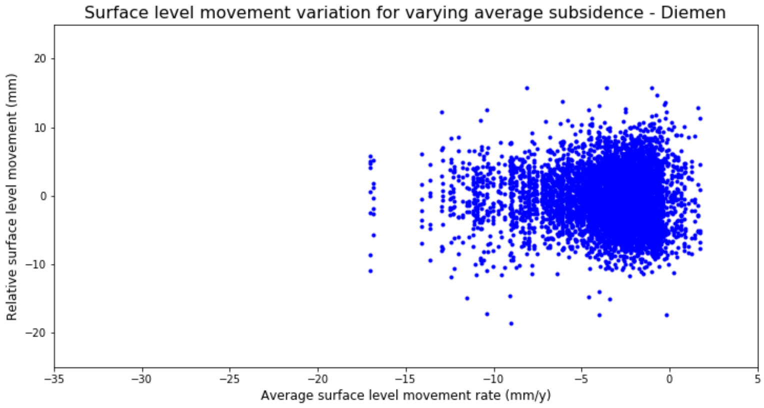

Figure G.4: *Relative surface level movements in several winter and summer periods for varying average surface level movement rates in Vogelweide, Diemen.*

G.2. Lag and difference in duration of groundwater level

A brief analysis of the lag and difference in duration of groundwater levels and surface level movements is conducted. Objective is to determine if there is a lag between peaks in cumulative precipitation surplus and groundwater levels and hence this might explain the lag between cumulative precipitation surplus and surface level movements.

The analysis is conducted by firstly looking at the time series of both Diemen and Kampen (Figures 5.2 and 5.12) and determining the date of groundwater level peaks and valleys corresponding to the start and end of a drought. Since this is done visually (manually) the determination might be prone to error or subjectivity. However, in Figure G.5 the difference between the dates of peaks of cumulative precipitation surplus and groundwater level is shown for both Diemen and Kampen. In Diemen at the year 2016 no calculation could be made since the groundwater level time series only starts later.

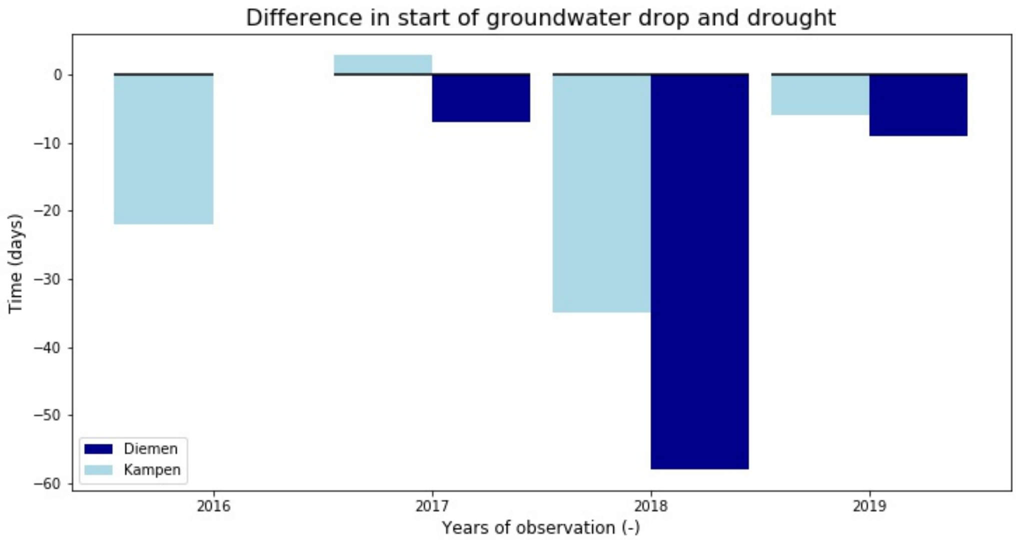

Figure G.5: *The calculated difference between peaks of cumulative precipitation surplus (start of drought) and peaks of groundwater levels in Diemen and Kampen.* In Diemen at the year 2016 no calculation could be made since the groundwater level time series only starts later. A negative value corresponds to a peak of groundwater level prior to the peak of cumulative precipitation surplus.

It is clear that overall there is a negative difference between the peaks, referring to a groundwater level drop prior to the peak of cumulative precipitation surplus. This is in line with the analysis in Chapter 5 that groundwater levels react impulsively on changes in cumulative precipitation surplus. Since evaporation already increases prior to the peak of cumulative precipitation surplus (the slope decreases) it also affects the groundwater level prior to the peak. In 2018 the difference of start of groundwater level drop and the estimated start of drought is large, approximately 50 days.

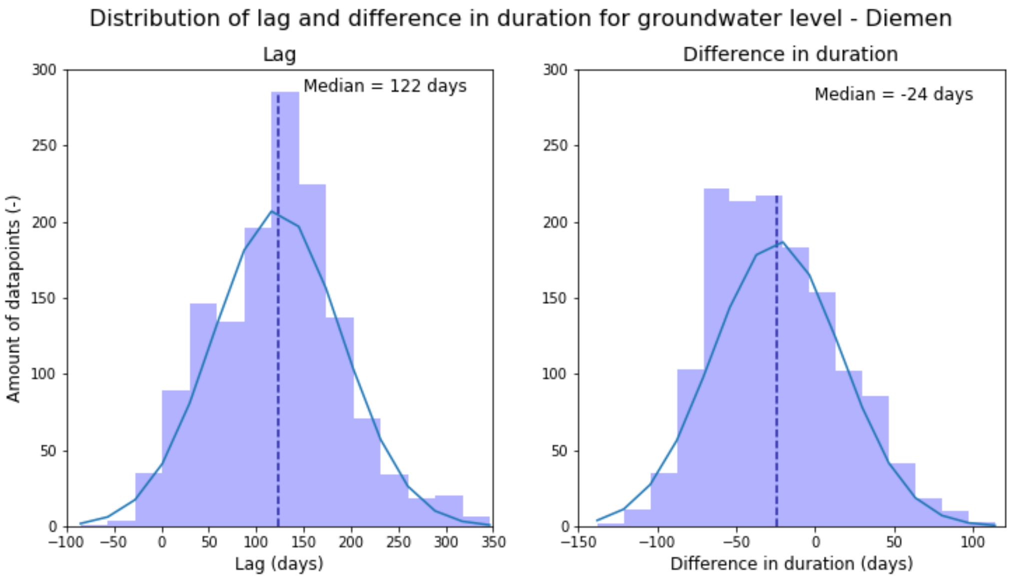

Figure G.6: *Lag and difference in duration between groundwater level and relative surface level movements in Diemen.*

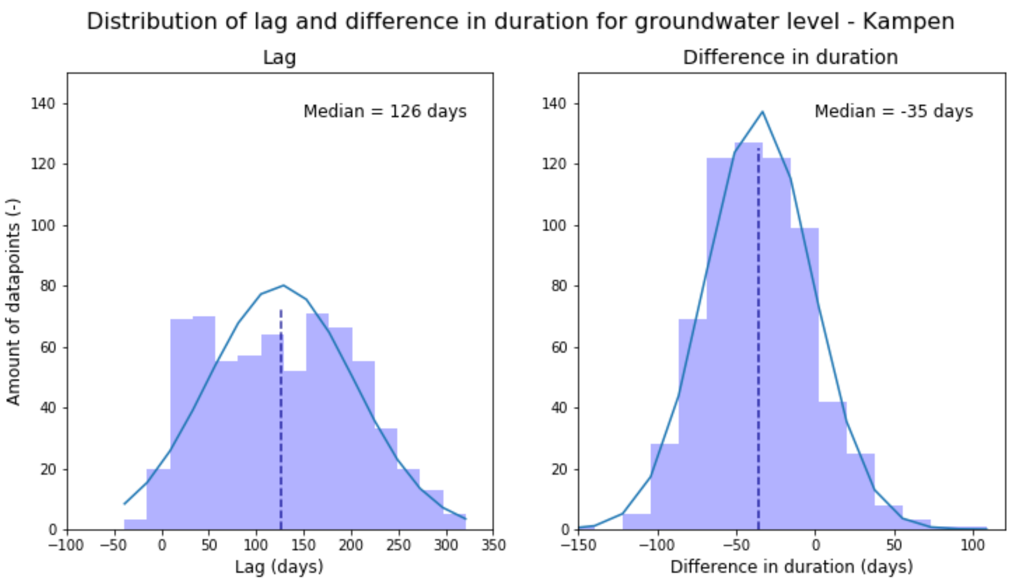

Figure G.7: *Lag and difference in duration between groundwater level and relative surface level movements in Kampen.*

In Figure G.6 the distribution of lag and difference in duration between groundwater level and relative surface level movements in Diemen is given. The same figure but for Kampen is shown in Figure G.7. In comparison to the lag calculated between cumulative precipitation surplus and relative surface level movements (Figures

3.8 and 5.5) there are some minor differences seen. The lag and difference in duration for groundwater levels differs mainly in its median value in Diemen being larger for the lag. This is mainly due to the start of groundwater level drop being prior to the start of droughts.

In Kampen, the analysis resulted in even more negative values for the lag for groundwater levels. This is mainly since in 2017 the groundwater level starts to drop later than the evaporation outnumbers precipitation (peak of cumulative precipitation surplus), as shown in Figure G.5. Figure G.8 illustrates a possible explanation of negative lags due to errors in the chosen method or the model. In Kampen too the lag between peaks of groundwater level and relative surface level movements increased. This indicates the lag between peaks of cumulative precipitation surplus and relative surface level movements are not induced by a lag of groundwater levels to the start of drought.

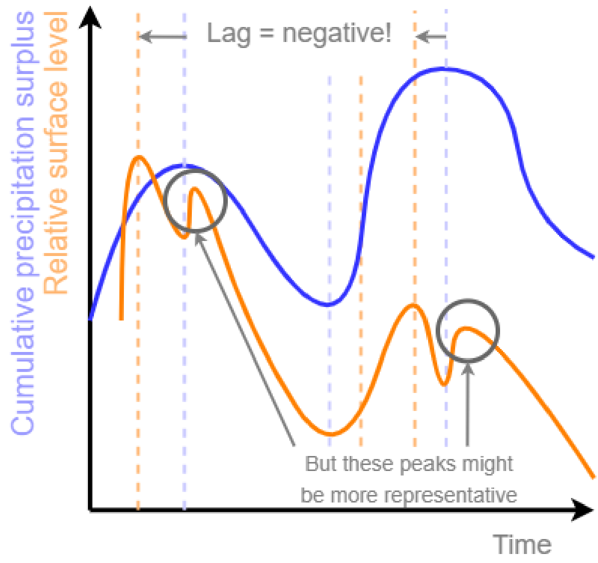

Figure G.8: *Schematizing the possible error in the model resulting in a negative calculated lag.*

G.3. Analysis of soil structure correlations

The analysis of soil structure correlations is given in this appendix since no explanation could be found for surface level movements of certain compressibility (soil structures) in Diemen. This appendix only covers a second analysis which has been conducted in addition to the research analysis of low/ high compressiblity comparison.

As shown in Figures G.9 and G.10 the compressibility in Diemen varies between approximately 1.5 and 2.5/3 meter. In the research analyses it was showed that a lower compressiblity results in larger surface level movements. This could not be explained by the soil structure given in Figure G.10. Another analysis below is conducted which tries to explain the surface level behaviour in Diemen.

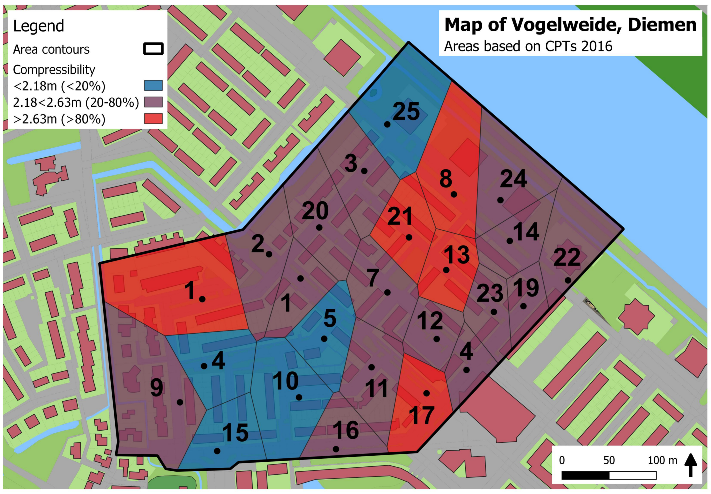

Figure G.9: *Compressibility regions (polygonized by Voronoi method) in Vogelweide, Diemen.*

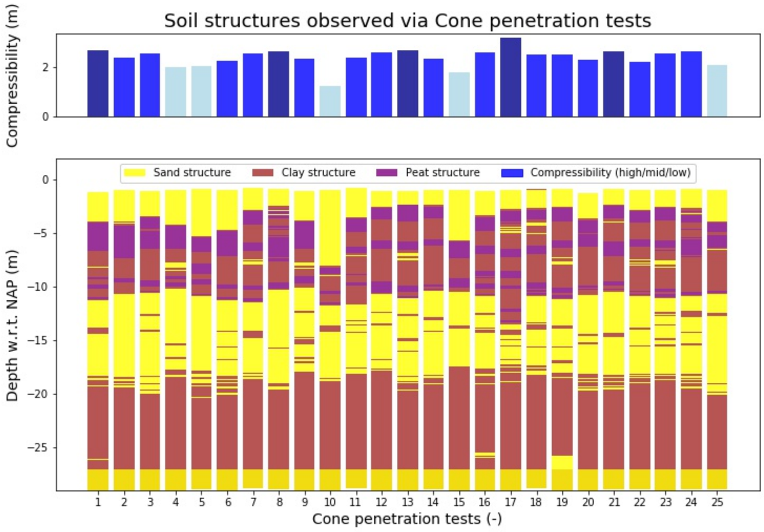

Figure G.10: *Soil structures as reprocessed from CPT results in Vogelweide, Diemen.*

Main cone penetration test number which is found interesting is CPT number 10, since it shows a smaller compressibility than other CPT results. This is mainly due to the large sand layer placed on top of the soft soil. Figure G.11 shows an old map of 1975 which has been laid on top that of the current situation. The cone penetration with number 10 was exactly placed within an old ditch. This explains the large sand layer found in the cone penetration test.

Figure G.11: *CPT in Diemen overlapping an old ditch (map of 1975).* Map retrieved from: https://www.arcgis.com/home/group.html?id=9cf0ea95e1b14f2e86a559ee620de15doverview.

Therefore, it might be interesting to analyse the surface level behaviour of CPT 10. In the figures below all surface level movements from individual CPTs are given. These figures show that CPTs 6; 7; 17; 19; and 23 have little movement compared to others, despite not having smallest compressibility (17 even has highest). CPTs 12; 14; 18 and 25 show larger movements, while not having largest compressiblity (25 has a low compressibility). Therefore, no explanation could be found for the surface level movements of several compressibility extents. This is probably due to Voronoi polygonization not being precise.

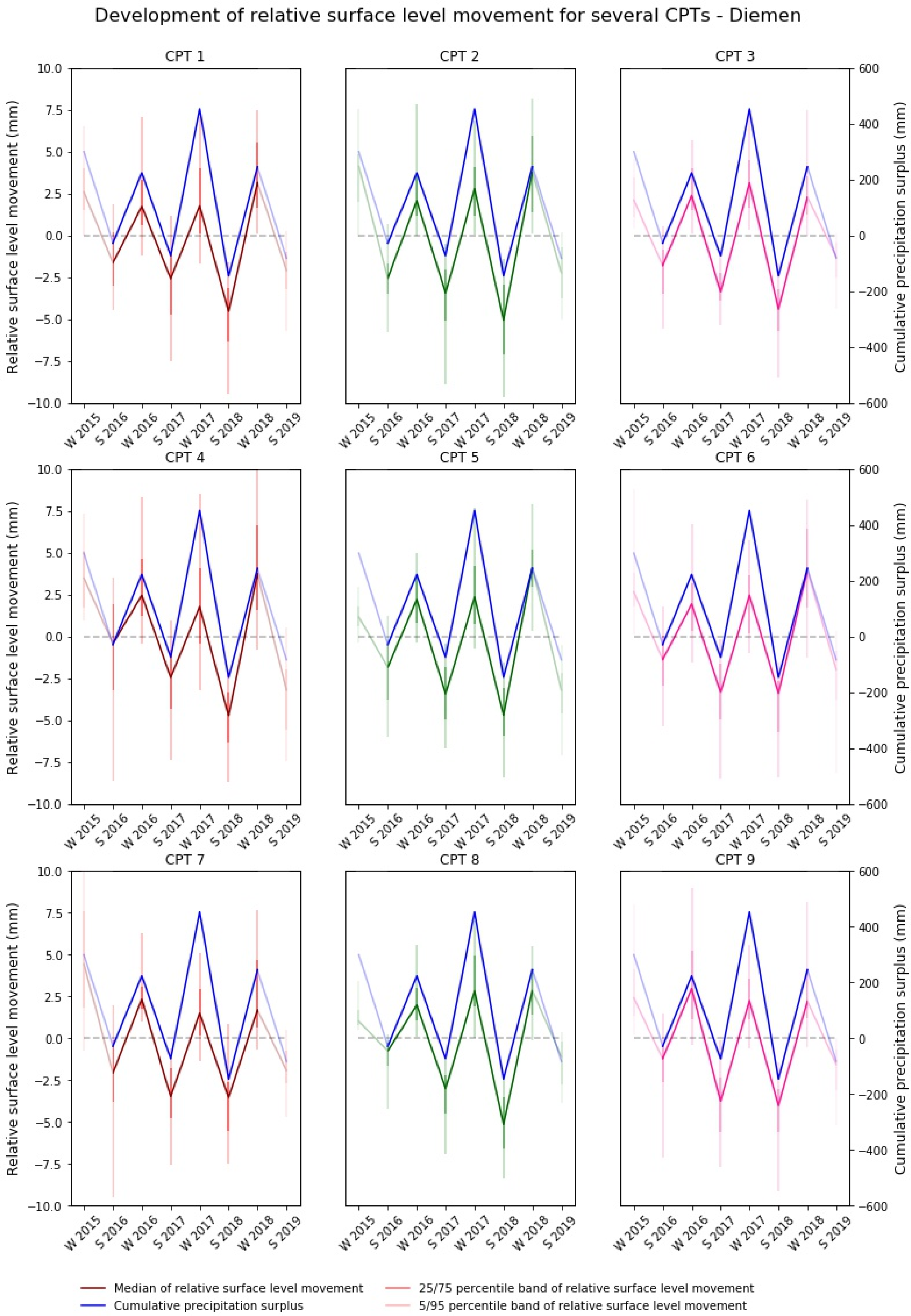

Figure G.12: *Chronological development of surface level movement of CPTs 1 to 9 in Vogelweide, Diemen.*

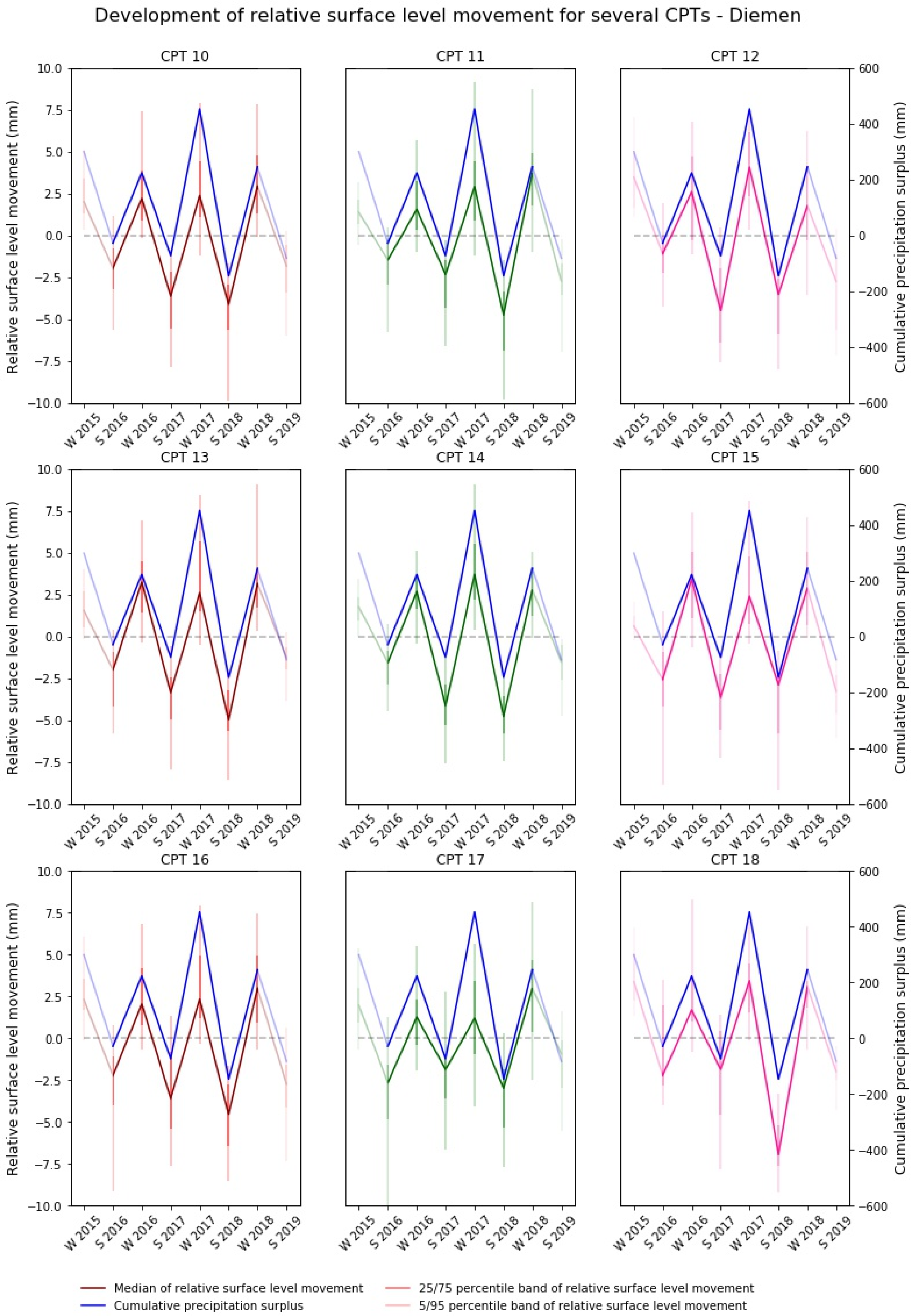

Figure G.13: *Chronological development of surface level movement of CPTs 10 to 18 in Vogelweide, Diemen.*

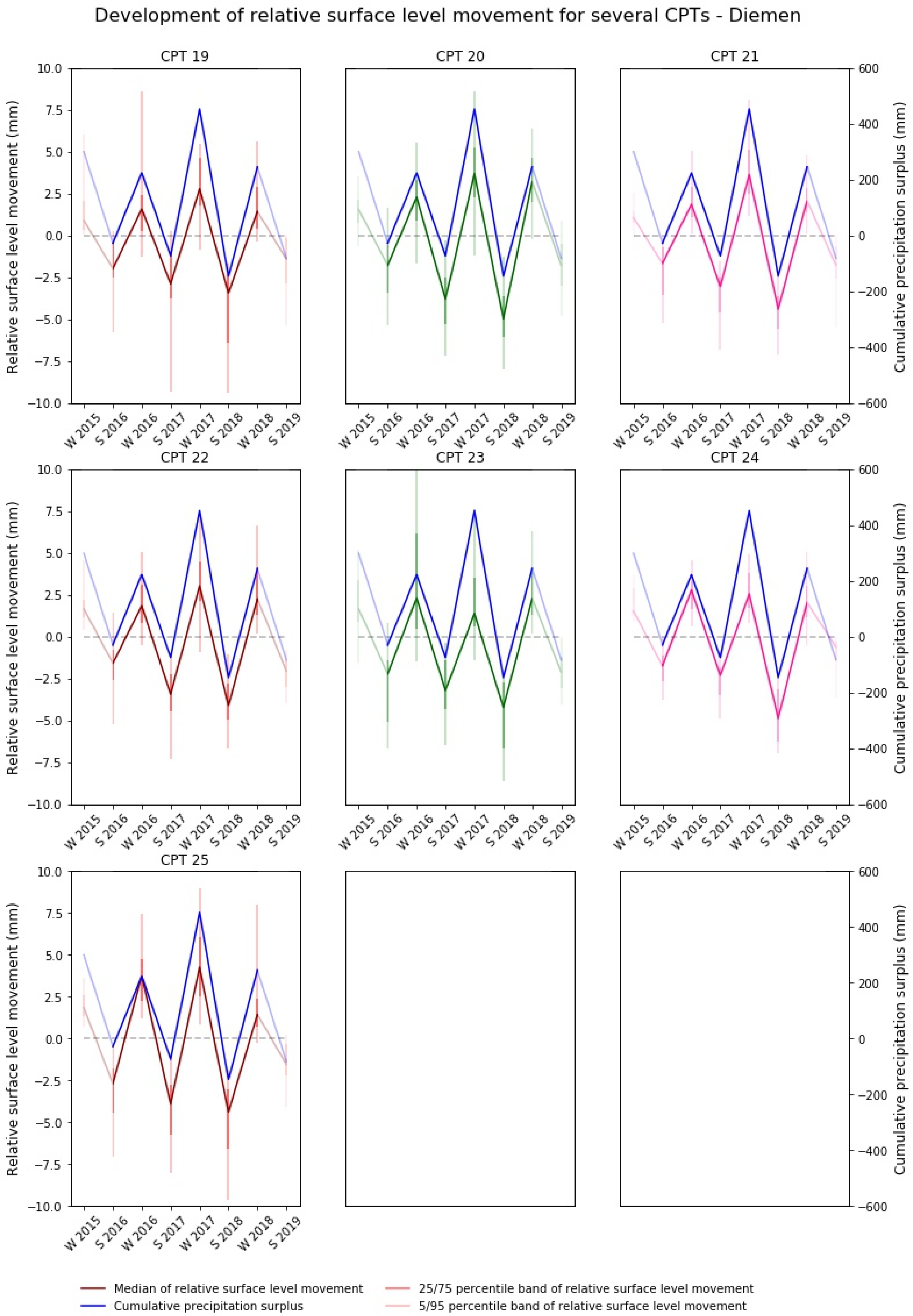

Figure G.14: *Chronological development of surface level movement of CPTs 19 to 25 in Vogelweide, Diemen.*

G.4. Former site preparation strategies

A brief analysis of differences in former site preparation strategies has been conducted for both Diemen and Kampen. The analysis consists of the previous raises and the influence of the thickness of cover layers upon drought-induced subsidence.

G.4.1. Influence of site preparation strategies in Diemen

Figure G.15 shows the year of last raising for various sub-zones of the Diemen neighbourhood. After the first preparations approximately in 1987 prior to constructing the buildings, the entire area was raised once, but in two distinct cycles. The north-western part of the area was raised approximately in 1999/2000, while the south-eastern part was raised few years later in 2006. The zone referred to as '2014' was initially included in the 1999/2000 sequence, but is actually a newly built area constructed in 2014 (all buildings were demolished, the site was raised, and new buildings were built).

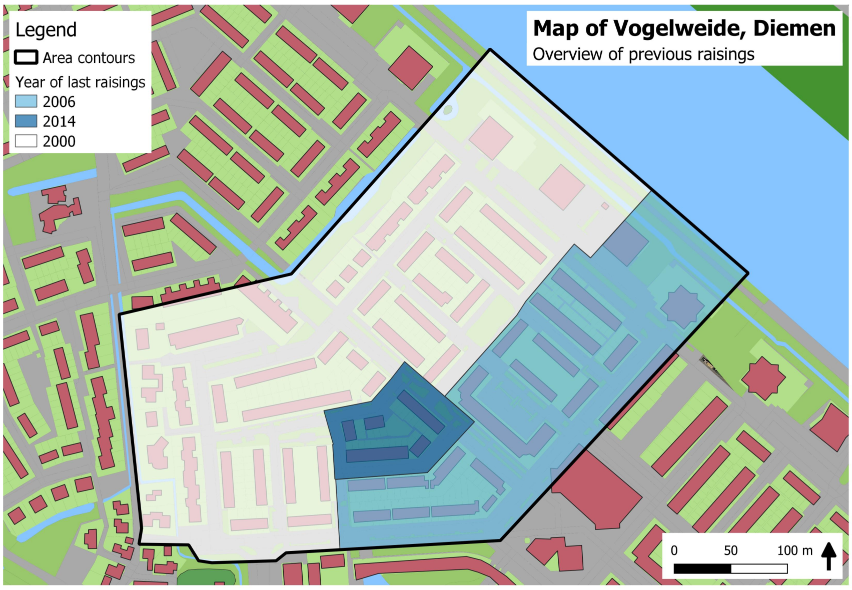

Figure G.15: *Previous raises and newly built area in Vogelweide, Diemen.* Reprocessed from Te Groen (2016).

Figure G.16 shows the chronological development of surface level movements for the several zones of different years of raises. It is observed that the areas having raises in later years (2006 and 2014 respectively) show less relative surface level movements. This is mainly seen by the less extreme peaks and valleys of the years 2006 and 2014 respectively to the movements corresponding to the raise in year 2000.

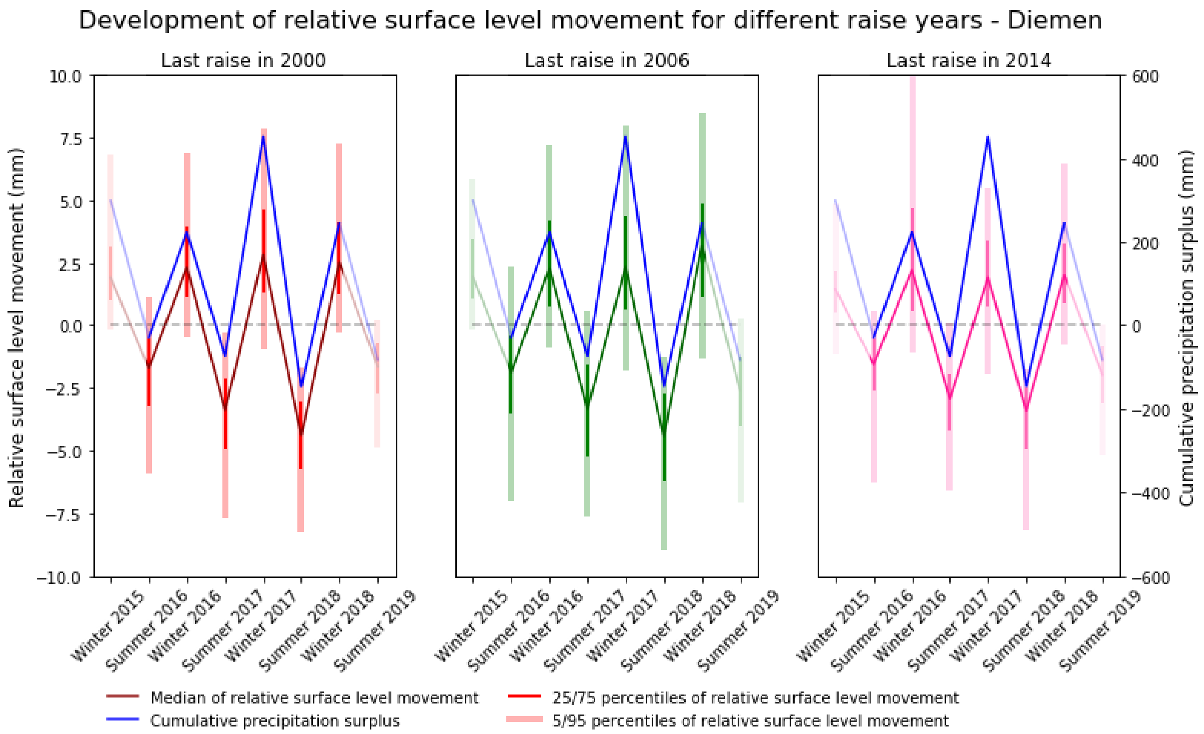

Figure G.16: *Chronological development of surface level movement for zones of different years of last raising or construction in Vogelweide, Diemen.*

An overview of the thickness of the sand cover layer as result of the raise sequences is given in Figure G.17 to fully understand the observed differences.

Figure G.17: *Thickness of sand cover layer in Vogelweide, Diemen.* Darkblue/ purple refers to a thickness of approximately 6-7 meters, green to approximately 3-4 meters, and red to approximately 1-2 meters. The image is acquired from an appendix of Te Groen (2016).

If the map of the year of last raise sequences is compared to the sand cover thickness it is understood why part of the area was raised in 1999/2000 and part only years after, in 2006. The thickness of the sand layer represents partly the extent of subsidence occurred in last tens of years since the top of the sand covers should be approximately the same (design surface level). Hence it is understood that part of the area was only raised in 2006 since it was prone to less intense subsidence rates than the other (northern) part raised in 2000. This directly also results in a smaller thickness of the sand cover. The area around the newly built housing block (2014) however shows a very thick sand cover layer, which might be result of thick soft soil layers.

The smaller movement of the soil for later years of raises can hence be explained. In 2006 the smaller movement can be referred to less compressible layers. This is contrary to the analysis of influence of soil structure on the surface level fluctuation presented in the research. The difference might be explained by the low accuracy of the Voronoi method and the conducted qualitative analyses. The result however verifies the analyses and discussion of the influence of soil structure on drought-induced subsidence in Kampen.

The later raise in 2014 resulting in even less surface level movements can be explained by the extra raise sequence causing the (extremely) large sand cover thickness. Due to this large thickness the soil is compressed to such extent that it reacts stiffer on the seasonal groundwater level fluctuation. It is hence assumed that a thicker sand cover layer results in less surface level fluctuation.

G.4.2. Influence of site preparation strategies in Kampen

A similar analysis is conducted in Kampen. Figure G.18 shows an estimation of the zones of different preparation (raise) strategies in Kampen, based on information of the preparation report (Joppe, 2012a). It is important to realise this is an estimation of the zones based on a very rough description (eastern urban area, western urban area, greenery). This might thus result in noisy data and larger uncertainties. In general it can be concluded that zone A has largest sand cover, and zone B and C have smaller thicknesses of sand covers respectively (A = 1.33m, B = 1.1m, C = 0.93m).

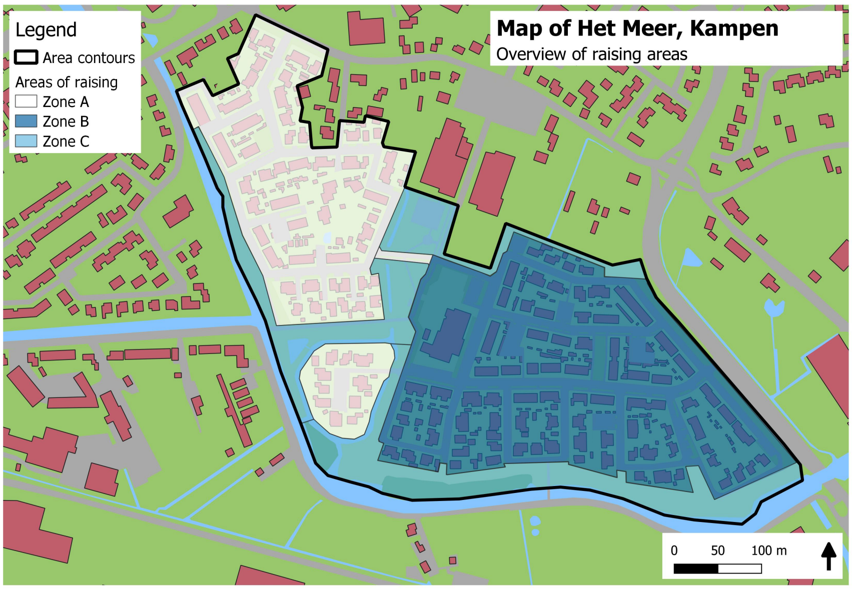

Figure G.18: *Estimation of zones with different preparation strategies in Het Meer, Kampen.*

Figure G.19 shows the relative surface level movements for the various zones. It is observed that zone B shows the largest surface level movements, but that it is almost similar to zone A. Moreover, it is observed that the urban zones (A and B) result in a large drop of surface levels during the drought in 2018 in comparison with zone C. Zone C results in least surface level movements on average.

It is assumed that the larger surface level movements in zone B are result of the large compressibility of the area. Most of the subsidence observations in zone B are located nearby CPTs showing largest compressiblity (13, 18 - Figure 4.20), while this is less the case for the other zones. This substantiates the findings in Diemen and the findings of the analysis of local characteristics in Kampen presented in the report. This estimation cannot be made for zone A since it lacks detailed info for soil structures.

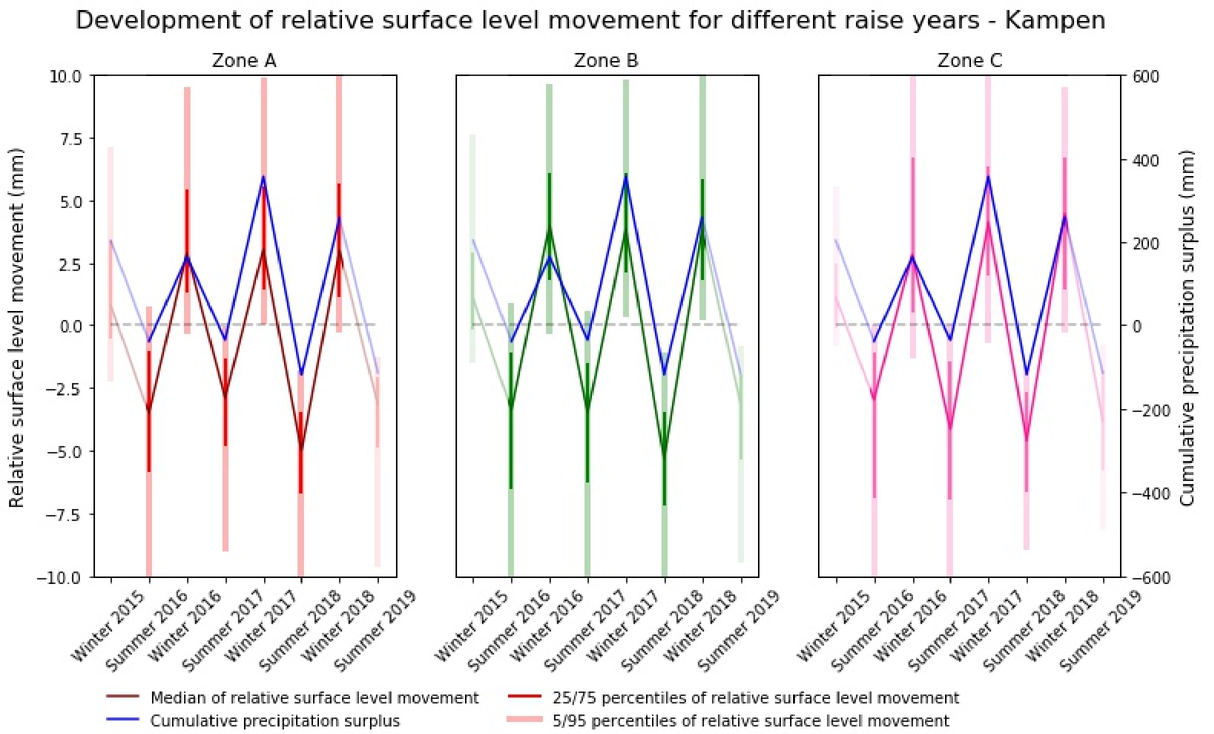

Figure G.19: *Chronological development of surface level movement for zones of different years of last raising or construction in Het Meer, Kampen.*

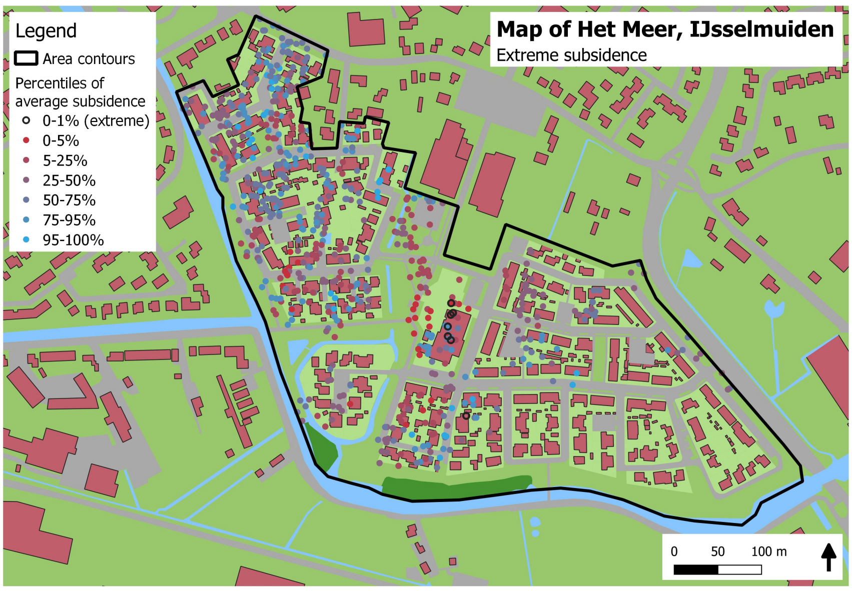

Figure G.20: *Average subsidence rates and extreme cases in Het Meer, Kampen.*

Since the sand cover thickness is insufficient, groundwater levels reach to peat layers below, as explained in Chapter 4. After the full settlement the sand cover will reach to -1.05 meter w.r.t. NAP for both zones A and B (Joppe, 2012a) - so its now still above this level, but this is not further considered. In zone C the sand cover will reach -0.93 meter w.r.t. NAP. Zone C is hence expected to show more surface level movement since groundwater levels drop quicker below the sand layer, but this is not observed.

However, Figure G.20 shows that the most extreme subsidence rates are located near zone C, but nonetheless correspond to zone B. From this figure it might be suspected that the extreme subsidence rates are actually placed in zone C and that an error is made in the estimation of the zones. It is further assumed that the subsidence rates in zone C are affected by the yearly drop of the groundwater level to greater extent than zone A and B. This is partly due to the higher bottom of the sand cover, and partly due to the existence of vegetation (grass) resulting in larger evaporation fluxes and hence lower groundwater levels. These two expectations might cause the larger seasonal fluctuation. However, since peat barely swells it can be expected that the extent of fluctuation is not affected in the model, but the subsidence rates.

G.5. Surface level movement calculations

An exemplary calculation of surface level movements due to decrease of groundwater levels (clinch) in summer 2018 has been conducted for both Diemen and Kampen. Main objective was to compare the calculations and observations to study the differences.

The calculations are made by Koppejan his formula as proposed in the research (appendices). This formula has several parameters as input:

- Soil structure (layers) as conducted from CPT results.
- Thickness of individual soil layers.
- Unit weight of individual soil layers.
- Consolidation parameters (primary and secondary) of individual soil layers.
- Unit weight of water.
- The extent of groundwater level drop.

An example of parameters used as input for CPT number 1 in Diemen is shown in Figure G.21. The unit weight and consolidation parameters (only cp1 and cs1 are used) for Diemen are gathered from the geotechnical report of the neighbourhood (Te Groen, 2016). This report probably gathered default information regarding unit weight and consolidation parameters from standardized tables (e.g. from NEN-EN-ISO 224760). In Kampen the unit weight and consolidation parameters are refined by a study (Joppe, 2012b) as shown in an example of CPT number 8 in Figure G.22.

	soort	thickness	Unit weight wet	Cp1	Cs1	Cp2	Cs2
0	zand unsaturated	0.63	18	1800	1000000	600	10000
1	zand saturated	1.97	20	1800	1000000	600	10000
2	klei, schoon slap	0.1	14	21	240	7	80
3	veen, schoon matig	0.5	12	22.5	75	7.5	30
4	veen, schoon slap	2.18	10	15	60	5	20
5	klei, schoon slap	2.42	14	21	240	7	80
6	veen, schoon slap	0.2	10	15	60	5	20
7	klei, schoon slap	0.46	14	21	240	7	80
8	veen, schoon slap	0.48	10	15	60	5	20
9	klei, schoon slap	0.72	14	21	240	7	80
10	veen, schoon slap	0.22	10	15	60	5	20
11	klei, schoon slap	0.06	14	21	240	7	80
12	zand saturated	2.54	20	1800	1000000	600	10000
13	klei, schoon vast	0.64	19	110	960	35	320
14	zand saturated	4.44	20	1800	1000000	600	10000
15	klei, schoon vast	8.6	19	110	960	35	320

17.10652679485858

Figure G.21: *Parameters used for consolidation calculations of CPT 1 in Diemen during drought 2018.*

	soort	thickness	Unit weight wet	Cp1	Cs1
0	zand unsaturated	1.25	17	600	1000000
1	zand saturated	0.08	19	600	1000000
2	veen	0.72	10.1	31.3	188
3	klei	0.28	16	150	781
4	veen	0.14	10.1	31.3	188
5	klei	0.12	16	150	781
6	veen	1.28	10.1	31.3	188
7	klei	0.1	16	150	781
8	veen	1.3	10.1	31.3	188
9	klei	0.12	16	150	781
10	veen	1.66	10.1	31.3	188

15.810252445340577

Figure G.22: *Parameters used for consolidation calculations of CPT 8 in Kampen during drought 2018.*

Since Koppejan formula is not to be used for single days, one time step has been executed consisting of approximately 90 days. This is still relatively short compared to normal consolidation calculations (up to for example 10,000 days). The used groundwater level drop is taken to be 0.3 meter for Diemen and 0.3 meter for Kampen. Only a groundwater level drop is considered and compared to the relative surface level movement of the two areas. Figures G.23 and G.24 show the comparison of surface level movements calculated and observed as consequence of the 2018 drought and accompanying groundwater level drop.

For both areas most calculations result in a higher surface level movement than the observed variations. This is more extreme in Kampen than in Diemen. The difference in calculations is due to a large peat layer in Kampen. This shows that the rule of thumb used for determining the compressibility in both areas (which is approximately the same for Diemen and Kampen) is not accurate.

Moreover the differences between calculations and observed relative surface level movements might be due to changing soil characteristics due to loading. The calculations were performed with a unit weight and compressibility parameters which were chosen as default from standardized tables in Diemen and estimated based on research in Kampen. Therefore the in-situ parameters in Diemen are in advance already different. The Kampen case however shows that the compressibility parameters are not accurately determined, or change significant between moment of research (2012) and the time interval used in modelling (2018). This temporally variation in compressibility parameters is explained by the compaction of the soil itself, which affects future/ new loading and hence reduces compressibility parameters of the soil. This phenomenon is explained by Verruijt (2010) for large loading and unloading resulting in two sets of primary and secondary compression parameters. The change in these parameters might also be applicable for smaller changes of loading and unloading (for example groundwater level variations).

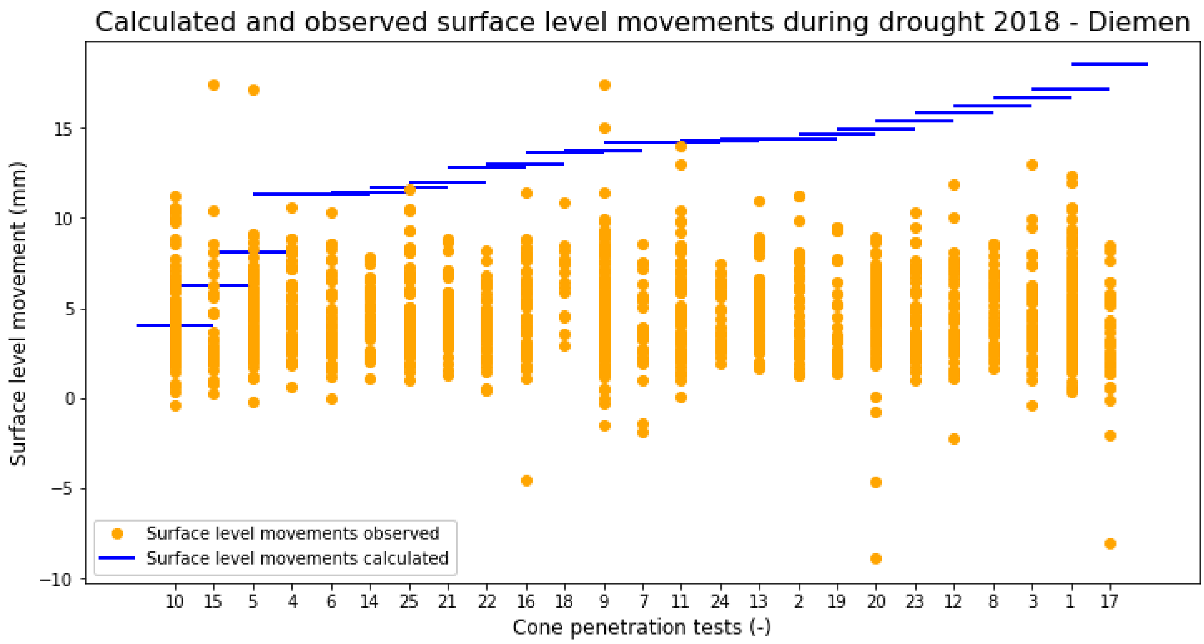

Figure G.23: *Calculated and observed surface level movements as consequence of groundwater level drop (0.3 meter in 90 days) in Diemen.*

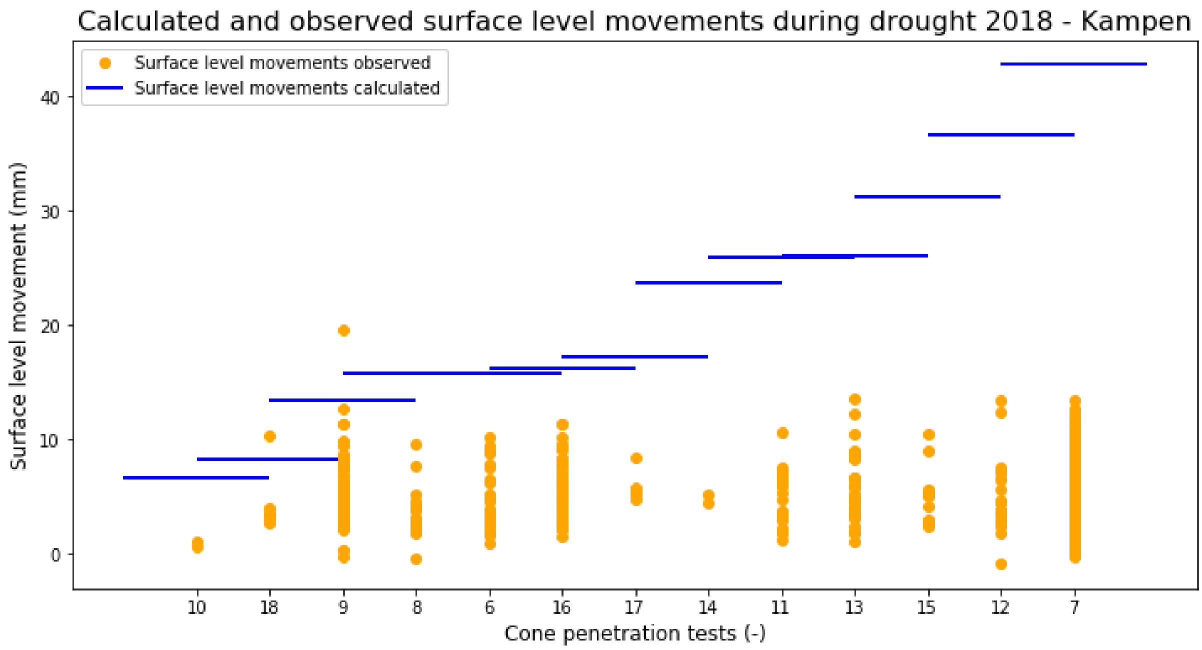

Figure G.24: *Calculated and observed surface level movements as consequence of groundwater level drop (0.3 meter in 90 days) in Kampen.*

G.6. Observations at buildings

This section covers a brief analysis of the relative surface level movements of observations located at buildings (roofs).

Figures G.25 and G.26 show the development of surface level movements in Diemen and Kampen for observations located at buildings (roofs). Both locations show a smaller extent of movement than the other locations (paved, unpaved, gardens). The graphs do however show an average movement of the surface of approximately 1 to 2 millimeters in Diemen and 2.5 millimeters in Kampen. This seasonal movement is not expected since buildings have a foundation in deep, solid, sand layers and therefore are expected not to move. Several explanations are however considered for this movement.

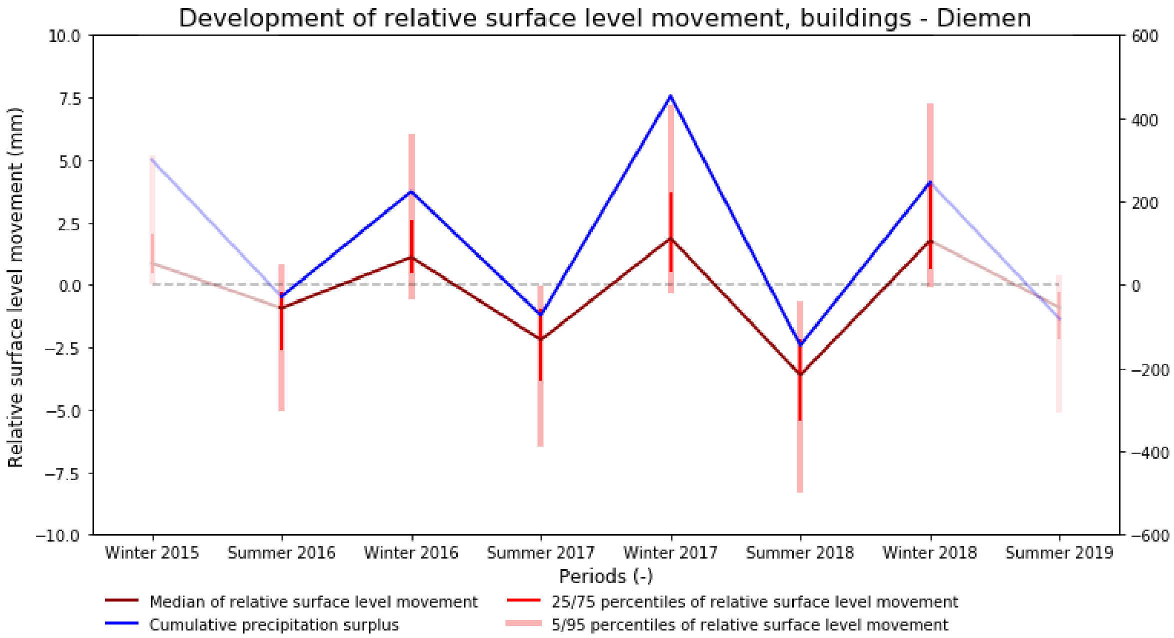

Figure G.25: *Development of relative surface level movement of observations on buildings in Vogelweide, Diemen.*

Firstly, the movement can be caused by atmospheric conditions affecting the InSAR radar signals, which are possibly not not perfectly corrected for in the processing (Sataloff et al., n.d.). It is however not known to what extent these atmospheric conditions affect the radar signals (Appendix B).

Secondly, the movement can be caused by the decrease and increase of volume of the buildings themselves. This is caused by the thermal expansion of their building materials (CeBa-Line, n.d.). Although the expansion coefficients of these materials seem low (magnitude of 10^{-6} meter per degree Celsius, per meter material), a building of 10 meter might have an expansion of few millimeter between a cold winter and hot summer (e.g. 35 degrees Celsius difference).

Thirdly, the movement might be caused by the spatially inaccuracy of the data. The acquired data (Bodemdalingskaart.nl, 2020) has a spatial accuracy of 2-3 meters for the locations of the observations (Sataloff et al., n.d.). Hence, an observation identified as being on a building may actually be located on the ground level nearby and thus might have a seasonal fluctuation. This can also be the same way around.

Lastly, the movement can be caused by the compaction and swell of the soil below the buildings. Although buildings have a foundation in the deeper, solid, sand layers it might be possible that these buildings still experience a (small) variation in their elevation throughout seasons. This explanation is however less likely than the others given above.

It is not known to what extent these processes explained have an impact on the change in surface level (roof) elevation observed in the two figures. This needs further research.

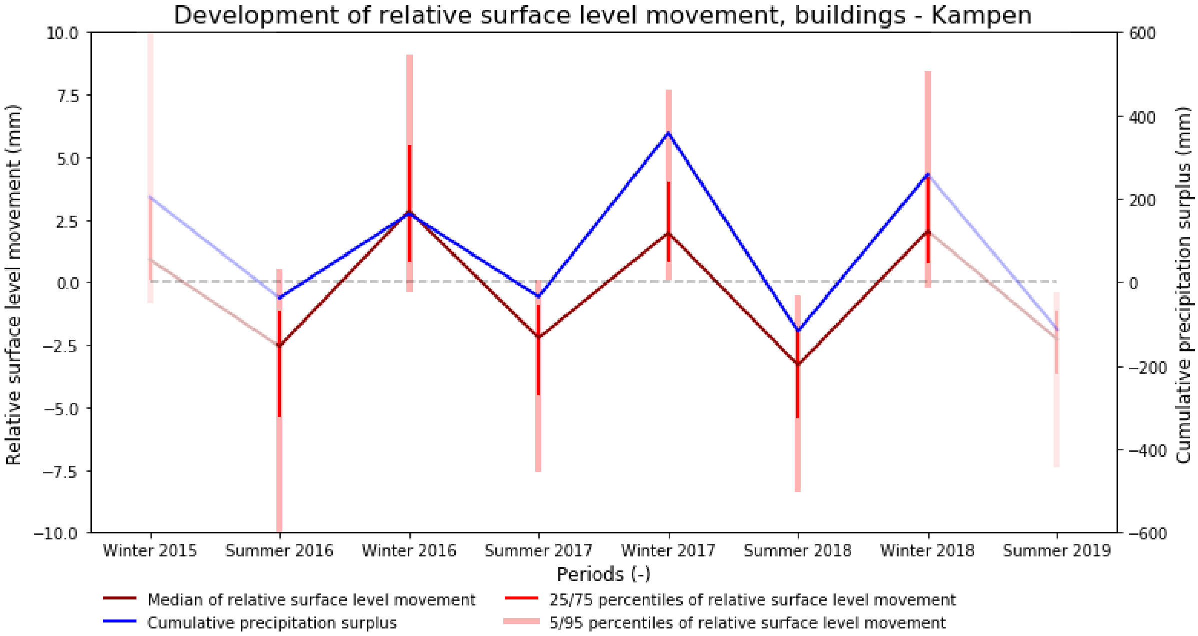

Figure G.26: *Development of relative surface level movement of observations on buildings in Het Meer, Kampen.*

H

Additional theory

This appendix covers some theory additional to information given in Chapter 2. Theory on individual subjects is given. Therefore it is recommended to read Chapter 2 to fully understand background theory.

H.1. Soils

Below various soil properties are given which are important for its soil structure classification and behaviours. Furthermore, groundwater and unsaturated zones are covered. Lastly stresses and pressures in soils are explained.

H.1.1. Soil properties

Porosity

The soil porosity represents the 'pore' space available for water and gasses. Therefore porosity (partly) depends on the granule size: larger granule sizes result in more pores between these granules and therefore a higher porosity. A larger porosity means more space for water and gasses to be present, but also a lower weight and higher soil permeability. The porosity is defined as the soil's pore volume divided by total volume:

$$n[-] = \frac{V_p}{V_g} \tag{H.1}$$

Pores between granules are filled with either water or gasses (air).

Saturation degree

The ratio of water in pores is described by dividing the water volume by pore volume, and is called saturation degree:

$$S[-] = \frac{V_w}{V_p} \tag{H.2}$$

Unit weight

In order to estimate the total weight of a volume of soil the porosity, saturation degree and averaged density of present particles is needed. Gasses or air may be neglected due to their (very) low density. The unit weight describes the soil's weight per unit of volume and is calculated by:

$$\gamma = W/V = Sn\rho_w g + (1-n)\rho_k g \tag{H.3}$$

Where:

W	Weight of soil sample [Kg]
V	Volume of soil sample [m^3]
S	Saturation degree [-]
n	porosity [-]
ρ_w	Average density of water in sample [Kg $\cdot m^{-3}$]
ρ_k	Average density of granules in sample [Kg $\cdot m^{-3}$]
g	Acceleration of gravity [m $\cdot s^{-2}$]

Sand has a high unit weight compared to peat which unit weight is very close to water. The unit weight of clay may vary between these of sand and peat.

Permeability
Soil permeability represents the ease of water to flow through the soil. It is affected by the soil geometry (granule size and shape, stacking of granules, and porosity) as well as properties of the flowing fluid (Verruijt, 2010). A higher permeability results in an easier and thus faster flow of water. The permeability of sandy soils is large compared to silt or clay soils (up to a factor 1000 difference). Therefore, in general sand soils are considered well-permeable (aquifer), while clay soils are referred to as poor-permeable (aquitard).

Compressibility
The compressibility of soil types refers to the ease to be compressed due to an increased pressure. Compressibility constants and coefficients describing the compressibility are empirically determined through (in-situ) testing of soil samples (Cirkel, 1985). Compression coefficients of sand are very high: sand is hardly compressible. Compression coefficients of clay respectively peat are lower.

H.1.2. Groundwater and unsaturated zone

Soils are called saturated in case pores consist only of water. Otherwise it is referred to as unsaturated. In general only the soil's upper space consists of both water and air. These saturated and unsaturated zones are divided by the so-called phreatic line, where water pressure is equal to atmospheric pressure (Verruijt, 2010).

Groundwater
Groundwater levels are generally equal to this phreatic line. However, in case of capillary rise saturated zones might be situated above phreatic lines. Capillary rise refers to upward flow of water from the saturated zone due to a surface stress between the soil's granules and due to suction pressure caused by root uptake of water (Van de Ven, 2016). Darcy defined the groundwater level as hydraulic head, the sum of elevation head and pressure head (Verruijt, 2010):

$$h = z + \frac{p}{\gamma_w} \tag{H.4}$$

Where:

- h Hydraulic head [m]
- z Elevation head [m]
- p Water pressure [kN$\cdot m^{-2}$]
- γ_w Unit weight of water [kN$\cdot m^{-3}$]

Groundwater starts to flow in case hydraulic head in two locations differs. The volume flow (and therefore velocity) of water is computed by Darcy as combination of difference in hydraulic heads (gradient) and soil permeability. Specifically groundwater flow in vertical direction should be of attention. The continuity equation (Navier Stokes) describes that, in case of constant density and soil properties, inflow of water into a saturated soil implicates a simultaneous flow of same volume of water out of the medium. At areas having differing hydraulic head with their surroundings this causes flows towards place of lower hydraulic head. This generated flux is called seepage, or if negative leakage, which affects present groundwater levels and thus water balances.

Unsaturated zone
The saturation degree (or soil moisture/ water content) is an important property of unsaturated zones. The soil moisture content in this zone generally depends on infiltration of water into the ground, percolation, evapo(transpi)ration, and capillary rise. Water flows in unsaturated zones are complex due to present roots and soil heterogeneity. Figure H.1 shows numerous so-called soil moisture retention curves, which define the relationship between soil water content and suction pressure of water (here in feet for general soil types). The field capacity -or saturation point- determines the minimal soil moisture content for water to percolate to groundwater. The wilting point represents the minimal soil moisture content for plants to uptake water (Geohring et al., 2016).

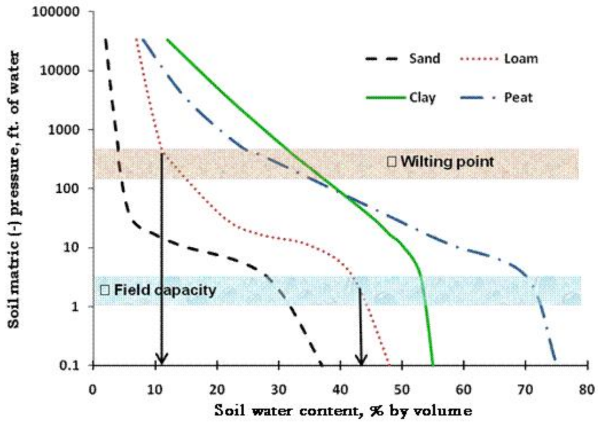

Figure H.1: *Overall differences in soil moisture retention curves between general soil types.* Soil suction pressure is given in feet. Acquired from Geohring et al. (2016).

H.1.3. Stresses and pressures in soil

Soil stresses exist due to its weight, present water and possible man-made structures. All weights combined define the soil's total stress. Part of this total weight is carried by water present in pores - called water stress or pressure. In general water stress is zero at phreatic level and increases linearly with depth. The remaining part of weight is carried by contact points in the granule structure - called effective stress. Terzaghi describes the total stress (in vertical direction) by adding water stress and effective stress (Verruijt, 2010):

$$\sigma = \sigma^{'} + p \tag{H.5}$$

This simplification shapes a good indication of soil balances and changes, despite groundwater flows and soil heterogeneity are not included. Effective stress of *saturated* soil layers is calculated by:

$$\sigma_i^{'} = (\gamma_i - \gamma_w) d_i \tag{H.6}$$

Where:

$\sigma_i^{'}$ Effective stress soil layer i [kN $\cdot m^{-2}$]
γ_i Volume weight of soil layer i [kN $\cdot m^{-3}$]
γ_w Volume weight of water [kN $\cdot m^{-3}$]
d_i Depth of soil layer i [m]

There are in general two ways to intervene in the stresses balance: by changing water stresses (groundwater level, seepage/ leakage, saturation degree) or by changing loads. The consequences of these changes is explained in Section 2.3.

H.2. Subsidence

Below the hydro-dynamic period and shrinkage curve are covered.

H.2.1. Consolidation time

Consolidation is a slow process where water is pressed out of pore spaces. The total elapsed time for this process in a layer, also called hydro-dynamic period, is described by Terzaghi (Van de Ven, 2016):

$$t_e = \frac{m_v \gamma_w h^2}{2K} \tag{H.7}$$

Where:

t_e End of hydro-dynamic period [s]
m_v Compression constant [m^2/kN]
γ_w Density of water [kN $\cdot m^{-3}$]
h Thickness of compressible layer [m]
K Permeability of the soil [m/s]

H.2.2. Shrinkage

The decrease of volume of soils due to a decrease of soil moisture content is illustrated by shrinkage curves, conceptualized in Figure H.2. Three separate phases are distinguished (Bronswijk & Evers-Vermeer, 1987): regular shrinkage, wherein decrease of volume of soil is equal to decrease of water volume; residual shrinkage, in which decrease of volume of soil is less due to entrance of air in pores; and null shrinkage, during which the soil volume remains constant by decreasing water volume. Shrinkage is prone to hysteresis: shrinking processes tend to be faster than swelling processes (Van Asselen et al., 2019). Volume decreases in clay soils are almost equal to volume decreases of water. More water might be evaporated at peat soils due to the high water content causing a large volume reduction.

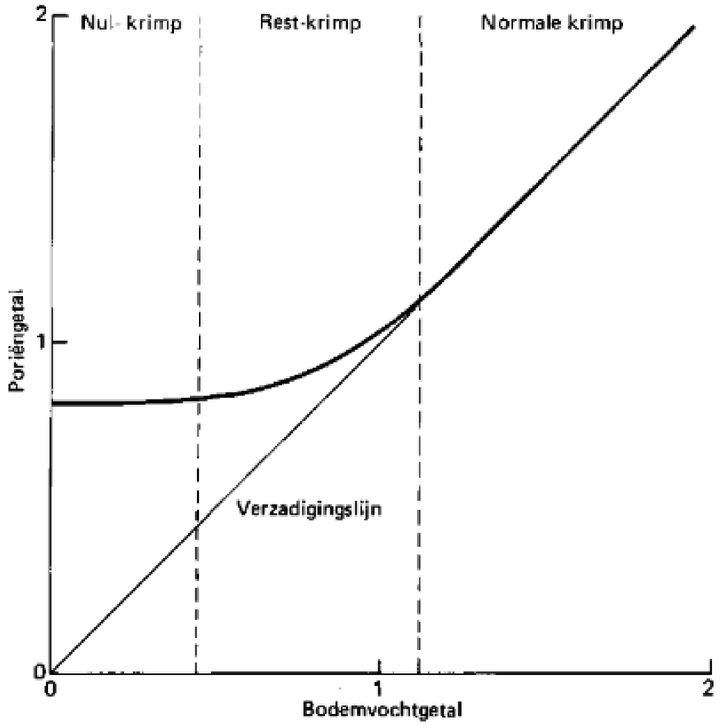

Figure H.2: *Three stages of shrinkage.*

H.3. Site preparation strategies

Below, the formulas for drainage depth calculation and required thickness of sand raises are given.

H.3.1. Drainage depth

Drainage depths can be calculated by Hooghoudt's equation for groundwater flow between two infinite parallel ditches/drainage pipes. Hooghoudt's equation is based on Donnan's, but includes extra resistance caused by radial flow in case ditches do not reach the impervious layer. A sketch of the variables of Donnan's equation is given in Figure 2.8. Hooghoudt's expression is:

$$q = \frac{8K_1 dh + 4K_2 h^2}{L^2} \tag{H.8}$$

Where:

- q Flow per unit length of ditch [$m^2 \cdot s^{-1}$]
- K Permeability (can be different for layers 1 and 2) [m/d]
- d Equivalent depth [m]
- h Bulging of water level halfway between both drainage channels [m]
- L Distance between drainage channels [m]

H.3.2. Net-raise

Sand raises are required if bearing capacity or freeboard is to be increased. Sand raises result in subsidence and therefore additional sand is needed in order to result in a net-raise. Generally the required thickness resulting in a net-raise is calculated by (Van de Ven, 2016):

$$\Delta p = (h-(z-b))\cdot\gamma_{ds} + (z-b)\cdot(\gamma_{gs}-\gamma_w) - b\cdot\gamma_w \tag{H.9}$$

Where:

Δp	Change in grain pressure [kN $\cdot m^{-2}$]
h	Gross raise [m]
z	Net raise [m]
b	Drainage depth [m]
h-(z-b)	Required freeboard [m]
γ_{ds}	Volume weight of dry sand [kN $\cdot m^{-3}$]
γ_{gs}	Volume weight of wet sand [kN $\cdot m^{-3}$]
γ_w	Volume weight of water [kN $\cdot m^{-3}$]