Deltares

Mining-induced subsidence and water level management

KEM-16 WP3

Mining-induced subsidence and water level management
KEM-16 WP3

Author(s)
Henk Kooi
Huite Bootsma
Daan Rooze
Roel Melman

Mining-induced subsidence and water level management
KEM-16 WP3

Client	Ministerie van Economische Zaken en Klimaat
Contact	Mevrouw K. van Thienen-Visser
Reference	
Keywords	Toolbox subsidence, mining, water management, shallow subsidence, Atlantis

Document control	
Version	1.0
Date	15-03-2023
Project nr.	11205981-003
Document ID	11205981-003-BGS-0001
Pages	52
Classification	
Status	final

Author(s)		
	Henk Kooi	
	Huite Bootsma	
	Daan Rooze	
	Roel Melman	

Summary

Surface water levels in The Netherlands are managed in a system of fixed water level areas, water courses, locks, weirs and pumping stations. This water management system is not static. Different factors have necessitated water levels to be adjusted and infrastructure to be added or changed and continue to do so. The three prime factors are: (i) shallow-sourced soft-soil subsidence due to oxidation of peat and compaction of clay in coastal lowlands; (ii) spatial development and land-use change, and (iii) mining-induced (deep-sourced) subsidence. In areas with mining-induced subsidence and Holocene peat and clay occurrences, such as in the areas of gas production and salt mining in the province of Groningen, all three factors tend to play a role. Governments and other stakeholders in The Netherlands increasingly wish to know which part of water management measures and the associated costs, is related to mining activity, and which part is related to other factors.

This report presents a project that aims to develop a practical tool which allows stakeholders to perform authoritative calculations to separate the effects of deep (mining) subsidence and other effects on freeboard[1] – freeboard is a key water level management parameter. The project was carried out the framework of the *Knowledge Program on Effects of Mining* (KEM-16 *Toolbox subsidence*), funded by the Ministry of Economic Affairs (EZK).

The new tool was built as an extension of the open source tool/platform Atlantis, which is used for production of national predictive land subsidence maps for The Netherlands (Bootsma et al., 2020; Erkens et al., 2021). Subsidence modelling in Atlantis addresses 'shallow subsidence' caused by various processes that occur primarily within the Holocene soft-soil strata (peat and clay). To achieve coupling with deep subsidence, code additions were made in Atlantis and pre- and postprocessing tooling was developed. Water management interferences[2] are incorporated via preprocessing.
Through the coupling, the tool calculates both the direct and the indirect effect of deep subsidence on freeboard. The direct change of freeboard develops because the land surface elevation sinks with the deep subsidence – this varies spatially – while the surface water level in a fixed water level area subsides uniformly, determined by the deep subsidence at the location of the water-level controlling infrastructure of the fixed-water level area. This direct change of freeboard by deep subsidence influences the shallow subsidence, and thereby also freeboard. The latter represents the indirect effect of deep subsidence on freeboard. The shallow subsidence can be both enhanced and suppressed by the deep subsidence. However, the indirect freeboard change by deep subsidence always is opposite to the direct freeboard change of deep subsidence. It represents a negative feedback. That is, the net effect of deep subsidence on freeboard is always is smaller than or equal to the direct effect.

In consultation with three northern water boards, two case studies were selected and conducted. Case 1, Nedmag-Veendam, concerns the historic effects of subsidence due to salt-mining; calculation was also extended about one decade into the future. The case illustrates how the tool can be used to separate the effects of (1) deep mining-induced subsidence, (2) water management interferences, (3) independent shallow subsidence, and (4) combinations thereof, on the temporal development of freeboard. Results indicate that effects of the water management adjustments in the area differ considerably from the effects required to offset the deep subsidence effects (this inference has at the time of writing not

[1] Difference between land surface elevation and surface water level of a fixed water level area (Dutch: drooglegging).
[2] Water level adjustment, with or without reorganization of fixed water-level areas and/or water-level controlling infrastructure such as weirs or pumping stations.

been evaluated/corroborated by the pertinent water board). The results further indicate that the indirect effect of the deep subsidence is very small and mostly consists of a reduction of shallow subsidence. This is explained by the fact that presence of soft soils is very limited in this area and predominantly occur at very shallow levels, above the mean lowest groundwater level.

Case 2 is a fictitious case that explores deep subsidence effects in an area (between Delfzijl and the city of Groningen) with thicker Holocene soft-soil layers. The deep subsidence of the Nedmag-Veendam case was imposed on this area, presuming deep subsidence started in 2020. Independent shallow subsidence is about three times higher in parts of the area (~30 cm in 30 years) than in the Veendam area. The freeboard change resulting from deep subsidence is larger than in the Veendam case due to the different positioning of both the fixed water level areas and the water-level controlling infrastructure relative to the subsidence bowl. The indirect effect of deep subsidence locally reduces the net effect of deep subsidence on freeboard up to 25%.
The presented case studies serve the purpose of tool demonstration. Results, therefore, are illustrative/indicative rather than authoritative.

Unique features of the tool are that (i) the indirect effects of deep subsidence and water management interferences are included and can be quantified separately, and (ii) complex temporal scenarios can be efficiently analysed. The tool can be applied to analyse historic development (hindcasting) but can also be used in a predictive sense (forecasting). The latter can be useful to evaluate impacts of planned new mining activities and/or water management interference. The tool allows evaluation of physical effects, notably on freeboard. Cost estimation is not included.

The closing chapter includes a discussion how the tool might be used to determine which part of water management measures is due to mining-induced deep subsidence. The chapter also addresses the validity, accuracy and authoritativeness of the tool and presents some recommendations.

Samenvatting

Oppervlaktewaterpeilen in Nederland worden beheerd via een systeem van peilgebieden, waterlopen, sluizen, stuwen en gemalen. Dit systeem is niet statisch. Verschillende factoren hebben in de loop van de tijd om aanpassingen gevraagd van waterpeilen en van de inrichting van het beheersysteem en doen dat nog steeds. De drie belangrijkste factoren zijn (i) ondiepe bodemdaling door veenoxidatie en compactie van kleilagen, (ii) ruimtelijk ontwikkeling en veranderend landgebruik, en (iii) mijnbouw-gerelateerde (diepe) bodemdaling. In gebieden met diepe bodemdaling en Holocene veen- en kleivoorkomens, zoals rond de gas- en zoutwinning in de provincie Groningen, spelen al deze factoren in principe een rol. Bij overheden en andere belanghebbenden leeft in toenemende mate de vraag welk deel van het waterbeheer en van de bijbehorende kosten toe te schrijven is aan diepe, mijnbouw-gerelateerde bodemdaling, en welk deel toe te schrijven is aan andere factoren.

Dit rapport presenteert een project dat beoogt een praktische en gezaghebbende *tool* te ontwikkelen om de bijdrage van diepe (mijnbouw) bodemdaling aan verandering in de drooglegging[3] – drooglegging is een belangrijke parameter in het waterbeheer – te scheiden van andere bijdragen, en deze tool beschikbaar te maken voor belanghebbende partijen. Het project is uitgevoerd in het kader van het Kennisprogramma Effecten Mijnbouw (KEM-16 Toolbox bodemdaling), gefinancierd door het ministerie van Economische Zaken en Klimaat (EZK).

De tool is gebouwd als een uitbreiding op het open de source tool Atlantis. Atlantis wordt gebruikt voor de productie van de nationale bodemdalingsvoorspellingskaarten in Nederland (Bootsma et al., 2020; Erkens et al., 2021). Bodemdalingsmodellering in Atlantis betreft ondiepe bodemdaling die wordt veroorzaakt door verschillende processen die hoofdzakelijk plaatsvinden in de slappe bodemlagen (veen en klei) in het Holocene pakket. Om de koppeling met diepe bodemdaling te realiseren is de code van Atlantis uitgebreid en zijn pre- en postprocessing tools ontwikkeld. Via de preprocessing kunnen ingrepen in het waterbeheer[4] worden meegenomen.
Door de koppeling berekent de tool zowel het directe als het indirecte effect van de diepe bodemdaling op de drooglegging. De directe verandering van de drooglegging ontstaat doordat het maaiveld meedaalt met de diepe bodemdaling – dit verschilt van plaats tot plaats – en het peil in een peilgebied gelijkmatig zakt omdat het wordt bepaald door de diepe bodemdaling op de locatie van het peilbepalende kunstwerk. Deze directe verandering van de drooglegging beïnvloedt de ondiepe bodemdaling. Daardoor heeft de diepe bodemdaling ook indirect effect op de verandering van de drooglegging. Omdat deze indirecte bijdrage er niet zou zijn zonder diepe bodemdaling, moet deze ook aan diepe bodemdaling worden toegeschreven. De ondiepe bodemdaling kan door de diepe bodemdaling zowel worden vergroot als verkleind. De indirecte bijdrage aan de verandering van de drooglegging is wel altijd tegengesteld aan de directe bijdrage; het netto effect van diepe bodemdaling op de drooglegging wordt daarom gereduceerd door het indirecte effect op de drooglegging. Het betreft een negatieve terugkoppeling.

[3] Verschil tussen maaiveldhoogte en het waterpeil.
[4] Waterpeilaanpassing met of zonder aanpassing van peilgebieden en/of waterpeilbeheer infrastructuur zoals stuwen en gemalen.

In samenspraak met drie noordelijke waterschappen zijn twee casussen geselecteerd en uitgevoerd. Casus 1, Nedmag-Veendam, betreft de historische effecten van de bodemdaling door de zoutwinning en bevat ook een prognose tot 2030. Deze casus illustreert hoe de tool kan worden gebruikt om onderscheid te maken in de bijdragen in de ontwikkeling van de drooglegging van (1) diepe mijnbouw-geïnduceerde bodemdaling, (2) waterbeheer ingrepen, (3) onafhankelijke ondiepe bodemdaling, en (4) combinaties daarvan. De resultaten suggereren dat de waterbeheer ingrepen in het gebied in sterke mate afwijken van ingrepen die nodig waren om de effecten van de diepe bodemdaling te compenseren (deze bevinding is nog niet besproken/geëvalueerd met het betreffende waterschap). De berekeningen geven aan dat het indirecte effect van de diepe bodemdaling heel klein is. Dat komt doordat slappe bodems beperkt aanwezig zijn in dit gebied en vooral ruim boven de gemiddeld diepste grondwaterstand. Deze invloed betreft hoofdzakelijk reductie van ondiepe bodemdaling. Voor de waterbeheer ingrepen geldt ook dat ze hier hoofdzakelijk de ondiepe bodemdaling reduceren.

Casus 2 is een fictieve casus die effecten onderzoekt van diepe bodemdaling in een gebied tussen Delfzijl en Groningen stad met dikkere slappe Holocene bodemlagen. In de analyse is de diepe bodemdaling van de Nedmag-Veendam casus toegepast in dit gebied waarbij deze bodemdaling verondersteld werd te starten in 2020. De onafhankelijke ondiepe bodemdaling is ongeveer drie maal groter (~30 cm in 30 jaar) dan in het studiegebied bij Veendam. Door een andere verdeling van peilgebieden en van de locaties van de peilbepalende kunstwerken ten opzichte van de bodemdalingskom, is de verandering van drooglegging door de diepe bodemdaling ook groter dan bij Veendam. Het indirecte effect van diepe bodemdaling vermindert het netto effect van diepe bodemdaling op de drooglegging plaatselijk met zo’n 25%.

Het doel van beide casussen studies betreft demonstratie van de tool. De resultaten zijn daarom niet gezaghebbend, maar illustratief en indicatief.

Unieke aspecten van de tool zijn (i) dat de indirecte effecten van diepe bodemdaling en waterbeheer ingrepen daarin zijn opgenomen en dat deze effecten apart kunnen worden geschat, en (ii) dat complexe veranderingen/ingrepen efficiënt kunnen worden doorgerekend.

De tool kan worden gebruikt voor analyse van de historische ontwikkeling (hindcasting), maar kan ook worden gebruikt voor prognose (forecasting). Het laatste kan van nut zijn voor impact analyse van geplande, nieuwe mijnbouwactiviteiten en/of waterbeheer maatregelen. De tool is gericht op evaluatie van fysische effecten, met name de ontwikkeling van drooglegging. Kosten analyse is geen onderdeel van de tool.

In het afsluitende hoofdstuk is een discussie opgenomen over hoe de tool gebruikt zou kunnen worden om te beoordelen welk deel van waterbeheersmaatregelen is toe te schrijven aan de diepe bodemdaling door de mijnbouw. Dit hoofdstuk bespreekt verder aspecten als validiteit, nauwkeurigheid en ‘gezaghebbendheid’ van de tool en sluit af met enkele aanbevelingen.

Contents

	Summary	**4**
	Samenvatting	**6**
1	**Introduction**	**10**
1.1	Framework	10
1.2	Issue and objective	10
1.3	Approach	10
1.4	Structure of the report	11
2	**Background information**	**12**
2.1	Focus of water level management: freeboard	12
2.2	The impact of ‘shallow’ land subsidence on freeboard	12
2.3	The impact of deep land subsidence on freeboard	13
2.4	An existing national tool for shallow subsidence calculation	15
3	**The new tool**	**17**
3.1	Design	17
3.2	Implementation	17
3.2.1	General aspects	17
3.2.2	Practical implementation and workflow	19
4	**Case study 1: Nedmag-Veendam, historic and future effects**	**21**
4.1	Introduction	21
4.2	Inputs for the calculations	21
4.3	Scenarios	24
4.4	Results	24
4.5	Discussion	32
4.5.1	Discussion of the graphical results	32
4.5.2	Consequences of neglecting subsidence due to gas production	34
4.5.3	Remarks	35
5	**Case study 2: fictitious case, future effects in a potentially sensitive area**	**36**
5.1	Introduction	36
5.2	Inputs for the calculations	37
5.3	Scenarios	38
5.4	Results	39
5.5	Discussion	46
5.5.1	Discussion of the graphical results	46

5.5.2 Comparison to the Nedmag-Veendam case 46
5.5.3 Remarks 47

6 Discussion and recommendations 49

6.1 Attribution of water management measures to deep subsidence 49

6.2 Authoritativeness 50

6.3 Tool availability and expected use 51

6.4 Recommendations 51

7 References 52

1 Introduction

1.1 Framework

The work reported in this document was carried out by Deltares in the framework of the *Knowledge Program on Effects of Mining* (KEM-16 *Toolbox subsidence*), funded by the Ministry of Economic Affairs (EZK). KEM-16 is executed within the Work Program of TNO-AGE. Deltares is subcontractor in this TNO-program.

KEM-16 aims to develop a set of tools that can be used to address various practical issues involving impacts of mining-induced subsidence. The tools or methods are intended to enable interested parties to perform authoritative and mutually comparable/consistent calculations. The selected issues that were adopted in the KEM-16 project plan were derived from stakeholder consultation and are addressed in three work packages:

WP3 The impact of ‘deep subsidence’ on water level management
WP4 Separating subsidence contributions from multiple mining activities
WP5 Damage risk for various components of subsidence

The present report concerns work, and results carried out in WP3.

1.2 Issue and objective

The issue

Land subsidence is an important factor in water management in The Netherlands already for many centuries, necessitating periodic adjustment of water levels and infrastructure (van de Ven, 1993). In early days, the subsidence was virtually solely related to volume loss within the relatively shallow Holocene soft-soil strata (peat and clay) driven by land drainage and land reclamation. In the last century, mining activities in much deeper strata, such as gas production and salt mining, brought additional subsidence. In several areas both the deep and shallow subsidence impacted and still impacts water management and its associated costs. Governments and other stakeholders increasingly wish to know which part of water management measures and the associated costs, are related to mining activity, and which are due to other, shallow subsidence processes. Separation of contributions is nontrivial, however, as deep subsidence can suppress or enhance shallow subsidence. More extensive background on the issue is provided in chapter 2.

Objective

The objective of the project is to develop a practical tool which allows stakeholders to perform authoritative calculations to separate the effects of deep (mining) subsidence on freeboard – freeboard is a key water level management parameter. With the separate effects on freeboard, stakeholders are provided with a basis to attribute measures and associated costs to the two components.

1.3 Approach

The project execution comprised the following steps.

1. Conceptual design of the tool based on general knowledge and ideas of Deltares.
2. Discussion of the conceptual design with the water boards of the provinces of Groningen and Friesland (Hunze en Aa's, Noorderzijlvest, Wetterskip) with the aim to learn about existing approaches, to explore interest in the tool, to obtain feedback for potential improvement of the concepts, and to decide on a case study application.
3. Fine tuning the design of the tool and coding.
4. Application of the tool in the chosen case study (Nedmag Veendam).
5. Discussion of results with the water boards and their wishes regarding further use of the tool. It was decided to carry out a second case study.
6. Application of the tool in the second case study
7. Final reporting

1.4 Structure of the report

The remainder of the report is structured as follows. Chapter 2 provides more extensive background information on water level management in The Netherlands in relation to land subsidence and on *Atlantis*, an existing tool that was extended to meet the objectives of the current project.
Chapter 3 elucidates the design and implementation of the new tool.
Chapters 4 and 5 present the two case studies that were performed.
Chapter 6 closes with a discussion and conclusions.

2 Background information

This chapter provides background information on water (level) management in The Netherlands and the role of land subsidence therein. Several concepts are introduced that are central to the new tool. Additionally, Atlantis, an existing tool that is used in The Netherlands to calculate shallow subsidence over large spatial areas is briefly introduced. Atlantis was chosen as a starting point / building block for the development of the new tool for the current project.

2.1 Focus of water level management: freeboard

Water boards and other governments in The Netherlands have a responsibility to establish and maintain surface water levels within the surface water bodies within their respective management areas (Water law, article 5.2.1). Appropriate water levels aim to minimize various problems concerning water nuisance, water deficiency (underload) and water quality.

One of the key parameters that determines appropriateness of water levels is the *freeboard (Dutch: drooglegging)*. Freeboard is the elevation difference between land level and the (winter) water level of the watercourses (ditches, canals) (Figure 1).

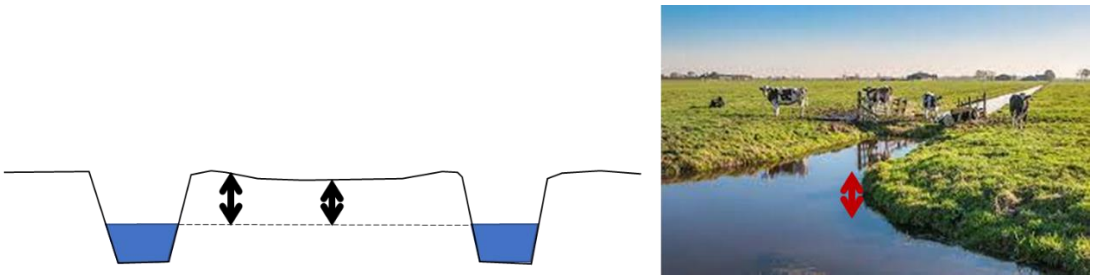

Figure 1 Key parameter for surface water management: freeboard, indicated by the double-sided arrow.

Freeboard determines the (temporary) water storage capacity during wet periods, but also serves as a base level for the groundwater system, controlling groundwater drainage and groundwater replenishment during wet and dry periods, respectively. The latter role of freeboard is finely tuned to land-use (agriculture, nature, urban). To meet these requirements, the Dutch landscape is generally subdivided in numerous fixed drainage level areas in which distinct surface water levels are maintained.

Albeit important, freeboard is not the sole target parameter in water level management. Other parameters include the depths of the watercourses and associated surface water discharge conditions, and the headspace for shipping (and even skating) below bridges.

2.2 The impact of ‘shallow’ land subsidence on freeboard

Large parts of the coastal lowlands of The Netherlands subside at rates that typically range from 0-10 mm/yr. The subsidence is predominantly caused by various processes that occur within the Holocene soft-soil strata:

- shrinkage of drained soils
- oxidation of peat which involves loss of organic matter solids to the atmosphere
- time-dependent compaction of saturated peat and clay.

These processes are fundamentally driven by land drainage, which is intimately linked to maintenance of freeboard.

Over the years, these shallow subsidence processes lower the ground surface, and thereby reduce the freeboard (Figure 2). Consequently, groundwater levels become too shallow and soils too wet. It has been common practice already for many centuries that water boards periodically lower the surface water level to restore the freeboard within the desired bounds. The periodic water level lowering tends to induce a new cycle of subsidence.

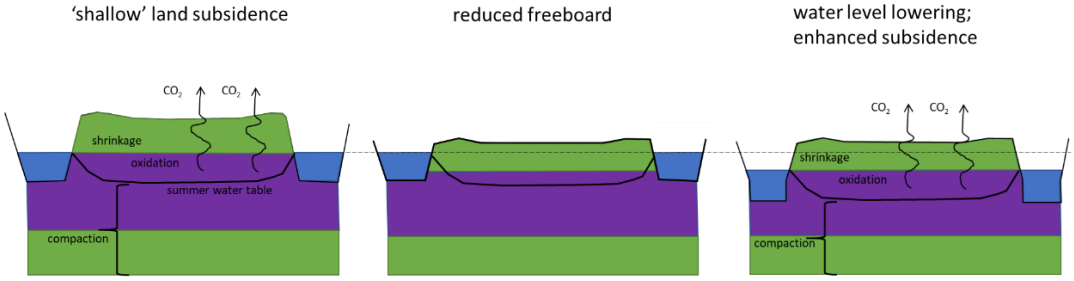

Figure 2 Illustration of the water management cycle in the presence of 'shallow' subsidence. Purple: peat; green: clay.

This 'water management cycle' and the associated shallow subsidence processes have lowered the coastal plain in The Netherlands by almost 2 m on average since Medieval times, and locally up to 5-6 m (Erkens et al., 2016). It also is a prime reasons why large parts of the country are presently below mean sea level. Only very recently, water boards have started to consider breaking the cycle to limit or prevent further land subsidence.

The decision to lower water levels in response to the shallow subsidence is generally based on recognised insufficiency of freeboard in the field rather than on models. However, to know the critical areas in their management district, water boards (e.g., Hunze and Aa's) also periodically map the freeboard by differencing the most recent elevation map of The Netherlands (AHN) and the prevailing water levels. In general, a decision to lower the water level requires the freeboard to be at least 5 cm less than the prevailing norm.

2.3 The impact of deep land subsidence on freeboard

The impacts of deep land subsidence due to mining on the surface water system have recently been summarized and discussed in a report to the Instituut Mijnbouwschade Groningen (IMG) (Kooi et al., 2021; in Dutch). In the framework of the present study, three causes of changes of freeboard due to deep land subsidence can be distinguished:

(1) without active interference by water management
(2) by active interference in water levels
(3) due to the impact of 1 and 2 on shallow subsidence

Without active interference in water levels:
In contrast to shallow subsidence, deep subsidence always causes subsidence of the water management infrastructure that is used to control surface water levels, such as pumping stations, locks, and weirs (as well as associated gauges). Changes in freeboard that are the focus of water level management, therefore, only develop when differential subsidence occurs within individual fixed water level areas (polders). In case of uniform subsidence, the land level and the surface water level subside in concert and no change in freeboard develops. Water boards then may periodically have to formally declare in a "water level

adjustment decision" (Dutch: peilbesluit) that the momentary lower water level relative to the Dutch ordinance level (NAP) is the prevailing level, but no active adjustment is required. However, where differential subsidence does occur over a fixed drainage level area, both increases and decreases of the freeboard tend to develop, depending on the location of the water level controlling infrastructure (Figure 3): freeboard increasing and decreasing where subsidence is less than and exceeds the subsidence of the water level controlling infrastructure, respectively.

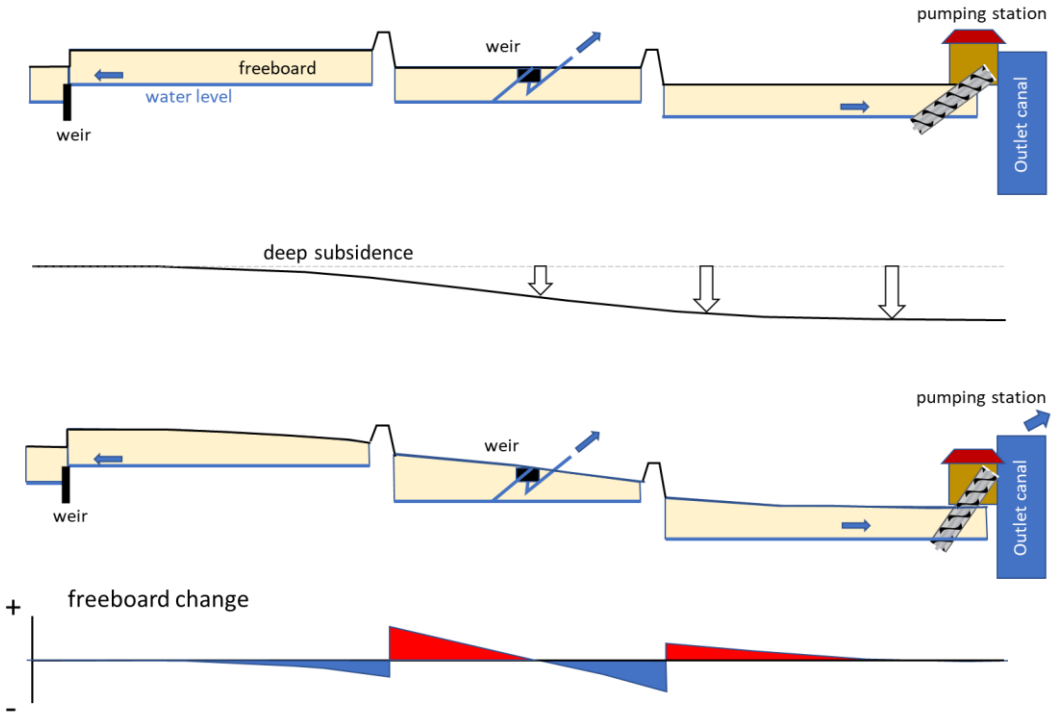

Figure 3 Schematic illustration of the effect of deep subsidence on freeboard in the absence of active interference and in the absence of shallow subsidence. Top panel: situation before deep subsidence, showing three fixed water level areas, each with a water level controlling infrastructure (weir or pumping station). At the middle area, the discharge at the weir occurs at the middle of the profile in an out-of-profile direction. The other panels respectively show the deep subsidence, the impact on land level, water level and freeboard, and the freeboard change (red = increase of freeboard, blue = decrease of freeboard). In the sketch is it assumed that the water level at the drainage outlet canal to the right is unaffected by the subsidence or maintained at the original level.

Active interference in water levels:
When changes in freeboard are expected to become too large, or have been recognized to have become too large, water boards tend to improve the freeboard which includes active adjustment of the momentary water level. In the province of Groningen, the adjustments have been done both informally, and formally via an official "peilbesluit". In areas with large differential subsidence, a uniform adjustment of the water level may not suffice to bring the freeboard within acceptable bounds. In those areas, the required adjustment can involve reorganization of the fixed water level areas and their infrastructure, for instance by splitting of individual fixed water level areas into two or more smaller ones with distinct water levels.

Impact on shallow subsidence and associated freeboard change:
Shallow subsidence does not influence deep, mining-induced subsidence. However, the reverse influence does exist. Deep subsidence does influence shallow subsidence via the

changes in freeboard and associated changes in drainage and groundwater levels. The following two situations may occur:

Deep subsidence → freeboard decrease → higher groundwater level relative to land surface → reduced shallow subsidence, less freeboard decrease by shallow subsidence.

Deep subsidence → freeboard increase → deeper groundwater level relative to land surface → enhanced shallow subsidence, enhanced freeboard decrease by shallow subsidence.

The impact in both situations is negative in the sense that net freeboard change would be larger without this coupling. In terms of water management requirement this can be considered fortuitous. However, otherwise the enhanced net loss of land elevation in the second situation generally is not a desirable effect in coastal lowlands.

Existing tools and approaches
Based on a literature survey and the discussions with the northern water boards in the current project, the following was learned regarding existing tools and approaches to evaluate the impact of deep subsidence on freeboard.

- In the most basic approach, only the incurred or expected maximum difference of deep subsidence within fixed water level areas is quantified and used in conjunction with the current freeboard (e.g. Arcadis, 2021). Note that the maximum subsidence difference provides a limiting value for possible freeboard increase/decrease in the fixed water level area rather than the actual freeboard change.
- Water board Hunze and Aa's has developed a somewhat more advanced GIS tool that allows calculation of freeboard maps at future dates (Grontmij, 2005). In this tool, the future land elevation is constructed by correcting the current land elevation for anticipated deep subsidence. The future water levels can be forecast based on the subsidence of the water level controlling infrastructure. And differencing of land elevation and water level yields the calculated freeboard map. Water board Hunze and Aa's has also considered to include a land elevation correction for shallow subsidence based on in-house estimates of the shallow subsidence component, but this has not (yet) been implemented.

The GIS tool of Hunze and Aa's includes several elements that are important to the objective of the present project and for the aspired new tool. Aspects that are not included or feasible in this tool are:
- Authoritative shallow subsidence calculation
- The impact of deep subsidence on shallow subsidence
- Temporal modelling of relatively complex historical or future interference/adjustment scenario's

2.4 An existing national tool for shallow subsidence calculation

In 2017, Deltares, TNO-GDN and WENR (Wageningen Environmental Research) developed *Atlantis*, an open source tool/platform for efficient production of national predictive land subsidence maps for The Netherlands (Bootsma et al., 2020; Erkens et al., 2021). The subsidence prediction in Atlantis consists of calculations of the shallow subsidence processes involved in the water management cycle (2.2; Figure 2). Independent deep subsidence can be added in the final maps but is not part of the predictive capabilities of Atlantis.
The predictive subsidence maps provide support for regional and national spatial planning and policymaking. The maps sets are published by the Climate Adaptation Services foundation in The Netherlands as a component of the national climate impact atlas.

Figure 4 illustrates key features of the tool. Input includes (a) a 3D lithological model covering most of the country to -50 m NAP (map resolution typically 100 m x 100 m, vertical resolution 0.5 m or better), produced using existing geological and soil models; (b) a model for the initial multi-annual mean lowest phreatic groundwater level (Dutch: GLG[5]); (c) fixed water level areas. With this input and sets of process parameters, Atlantis then calculates the time development of subsidence due to peat oxidation and consolidation (time history of compression and dewatering of soil layers). Water management scenarios can be chosen, such as fixation of (ground)water level with respect to NAP, or the typical periodic lowering of (ground)water levels to compensate for incurred subsidence within fixed water level areas.

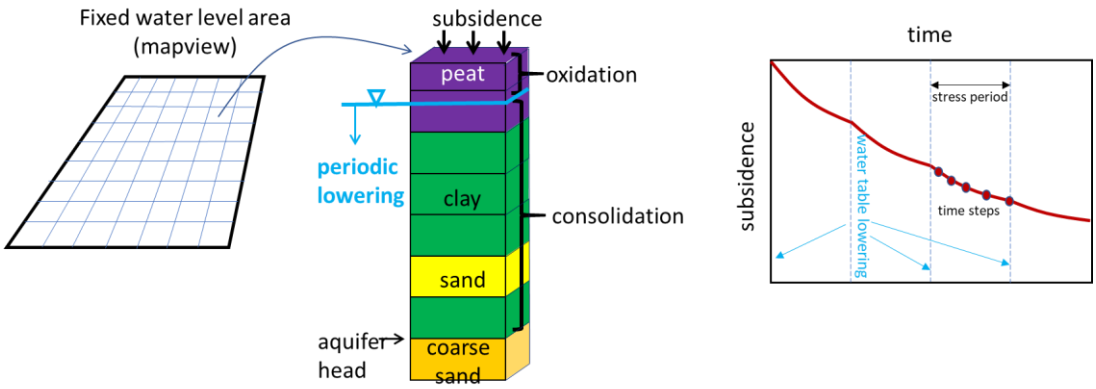

Figure 4 Key features of Atlantis. Spatial data on fixed water level areas, groundwater level and geology are used to calculate subsidence by peat oxidation and consolidation of compressible soils for water management scenarios.

Even though the predictive uncertainty of shallow subsidence remains relatively high[6], Atlantis does represent the current authoritative national framework for the prediction of shallow subsidence on time periods of a decade to centuries.

Atlantis is built on several open-source Python libraries. Currently the code is transferred to the Julia programming language.

[5] The Dutch acronym GLG will be uses throughout this report for 'mean lowest groundwater level'. GLG is the mean of the 3 annual lowest groundwater levels, averaged over a period of 8 years, where the time series should have a resolution of at least fortnightly measurements.

[6] High quality historic data sets required for formal calibration are very limited and with a very poor national coverage; efforts are presently undertaken to try to quantify the predictive uncertainty.

3 The new tool

3.1 Design

Figure 5 shows the basic system components of the new tool and their interactions. The prime target parameter of the new tool is freeboard, the temporal development of which can be assessed in response to both deep and shallow subsidence and the effect of deep subsidence on shallow subsidence (via freeboard). A secondary target parameter that may be of interest is the shallow subsidence. Total subsidence is a further output that can be of interest to potential users.

By differencing calculation results in which one or more forcing components are respectively included and left out, the tool allows the assessment of the contribution of specific components. For instance, the contribution by:

- Deep subsidence and associated water level adjustments
- Solely the water level adjustments associated with deep subsidence
- The impact of deep subsidence on shallow subsidence

Also, what-if questions can be addressed, such as: how would freeboard have developed without management interference?

The tool can be applied to historical development in a reconstruction sense (hindcasting) but can also be useful in a predictive sense for decision making (forecasting).

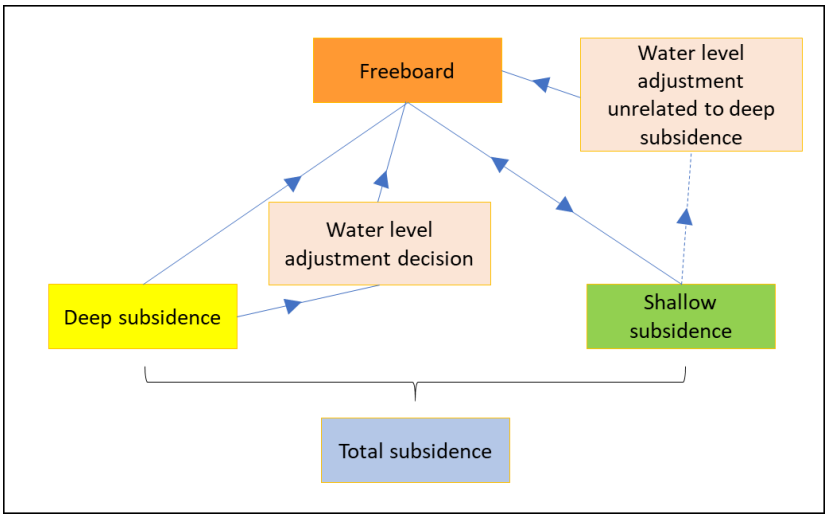

Figure 5 Basic system components of the new tool and their interactions.

3.2 Implementation

3.2.1 General aspects

The new tool was built as an extension of Atlantis (2.4). In Atlantis, the fundamental quantity that controls the shallow subsidence is GLG, the mean deepest groundwater level[7] (Figure

[7] More specifically the position of GLG relative to the soil layers and changes therein.

6). Surface water level (SWL) and freeboard (land surface - SWL) are not quantified in Atlantis.

However, deep subsidence affects the position of the SWL (Figure 3; Figure 6). Coupling, of the deep and shallow subsidence systems therefore not only requires extension of Atlantis with SWL and the SWL influencing factors, but also necessitates establishing a relationship between SWL and GLG. In the new tool, the most straightforward assumption has been adopted that for a change of SWL, GLG changes by the same amount[8]. The impact of deep subsidence on the voxel stack is a straightforward uniform subsidence.

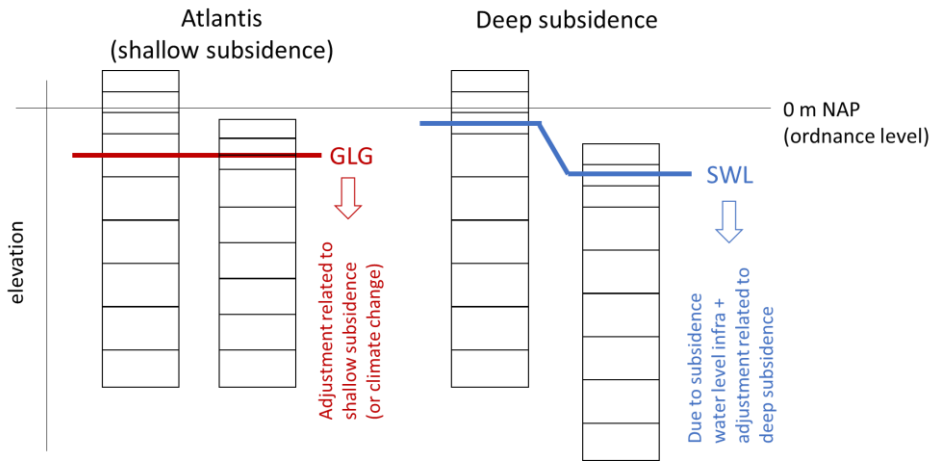

Figure 6 Illustration of the key features of Atlantis (left) and the required additional features related to the effects of deep subsidence (right). In Atlantis shallow subsidence causes thickness loss and property change of voxels and processes are controlled by GLG and GLG change. Deep subsidence causes elevation change of the entire voxel stack and can change the surface water level (SWL) due to elevation change of the relevant SWL controlling infrastructure (weir/pumping station). Additional factors which can cause either GLG or SWL change are indicated

Figure 7 illustrates the main time loop of the tool, consisting of stress periods with a length of 1 year. In each stress period relevant quantities are updated for a priori selected influences. Calculations are done on a spatial grid (in map view), where each grid (voxel stack) in any given stress period is associated with a fixed water level area and its water level control point. The latter is used to update the SWL for deep subsidence (in option 2). At the start of a new stress period, the boundaries of fixed water level areas, the location of their respective water level control infrastructure and SWL can be modified (active interference in the water system; blue panel).

[8] Within WP5 the relationship between SLW lowering and associated freeboard increase on the one hand, and GLG lowering on the other, is investigated with a focus on damage risk to building. Possibly, the insights may provide a basis to improve the adopted relationship in the current tool.

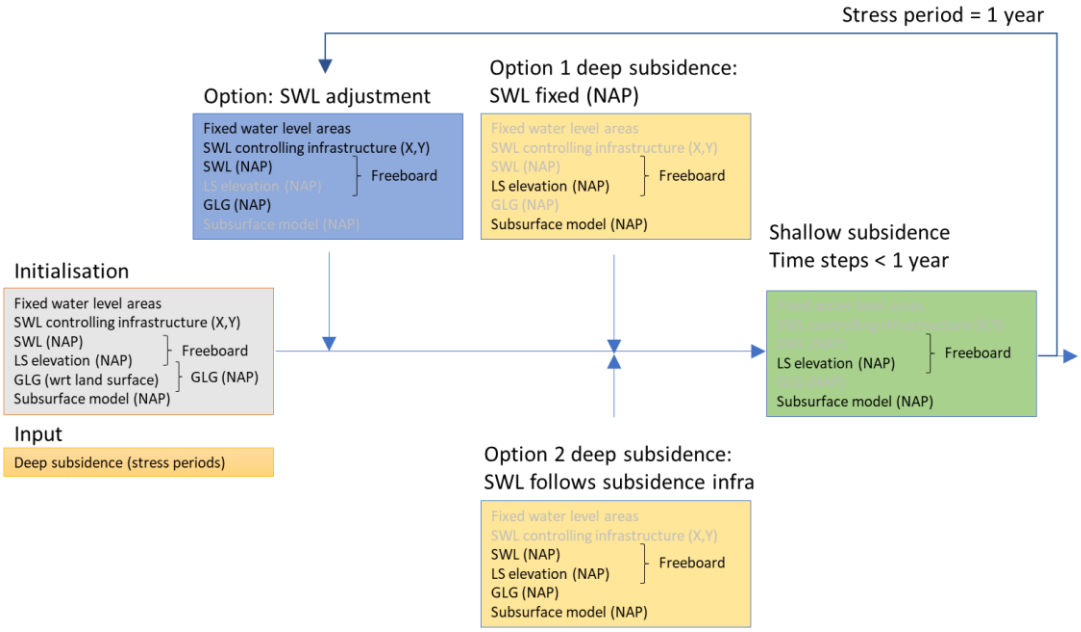

Figure 7 Flow diagram showing key quantities that are initialized and subsequently updated in a sequence of stress periods of one year each. Updating accounts for shallow subsidence (green), deep subsidence (yellow, two options to choose from), and active interference in the surface water system (blue). LS = land subsidence. All large boxes list the same items. The items that are modified/addressed by the option or action associated with the box are shown by the black lettering, unmodified items in light grey lettering.

3.2.2 Practical implementation and workflow

Implementation was done as much as possible in separate Python scripts that handle pre- and post-processing tasks (Figure 8). Compared to the original Atlantis workflow, the new tool requires two new inputs (dark blue blocks): the deep subsidence grids for each stress period, and the surface water level change grids due to deep subsidence. The latter input is constructed in a pre-processing step. Deep subsidence is used by Atlantis to modify the vertical position of the voxel stacks. The surface water level change is transferred to GLG change. This affects the shallow subsidence processes that are calculated by Atlantis. Outputs that are of interest (freeboard, total subsidence etc.) are constructed by a post-processing module from the Atlantis outputs and the original input data.

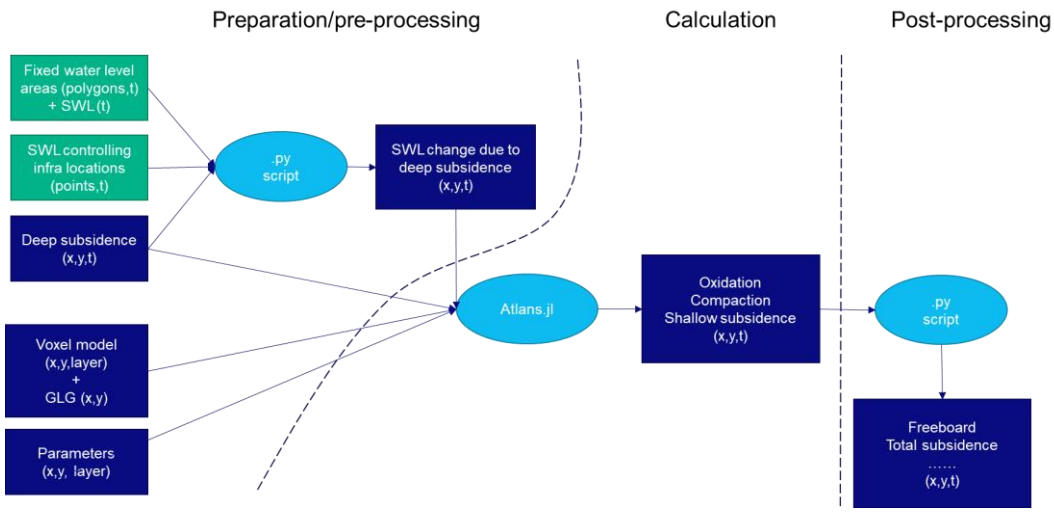

Figure 8 Workflow illustrating how the tool was implemented as an extension to Atlantis (calculation part), requiring minor interference in the Atlantis code (Atlans.jl). Rectangles: input/output. Ovals: code/script. Green: (water system) data that are used to generate input for Atlantis in a pre-processing step, but that are not read by Atlantis.

4 Case study 1: Nedmag-Veendam, historic and future effects

4.1 Introduction

The case concerns the effects of salt-mining. It was selected for its presumed suitability to provide a comprehensive demonstration of the new tool, to support the tool development, and study what insights can be gleaned from the tool for this area.

Since 1981, Nedmag produces magnesium-salt from the Zechstein formation (1300-1800 m depth) close to the town of Veendam. Initially the subsidence induced by the mining was minor, but since 1995 subsidence increased following use of new mining techniques (Grontmij, 2002; Figure 9). The mine was permitted to operate to a maximum subsidence of 65 cm. The production plan has been submitted for a renewal, including new estimates of subsidence. Since 2001 water management adjustments have been implemented on a regular basis to adapt to the deep subsidence.

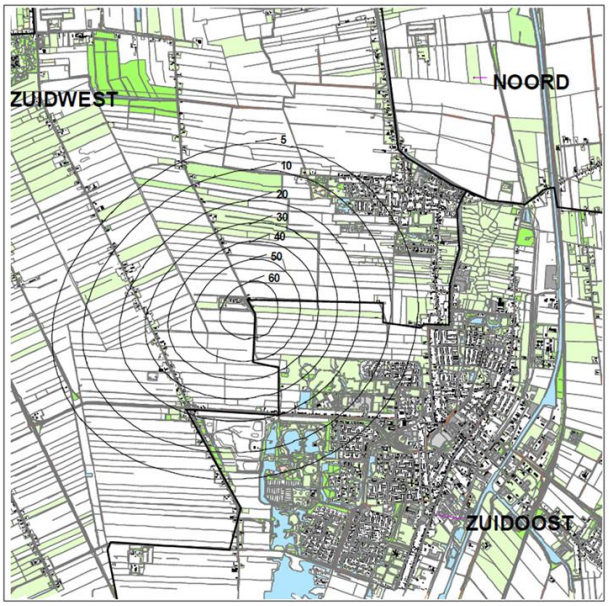

Figure 9 Projection (Witteveen en Bos, 2004) of the deep subsidence (in cm) in 2025 due to the salt mining by Nedmag. Veendam is located to the southeast of the subsidence bowl.

4.2 Inputs for the calculations

Simulated period
The simulated period starts in 1994, when subsidence was still minor/negligible and runs to 2030. The analysis focuses on the historic development (hindcasting), but also includes a projection period (forecasting).

Water management
Documentation and datasets regarding water management conditions and adjustments were provided by water board Hunze en Aa's. Adjustments were carried through in 2001, 2006, 2012 and 2021. The adjustments involved reorganization of fixed water level areas and locations of water-level controlling infrastructure. The four adjustments subdivide the simulated time in five periods. For each of the five periods, datasets were prepared for the

fixed water level areas, each with a (single) position of the water-level controlling infrastructure and a prevailing, administrative summer water level (Figure 10).
For older periods, locations of water-level controlling infrastructure were inferred from historical maps.

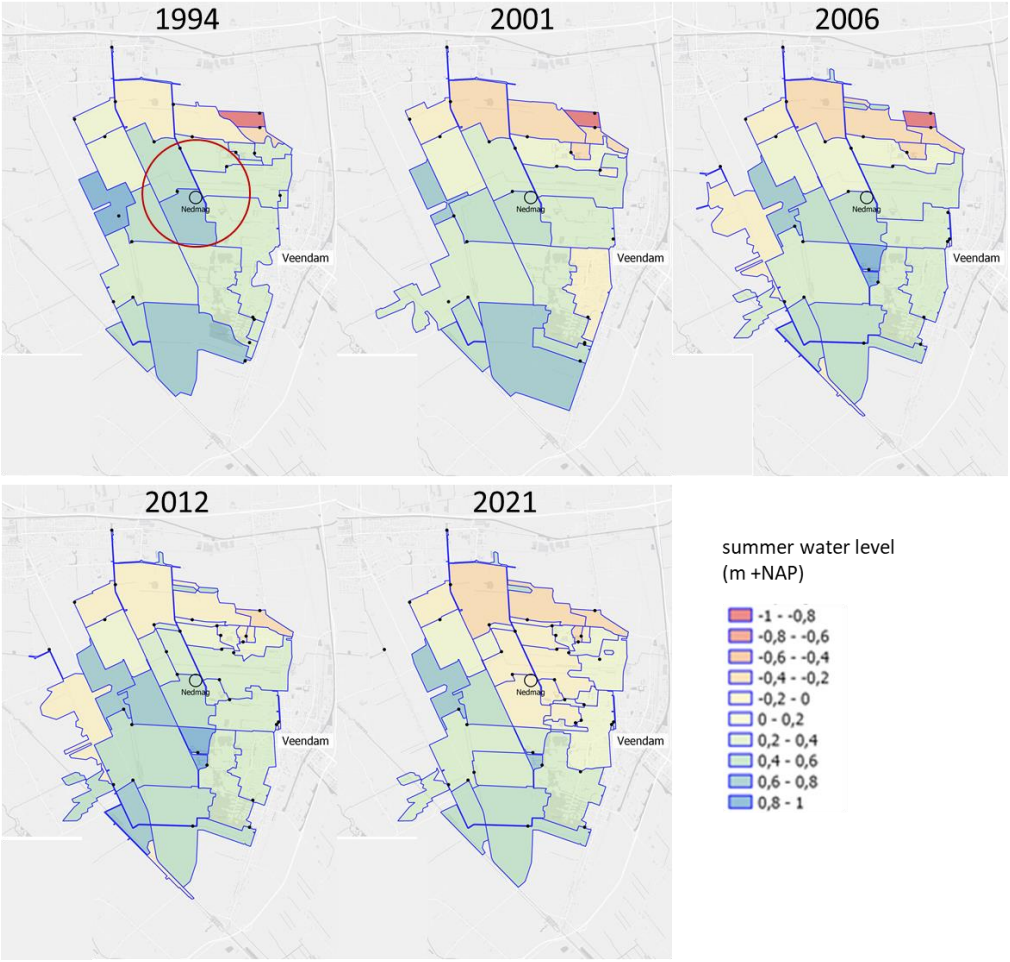

Figure 10 Constructed fixed water level areas (polygons), location of the water-level controlling infrastructure (black dots) and administrative (target) summer water level (legend) for the periods following the indicated year. The calculated area corresponds to the locations where the data is available for the full modelling period.

Deep subsidence

Deep subsidence estimates caused by the salt mining were provided by TNO as yearly grids for the period 1994-2031. Grid resolution is 50 m x 50 m. Figure 11 shows the subsidence in 2020.
The contribution to the subsidence by the Groningen gas field was left out. In hindsight this is formally not correct and result in errors in the calculated freeboard change. However, the consequences in this case are relatively small and are elucidated in the discussion section (4.5).

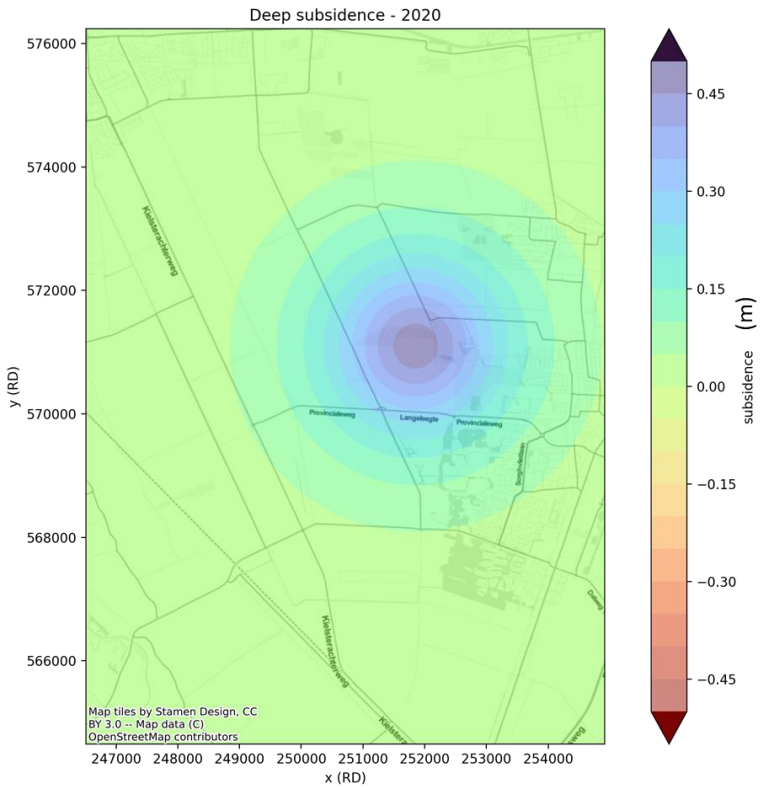

Figure 11 Deep subsidence in 2020 (input analysis).

Voxel model

The existing voxel model that was used for the prevailing national predictive land subsidence map (Erkens et al., 2021) was used to build the voxel model for this case study. The following steps were taken to generate the voxel model for this case study:

1. A cut out of the model was made for the study area.
2. Correction for incurred subsidence. The land surface of the existing model is based on the national elevation database model AHN3, which represents the elevation in 2019. The voxel stacks were vertically shifted/corrected for the deep subsidence in the period 1994-2019 based on the TNO subsidence grids.
3. Grid refinement. The horizontal dimensions of the voxels in the existing model is 100 m x 100 m. The voxel model was resampled to voxel dimensions of 10 m x 10 m. That is, each original voxel stack is represented by 100 new voxel stacks. Properties and parameters of the original model were retained. The refinement allowed more accurate representation of elongated, narrow (< 100 m wide) extensions of fixed water level areas.

GLG

The existing GLG map (relative to land surface) that was used for the prevailing national predictive land subsidence map (Erkens et al., 2021) was used and sub-sampled to the required 10 m x 10 m grid.

Parameterization

The parameterization of the shallow subsidence processes that was used to produce the prevailing national predictive land subsidence map (Erkens et al., 2021) was adopted. This pertains to the starting parameterization. Temporal evolution of parameter values to represent climate change scenarios adopted in the national prognoses were not used.

4.3 Scenarios

Calculations were done for the four scenarios listed in Table 1. The scenarios are meant to approximate the following:

Scenario A: Independent development in the absence of salt mining and water management, solely shallow subsidence.
Scenario B: Development with deep subsidence, but no interference by the water board since the start of the salt mining.
Scenario C: What would have occurred if the water board had strived to maintain the original water levels (relative to NAP). This is an unrealistic and unpractical scenario that is included for reference.
Scenario D: The actual historical development.

Table 1 Applied scenarios in the Veendam Nedmag case

Scenario	Deep subsidence	Water management
A	no	no
B	yes	no
C	yes	yes (fixed at 1994 levels)
D	yes	yes (as reconstructed)

Of particular interest are the differences of results of the following scenarios:

D – A: The effect of deep subsidence + water management
B – A: The effect of deep subsidence
D – B: The effect of water management

All these scenarios include the impact on shallow subsidence.

4.4 Results

Results of the calculations are illustrated with the following a set of maps:

- Freeboard scenario D Figure 12
- Freeboard change scenario D Figure 13
- Surface water level change scenario D Figure 14
- Shallow subsidence scenario D Figure 15
- Impact on shallow subsidence scenario D-A Figure 16
- Freeboard change (2020) scenarios ABCD Figure 17
- Deep subsidence freeboard effect B-A Figure 18
- Management freeboard effect D-B Figure 19

The graphical results are discussed in the discussion section 4.5.

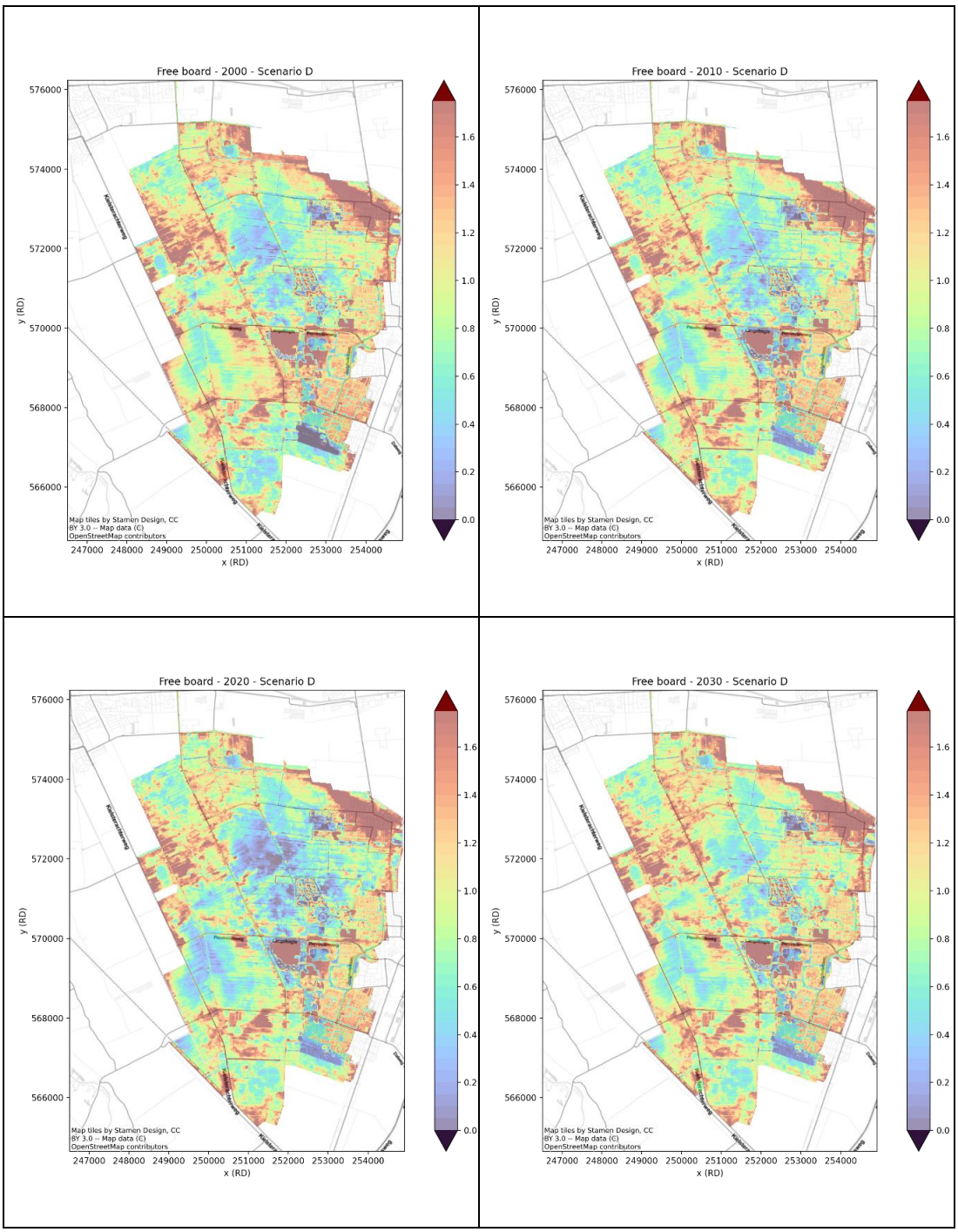

Figure 12 Scenario D, freeboard (in m), based on summer water level (2000, 2010, 2020, 2030).

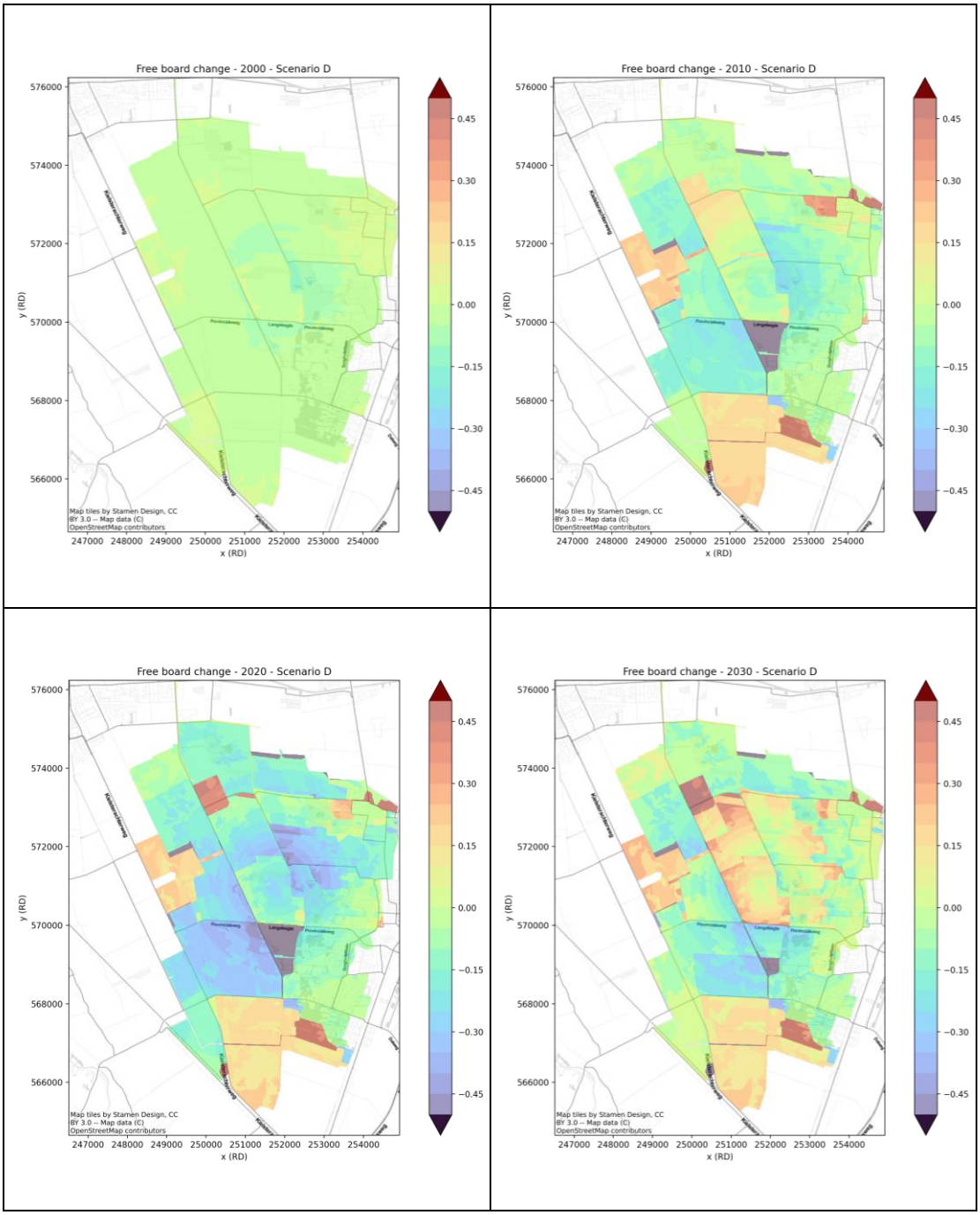

Figure 13 Scenario D, freeboard change (in m since 1994) (2000, 2010, 2020, 2030)

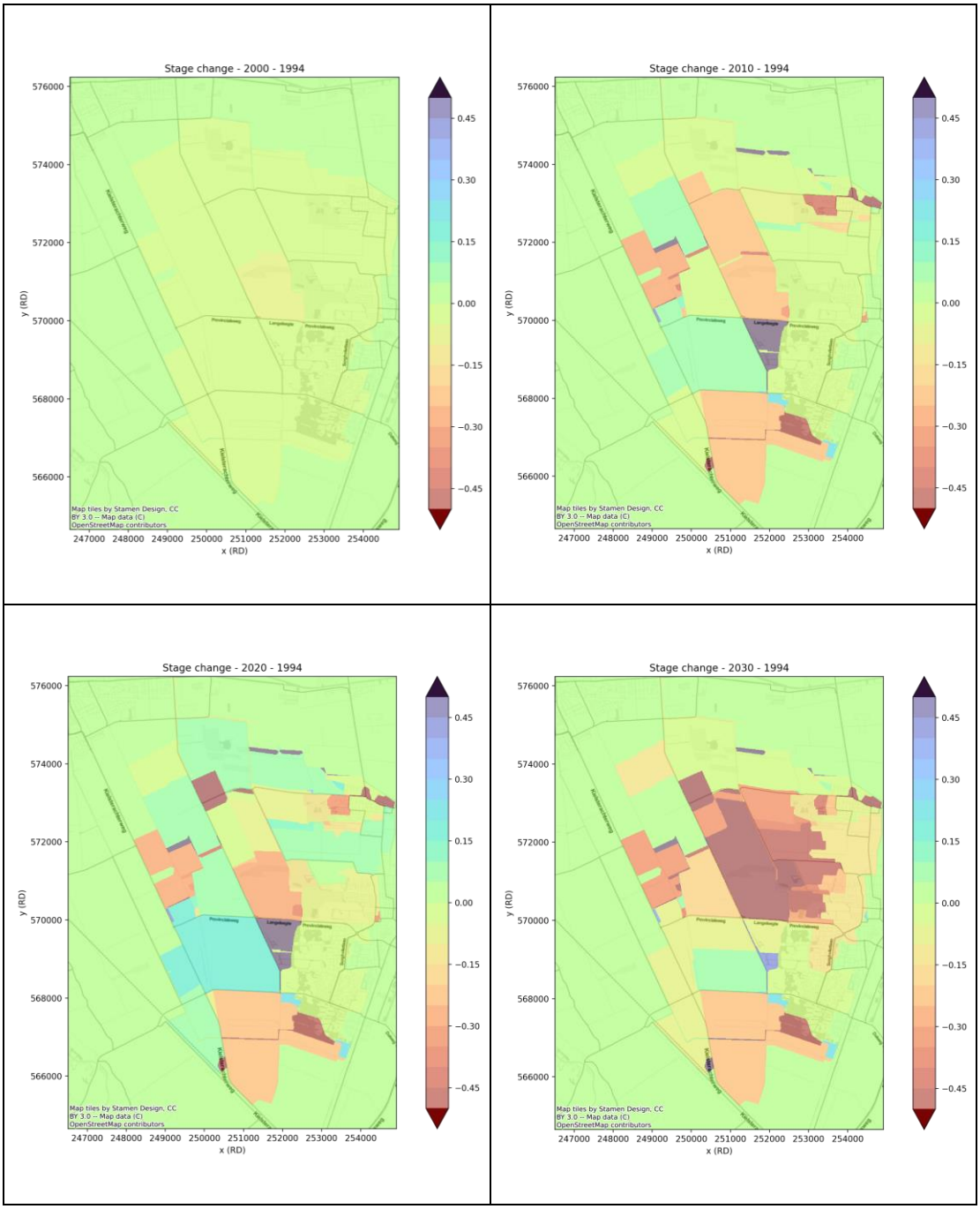

Figure 14 Scenario D, surface water level change (summer) (in m) (2000, 2010, 2020, 2030)

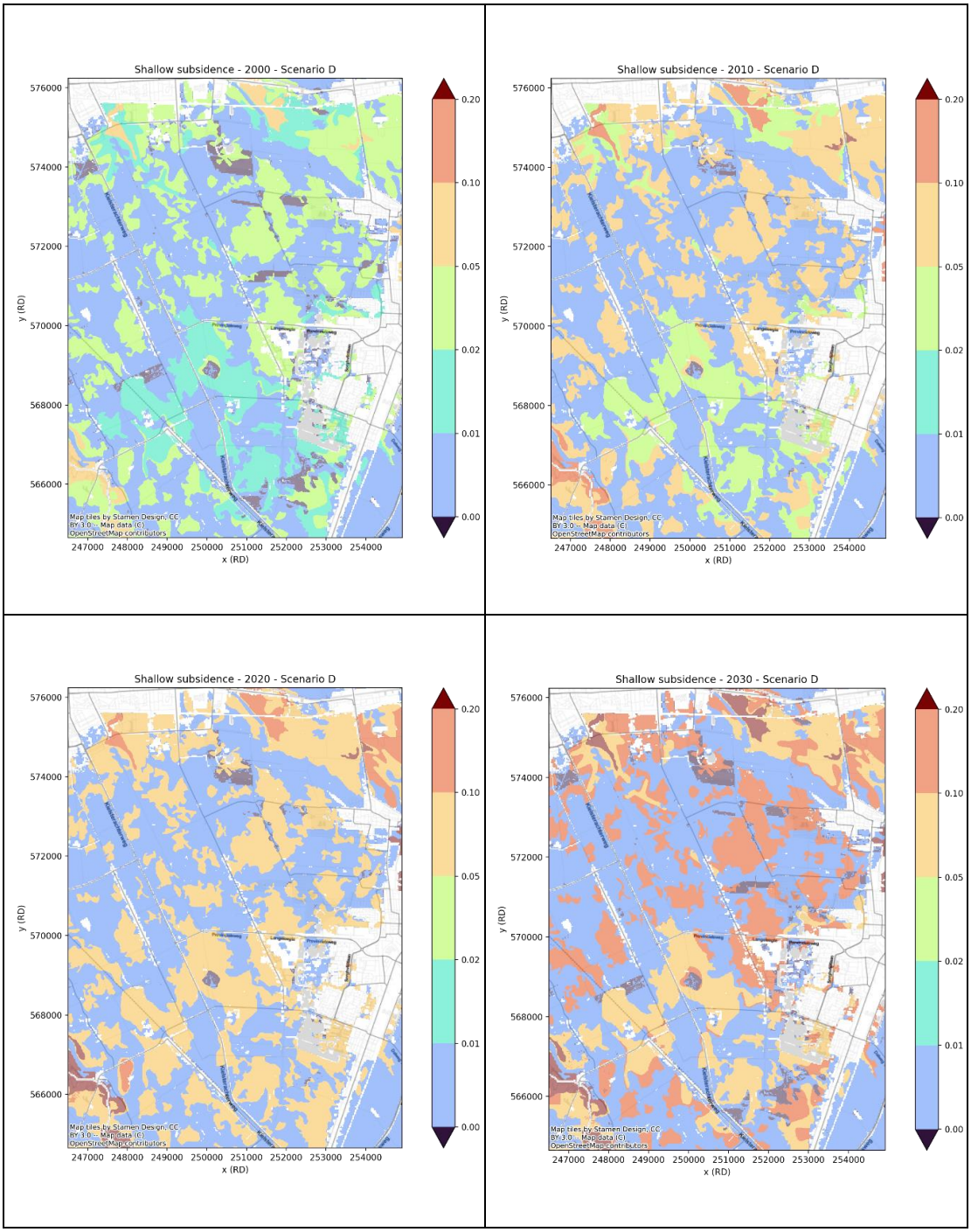

Figure 15 Scenario D, shallow subsidence (in m) (2000, 2010, 2020, 2030). Positive sign indicates subsidence.

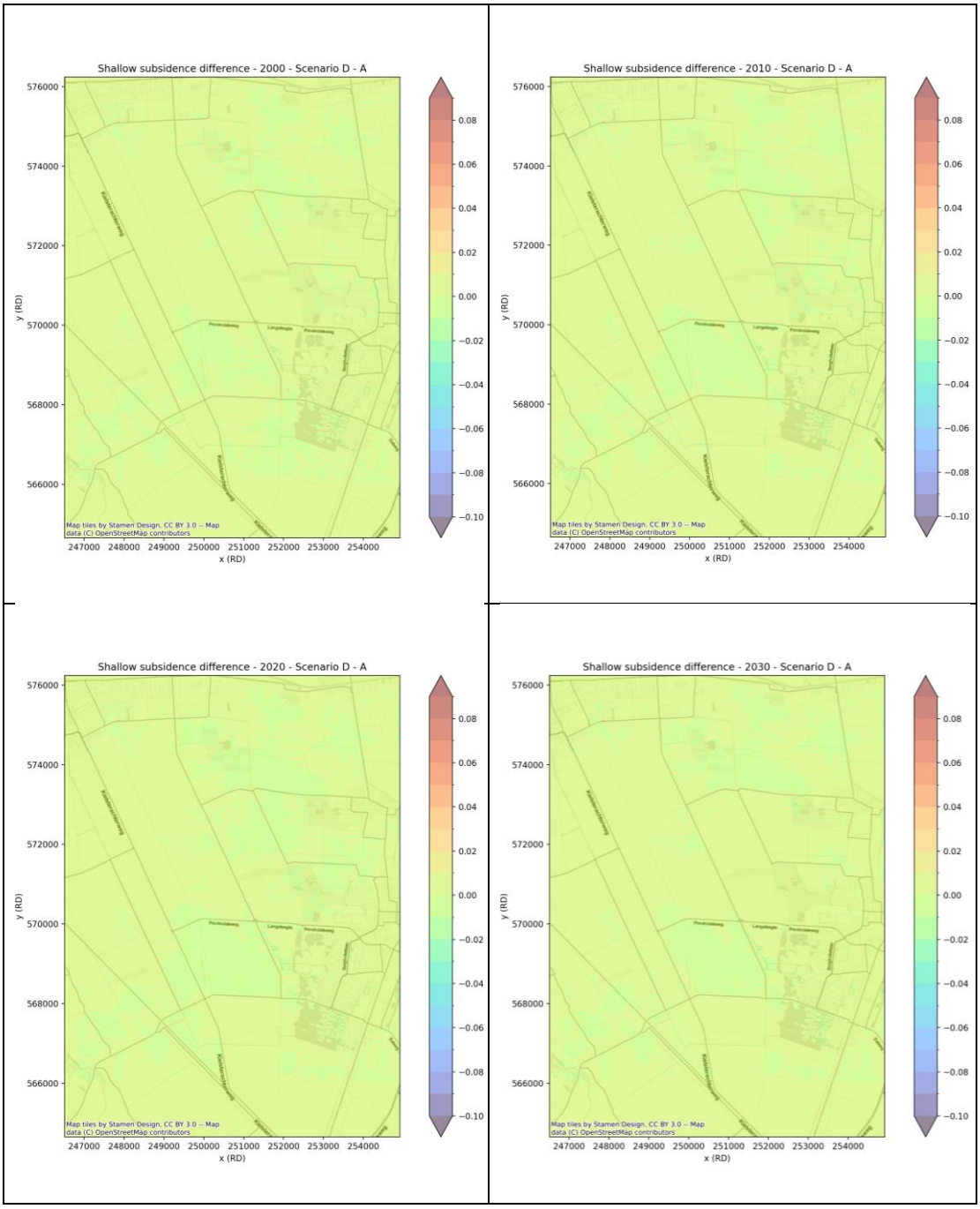

Figure 16 Effect of deep subsidence and water management measures on shallow subsidence (D – A) (in m).

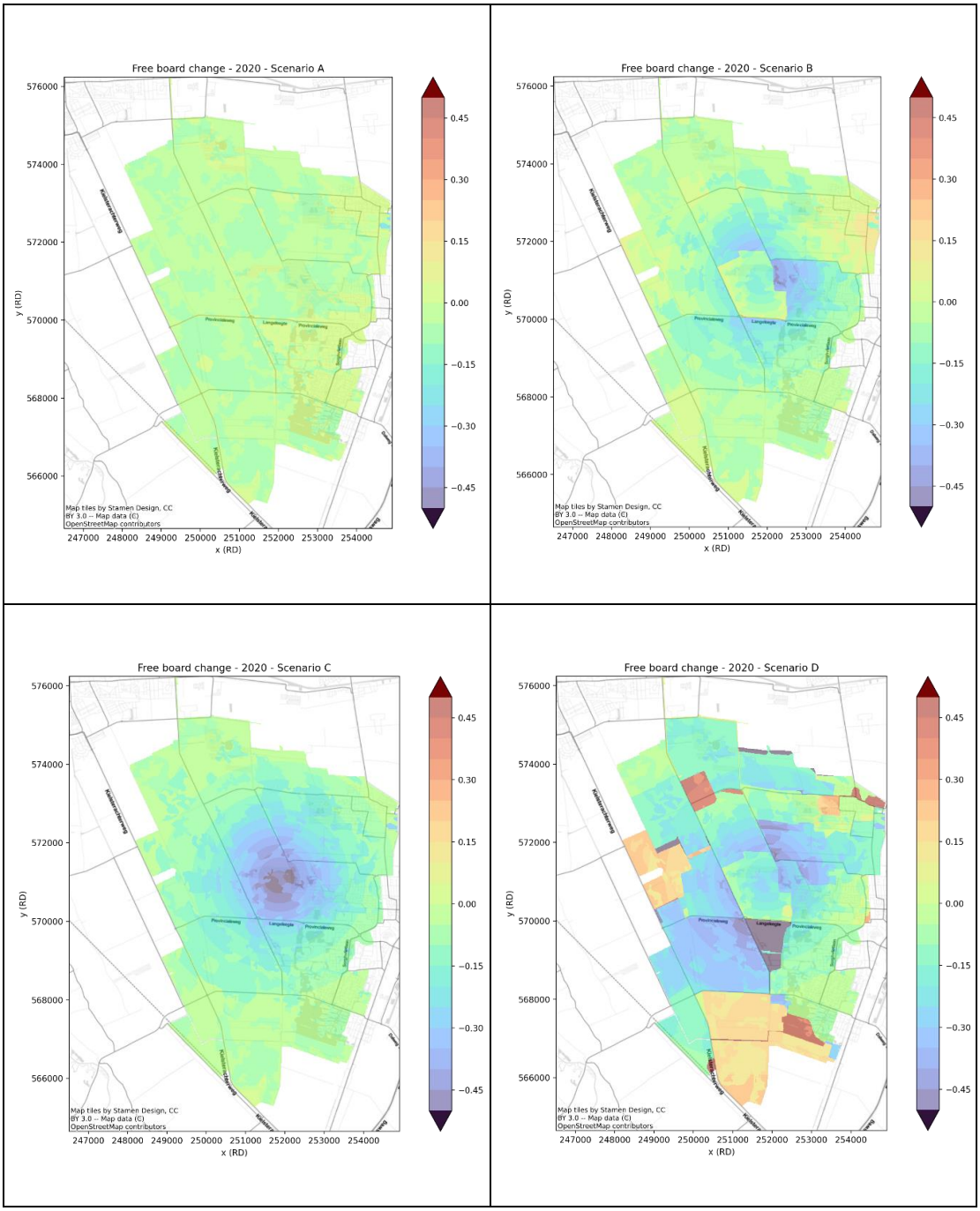

Figure 17 Scenarios A, B, C, D, freeboard change (summer water levels) in 2020 (in m).

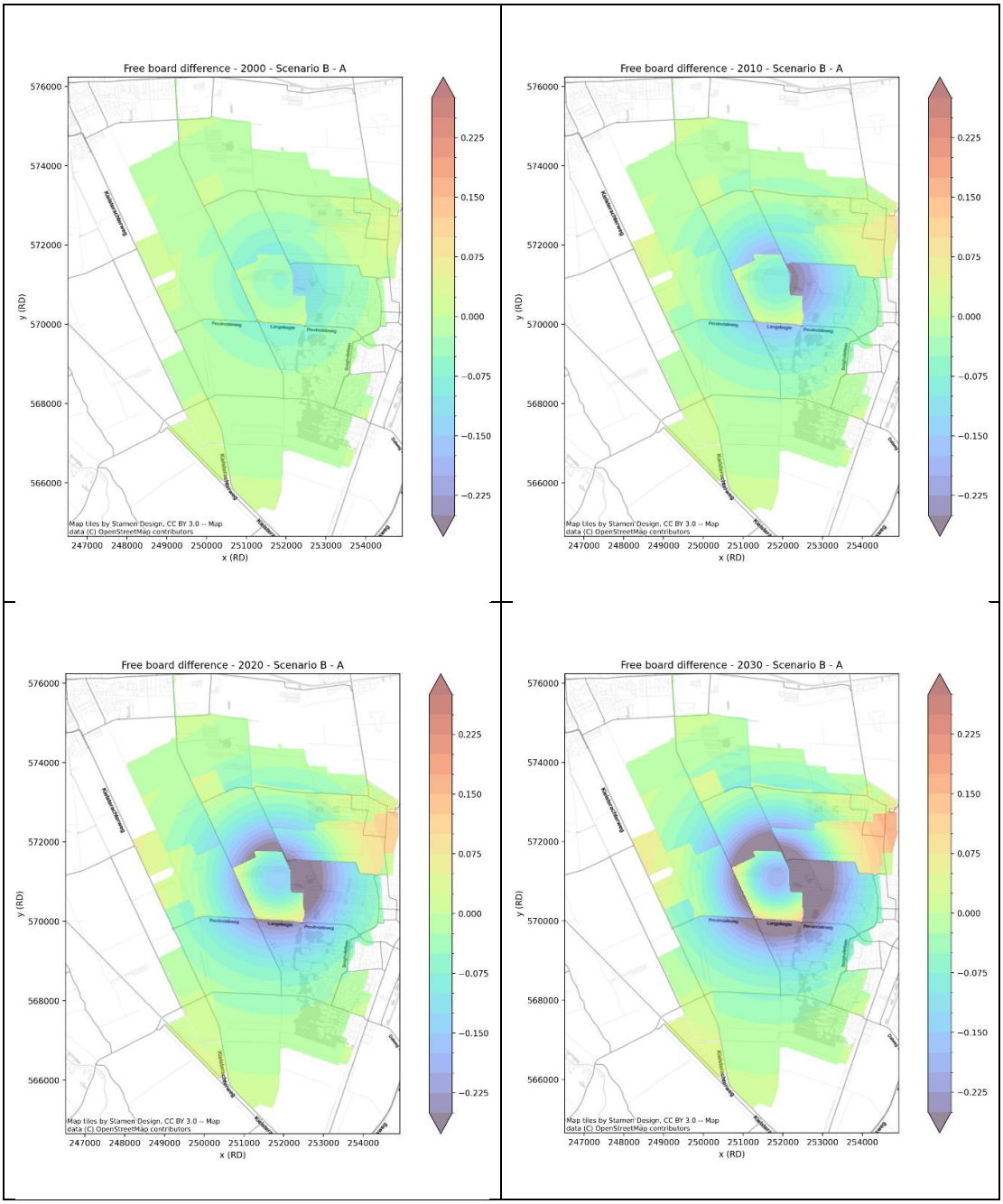

Figure 18 Deep subsidence effect on freeboard (B-A) (in m)

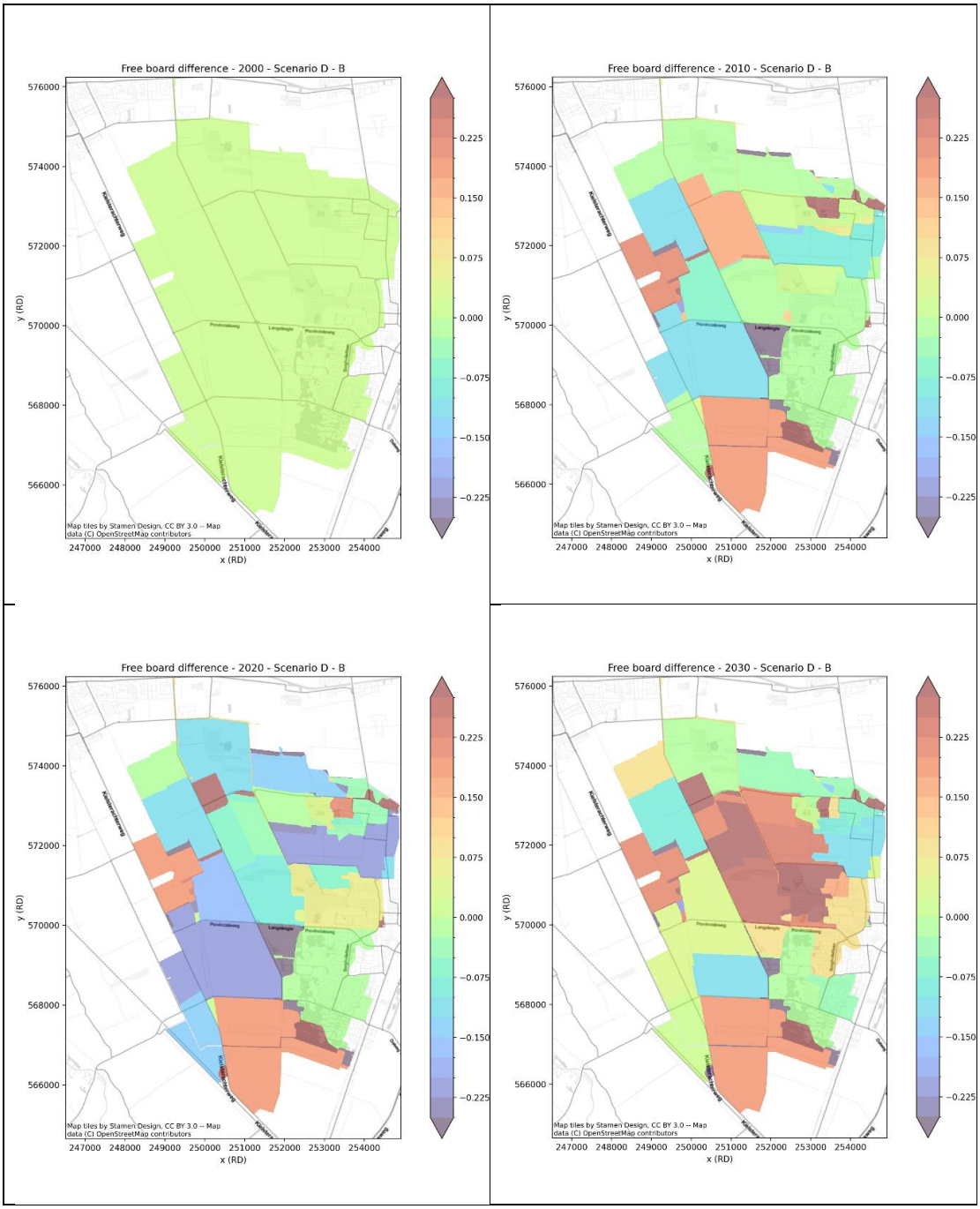

Figure 19 Water management effect on freeboard (D-B) (in m).

4.5 Discussion

4.5.1 Discussion of the graphical results

Total effects (scenario D)

Figure 12 shows that freeboard for scenario D varies spatially in the study area from a few decimetres to about two meters; effects of topographic relief can be clearly seen. Compared to this range, temporal changes of freeboard are relatively small, which makes these changes harder to discern. Figure 13 shows the changes separately. By 2000, before water level

adjustments were carried through, some combined effects of deep and shallow subsidence are visible. The subsequent development is rather complex. The patchiness of the maps indicate that the water level adjustments play a relatively large part. Freeboard increases and decreases locally by up to about half a meter. Also, further away from the subsidence bowl (Figure 11) increases of freeboard due to water level adjustments (Figure 14) are seen that seem unrelated to the deep subsidence.

Figure 15 displays the development of shallow subsidence for scenario D. The patchiness of the subsidence reflects the patchy distribution of organic-matter-rich soil layers at shallow depth (Figure 20), which contribute to the subsidence by oxidation. By 2020, locally some 5-10 cm of shallow subsidence is modelled. By 2030 values > 10 cm are predicted.

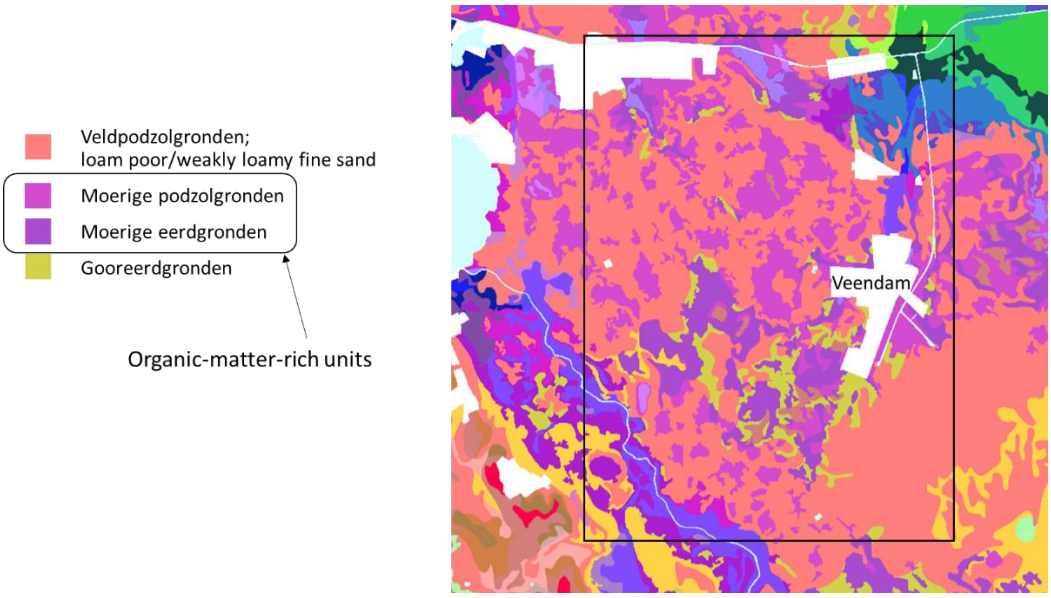

Figure 20 Excerpt of the soil map covering the study area (black rectangle).The pink/purple units are organic-matter-rich units that dominate the shallow subsidence response in this area.

Figure 16 demonstrates that the changes of shallow subsidence caused by the combined impacts of the deep subsidence and water management measures are very small (up to a few cm or about 20%). The predominantly negative values in the maps indicate that the impact mostly consist of a reduction of shallow subsidence. The reduction is due to predominantly wetter conditions (reduction of freeboard and associated rise in GLG relative to soil layers). Increase of shallow subsidence is not inferred in the study area, even though freeboard has locally significantly increased (Figure 13). This is explained by the fact that the oxidation-sensitive soil layers were generally already located above the GLG in 1994, and therefore subject to oxidation anyway (Figure 21). Further lowering of GLG does not enhance the ongoing oxidation (in Atlantis). Moreover, because compressible soil layers are virtually absent in the area below the GLG, lowering of GLG relative to soil layers also does not significantly enhance the compaction contribution in shallow subsidence.

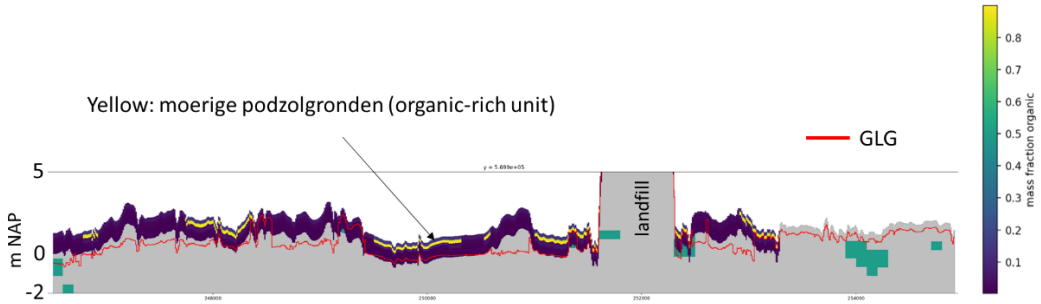

Figure 21 West-east transect through the subsurface model (1994), illustrating that the most oxidation-sensitive units were already situated above the GLG before the deep subsidence due to salt mining.

Deep subsidence and water management effects.
Figure 17 shows the freeboard changes in 2020 calculated for all four scenarios. Freeboard reductions of 5-10 cm for scenario A reflect the indepdent shallow subsidence depicted in Figure 15. For scenario B, freeboard reductions are mostly enhanced in the deep subsidence bowl, but not or much less in the centre of the bowl, where differential subsidence is less and the water-level controlling infrastructure subsides largely in concert with the land. Freeboard reductions are seen further away from the centre of the subsidence bowl, where the land subsides less than the water-level control infrastructure which is located more towards the centre of subsidence bowl. Scenario C illustrates how much freeboard would rise if surface water levels would be maintained. The map basically corresponds to the total subsidence. Scenario D again shows the changes when including the actual water management measures.
Figure 18 and Figure 19 show the separate effect of deep subsidence (D-A) and of the management measures (D-B) on freeboard, respectively. As expected, the impact on shallow subsidence is not discernible in the figures because of its small magnitude (Figure 16). Comparison of the figures confirm the notion that the management interferences served aims in addition to mitigation of deep subsidence. A discussion on how the tool and these products might be used to determine which part of the water management interferences are related to deep subsidence is provided in 6.1.

4.5.2 Consequences of neglecting subsidence due to gas production

According the subsidence status reports of the NAM in 2000 and 2020, the subsidence due to gas extraction in the study area was about 7 cm and 10 cm in 1998 and 2018, respectively. The contribution to deep subsidence in the historic part of the simulation period (~1994-2020), therefore amounts to 3 to 4 cm. The vertical position of voxel model for 1994 was, therefore, underestimated by this amount. Consequently, the 1994 freeboard was overestimated by 3 or 4 cm due to this omission. Towards 2020, the ‘error’ in the vertical position of the voxel model due to the negligence of subsidence due to gas extraction decreases to virtually nil. Importantly, the initial GLG for 1994 is set relative to the land surface, independent of freeboard. In the starting conditions, therefore, the intended GLG relative to soil layers was used. Towards 2020, GLG lowering relative to soil layers is overestimated by up to 3 to 4 cm due to the stepwise enforcing of the lowing during water level adjustments (GLG change is coupled to surface water level change). These consequences of neglecting the subsidence due to the Groningen gas field are small compared to the overall freeboard and water-level changes of 20 to 50 cm.

4.5.3 Remarks

- The case study was a first exercise in the application of the tool. The results are indicative and are not meant to have an authoritative status. No checks were done, for instance, by the water board(s) on the processing of the provided data and the choices made to add missing data (4.2).

- The case demonstrates the two unique capabilities of the tool: quantification of the impact of deep subsidence and water management measures on shallow subsidence and quantification of the temporal development of coupled effects for relatively complex water management scenarios.

- In a hindcasting/reconstruction application like the one reported here, it is important to include/consider the total deep subsidence if multiple components are involved. If two components are involved, the separate effects of both components can be quantified by calculating the equivalent B scenarios, for instance the B effect due to the deep subsidence of gas production and the B effect due to the deep subsidence associated with the salt mining.

- To improve accuracy of the calculated absolute values of freeboard, an iterative approach may be used. First a calculation is done in which the vertical positioning of the initial voxel model is done by correcting a model for recent times for deep subsidence only, as was done here. The tool then provides an estimate for the shallow subsidence (full scenario D). Subsequently, a second, improved calculation can be done in which the vertical positioning of the initial voxel model is further corrected for the shallow subsidence inferred from the first iteration.

- The issue of determining which part of the water management interferences can/should be attributed to deep subsidence needs further elaboration. It cannot be directly resolved based on the outcomes generated with the tool. This aspect is further discussed in 6.1.

- Shallow subsidence in the study area is relatively insensitive to the deep subsidence (and associated water management adjustments). Moreover, the calculations suggest shallow subsidence is predominantly suppressed and little, or not enhanced. These effects are interpreted to be caused by the specific subsurface conditions (groundwater and lithology) in the area.

- For calculations involving water-level adjustments, datasets (shape files) are required in which unadjusted boundaries of fixed water level areas are identical from one dataset to the next. The original datasets for the Nedmag case study contained irregular offsets in such boundaries, reflecting limited accuracy of their ‘drawing’. These offsets correspond to gaps or overlaps in the boundary region from one year to another that can lead to spurious results in the calculations (spurious jumps in area and associated water level). Considerable effort had to be put in to produce consistent datasets for the calculations.

5 Case study 2: fictitious case, future effects in a potentially sensitive area

5.1 Introduction

Subsurface conditions for the Nedmag Veendam case (chapter 4) render the area relatively insensitive to effects of deep subsidence, in particular regarding lowering of GLG relative to soil layers. Together with the northern water boards, it was decided to carry out a second case study for an area with an anticipated greater sensitivity. An area was chosen between Delfzijl and the city of Groningen (Figure 22). Shallow peat occurs in a zone parallel to the Eemskanaal which trends WSW-ENE (Figure 23). Peatlands are present at the lowest elevations, south of the canal. Towards the northwest, the peat is covered by clays. To the southeast the soft-soils transition to sand dominated soils and topography rises a few meters (Figure 23).

To facilitate comparison with the Nedmag Veendam case, the deep subsidence of the Nedmag Veendam case was also applied in this second case. This makes this a fictitious case.

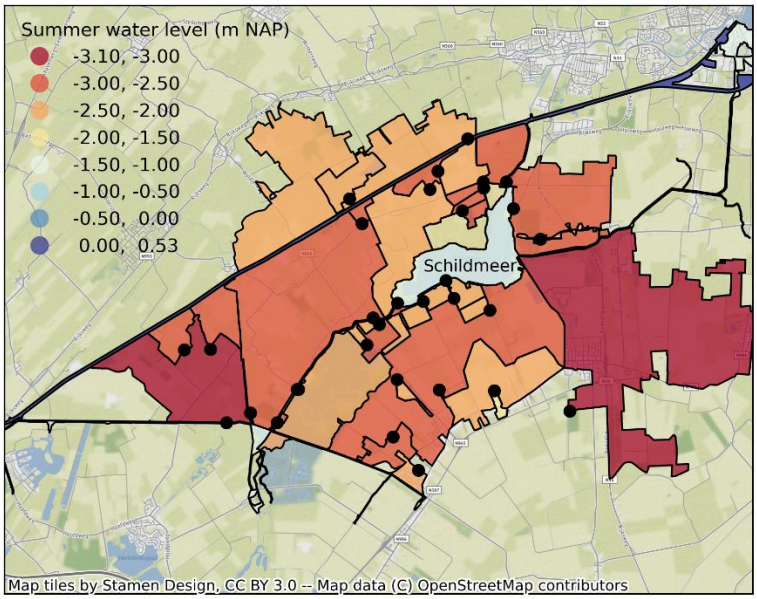

Figure 22 Study are for the 2nd case study showing fixed water level areas and water-level controlling infrastructure (black dots). The continuous black line traversing the area WSW-ENE, is the Eemskanaal.

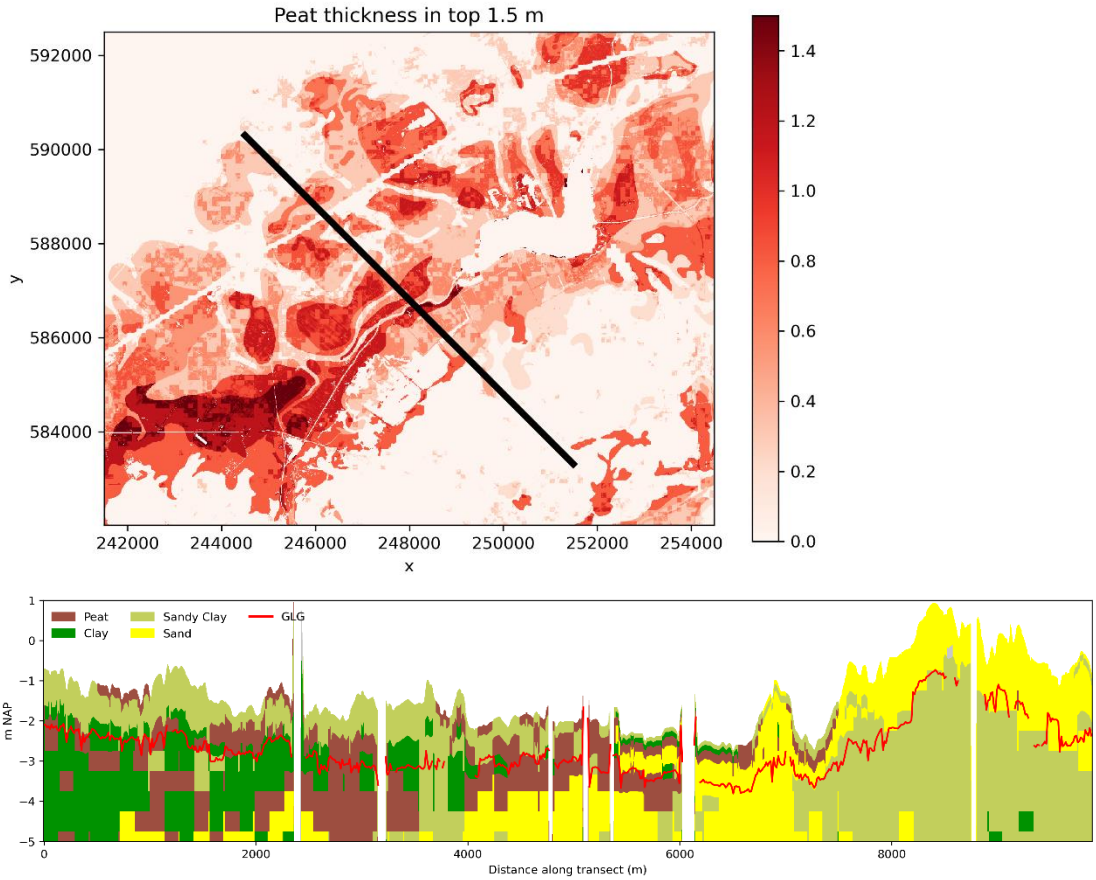

Figure 23 Shallow geological conditions of the study area. Top: peat thickness in the top 1.5 m. Bottom: NW-SE transect (location shown by the black line in the top panel) showing lithologies to -5 m NAP. The information shown corresponds to the employed voxel model that is used in the calculations.

5.2 Inputs for the calculations

Simulated period
The simulated period starts January 2020 and runs to 2050. To facilitate intercomparison with the Veendam case, output is shown at the same times since the start of the deep subsidence: 2026, 2036, 2046. These years are equivalent to the years 2000, 2010 and 2020 for the Veendam case in terms of deep subsidence.

Water management
Actual water management conditions (fixed drainage areas, summer water levels and water-level controlling infrastructure) were gleaned from shape files obtained from the water boards Hunze en Aa's and Noorderzijlvest (Figure 22). No fictitious future management adjustments were used.

Deep subsidence
Compared to the Nedmag-Veendam case, the locus of subsidence was shifted to a position near the southwestern shore of the lake Schildmeer (Figure 24). The start of subsidence was moved to January 2020.

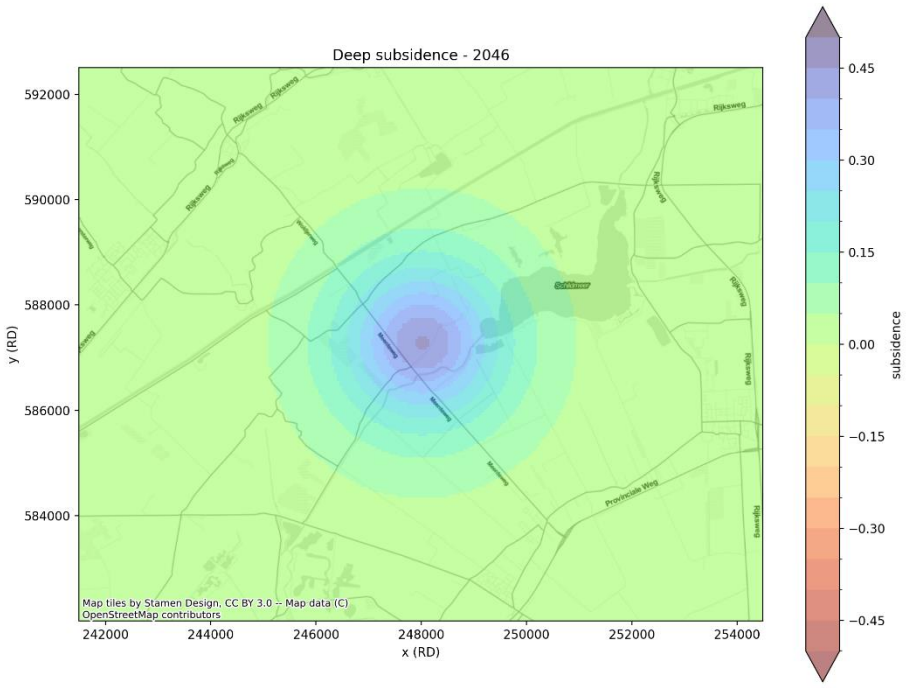

Figure 24 Deep subsidence (fictitious) used in the calculation (in m); shown for 2046.

Voxel model
The voxel model consists of a cut out of the voxel model of the prevailing national predictive land subsidence map (Erkens et al., 2021) for the study area and the voxels were resampled to 10 m x 10 m, analogous to that of the Nedmag-Veendam case. No subsidence correction was applied.

GLG
The existing GLG map (relative to land surface) that was used for the prevailing national predictive land subsidence map (Erkens et al., 2021) was used and sub-sampled to the required 10 m x 10 m grid.

Parameterization
The parameterization for the calculation of the shallow subsidence processes that were used in the prevailing national predictive land subsidence map (Erkens et al., 2021) were adopted without modification.

5.3 Scenarios

Calculations were done for the four scenarios listed in Table 2. The scenarios are meant to approximate the following:

Scenario A: Independent development in the absence of salt mining and water management, solely shallow subsidence.
Scenario B: Development with deep subsidence, but without management interference; water levels subside with infrastructure.
Scenario C: What would occur if the water board would strive to maintain the original water levels. This is an unrealistic and unpractical scenario that is included for reference.

Scenarios B and C include the impact on shallow subsidence.

Table 2 Applied scenarios in the Veendam Nedmag case

Scenario	Deep subsidence	Water management
A	no	no
B	yes	no
C	yes	yes (fixed at 2020 levels)

Of particular interest here are the differences of results of the following scenarios:

B – A: The effect of deep subsidence

5.4 Results

Results of the calculations are illustrated with the following a set of maps:

- Freeboard scenario B Figure 25
- Freeboard change scenario B Figure 26
- Surface water level change scenario B Figure 27
- Shallow subsidence & effects (2046) scenario ABC Figure 28
- Freeboard change (2046) scenarios ABC Figure 29
- Deep subsidence freeboard effect scenario B-A Figure 30

The graphical results are discussed in the discussion section 5.5.

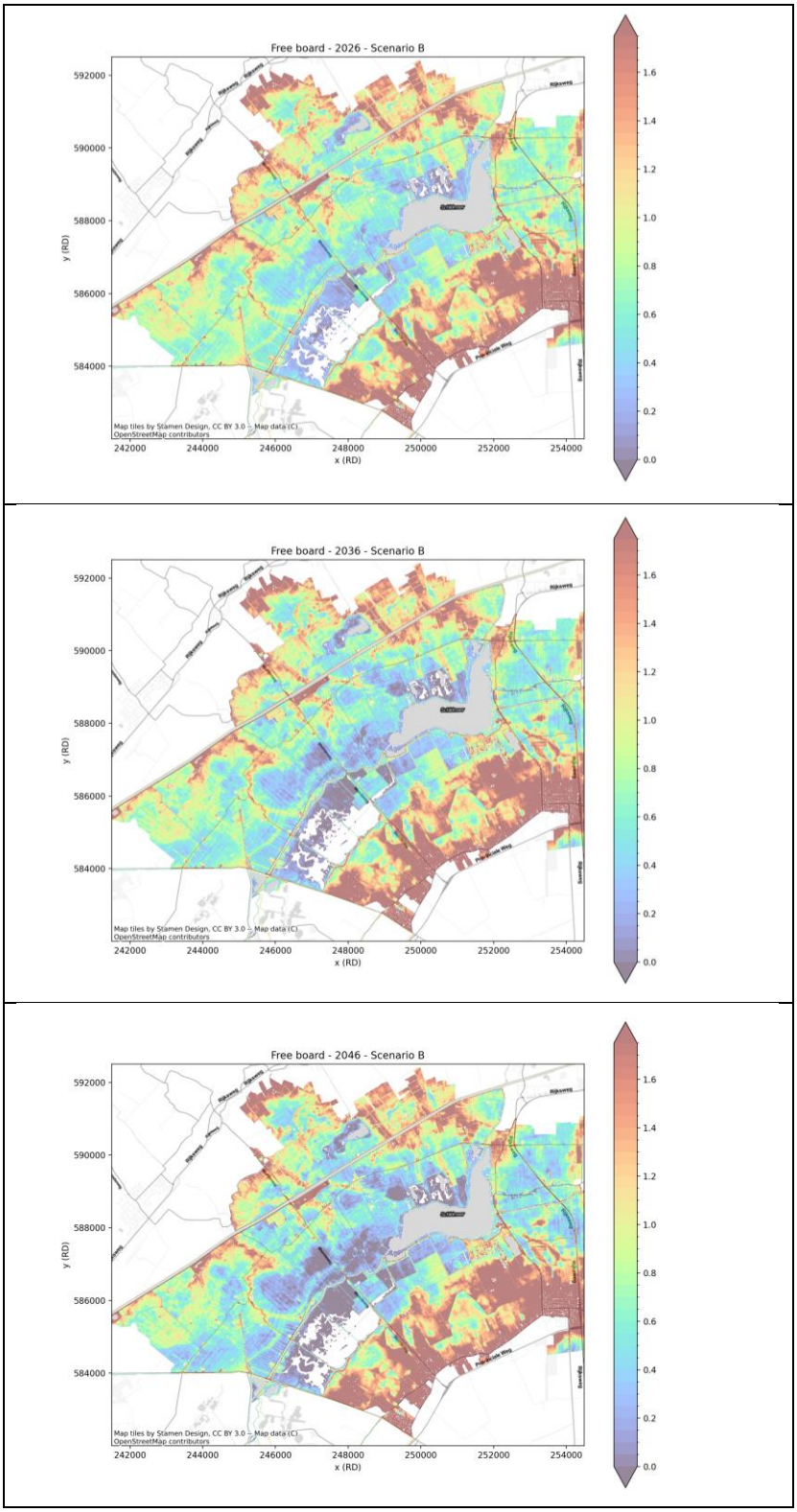

Figure 25 Scenario B, freeboard (in m), based on summer water level (2026, 2036, 2046).

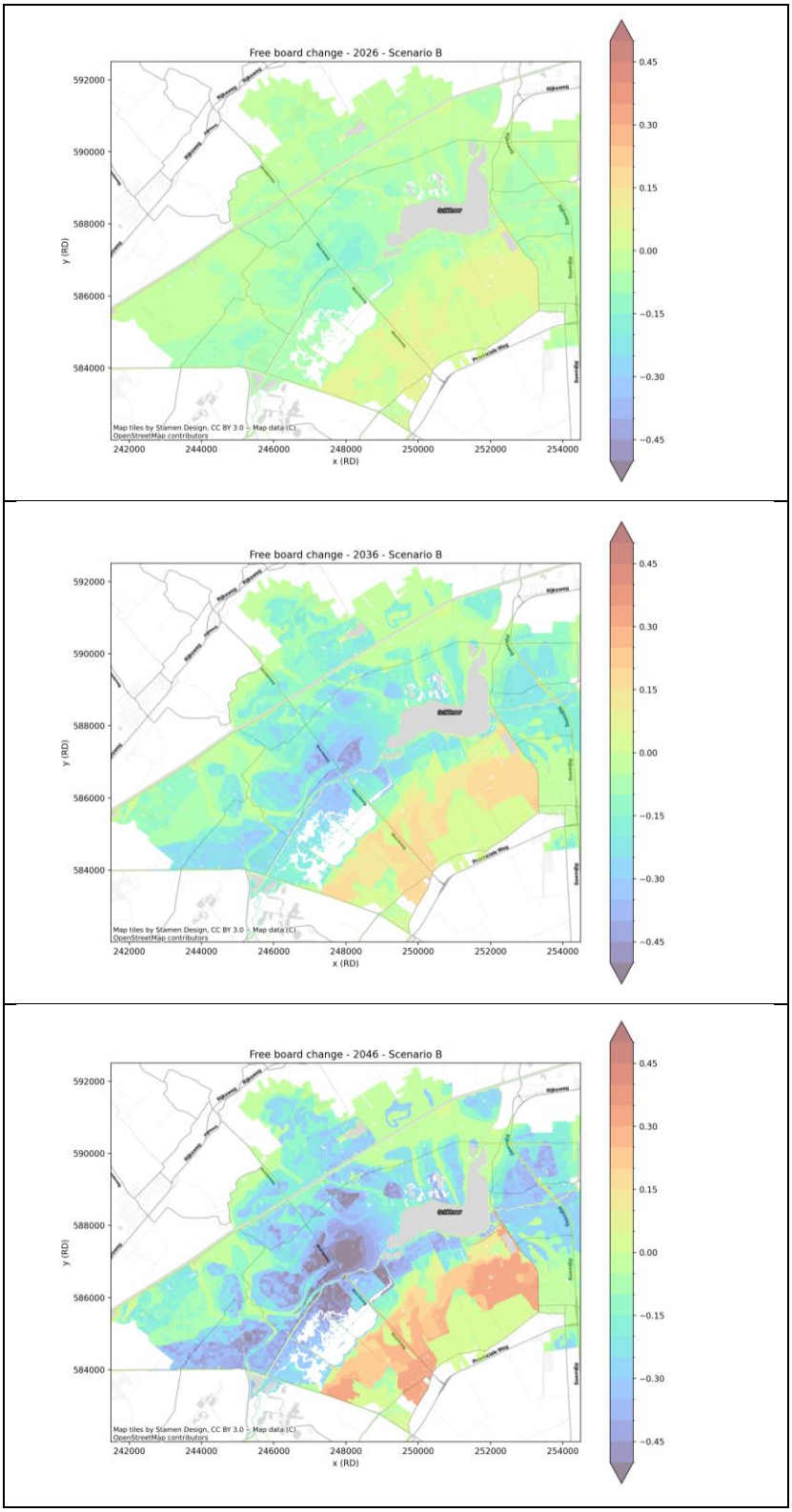

Figure 26 Scenario B. Freeboard change (in m since 2020) (2026, 2036, 2046)

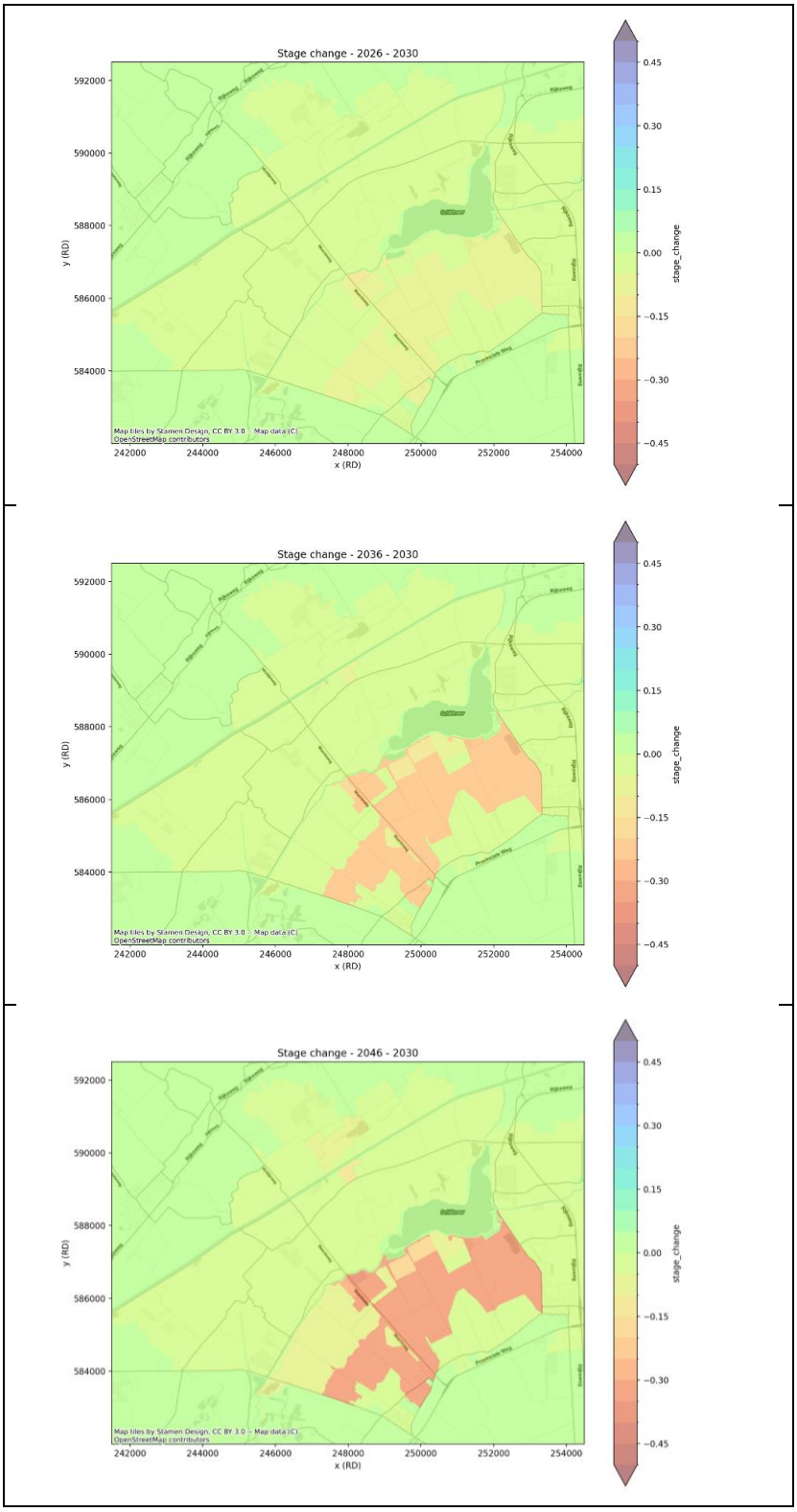

Figure 27 Scenario B, Surface water level change (summer) (in m) (2026, 2036, 2046)

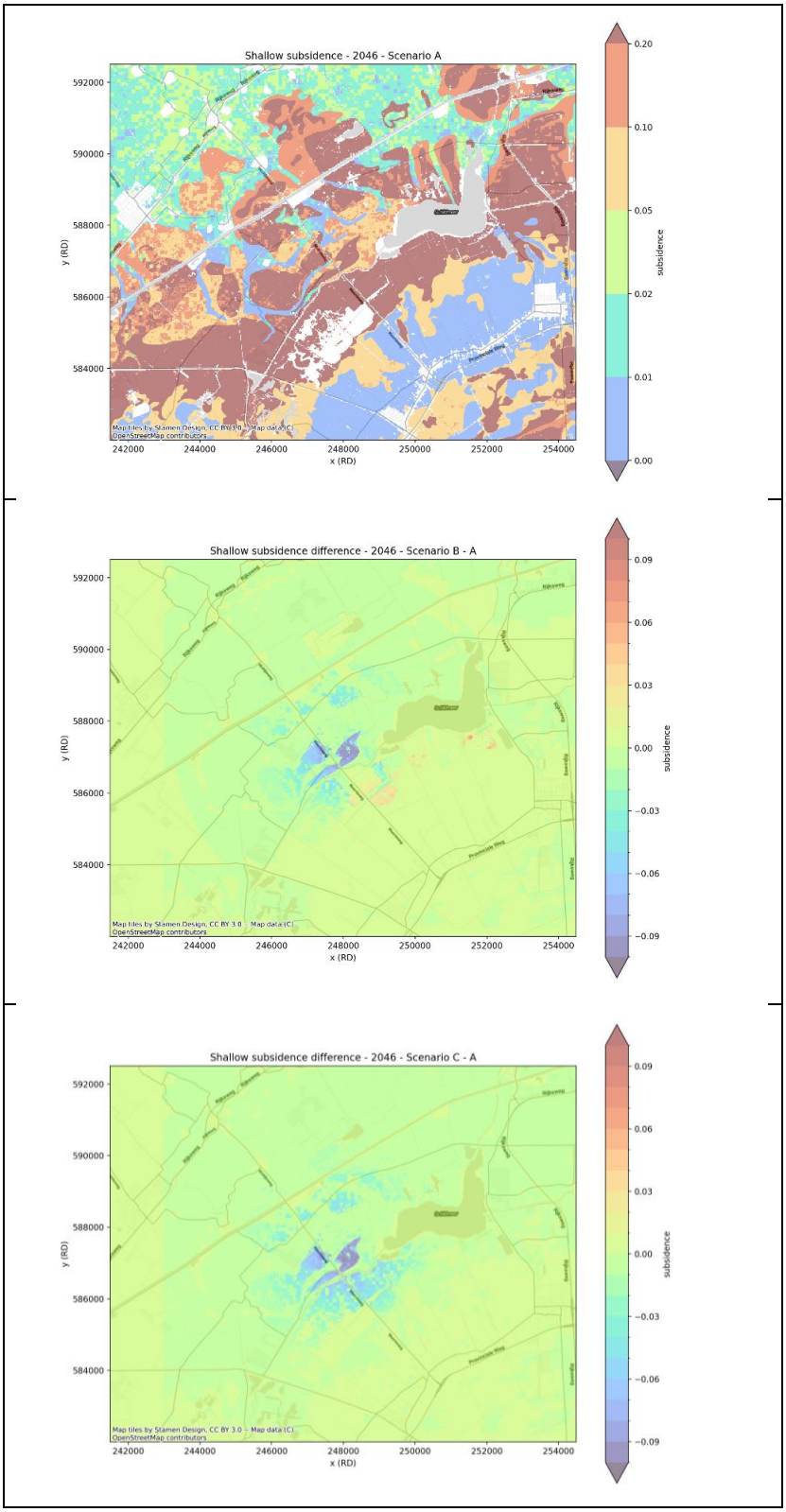

Figure 28 Top: Scenario A, shallow subsidence (in m) (2046). Positive sign indicates subsidence. Middle and bottom: Effects on shallow subsidence (in m) (2046); B-A and C-A. Positive indicates enhancement of shallow subsidence.

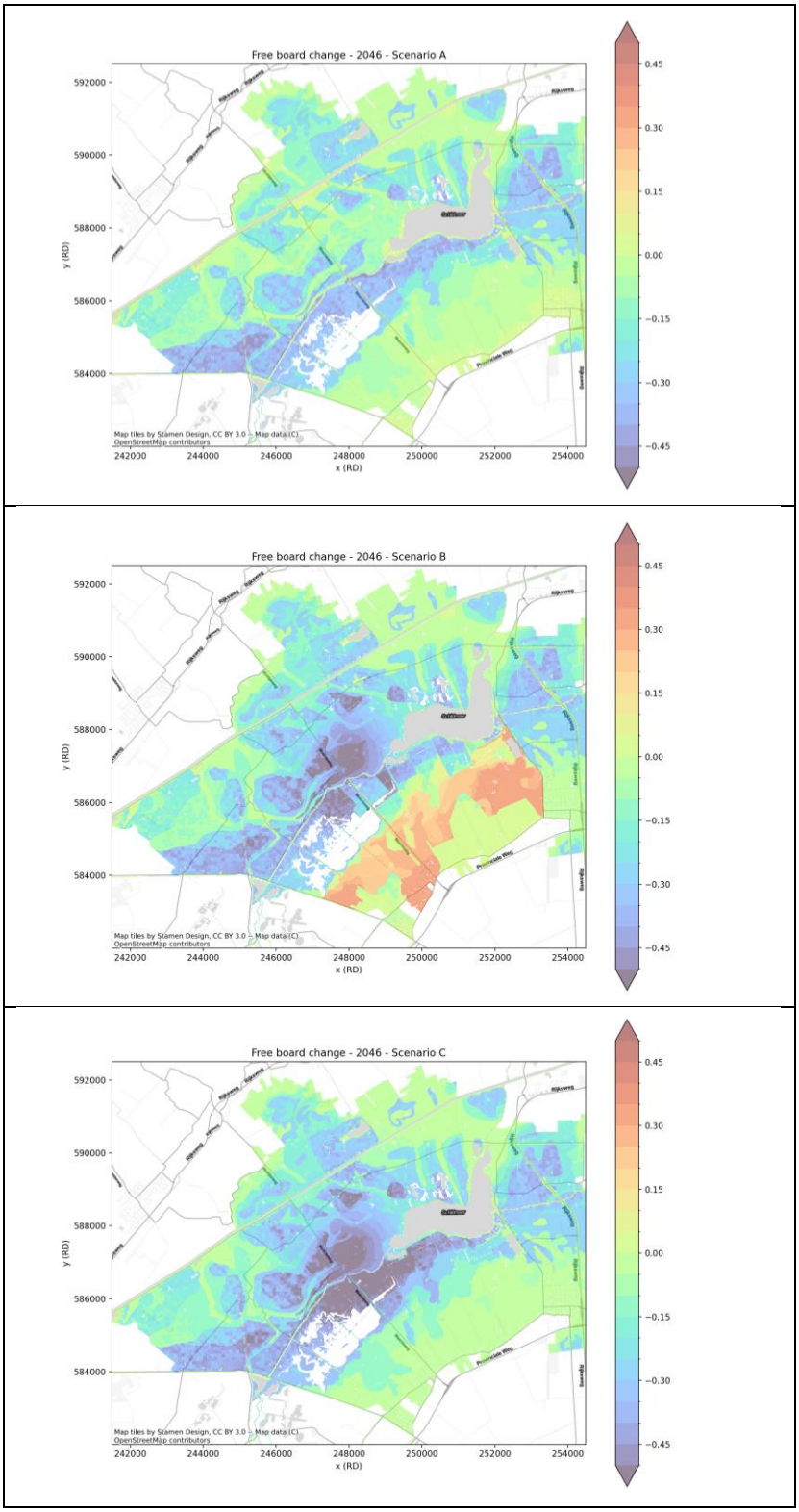

Figure 29 Scenarios A, B, C, freeboard change (summer water levels) in 2046 (in m).

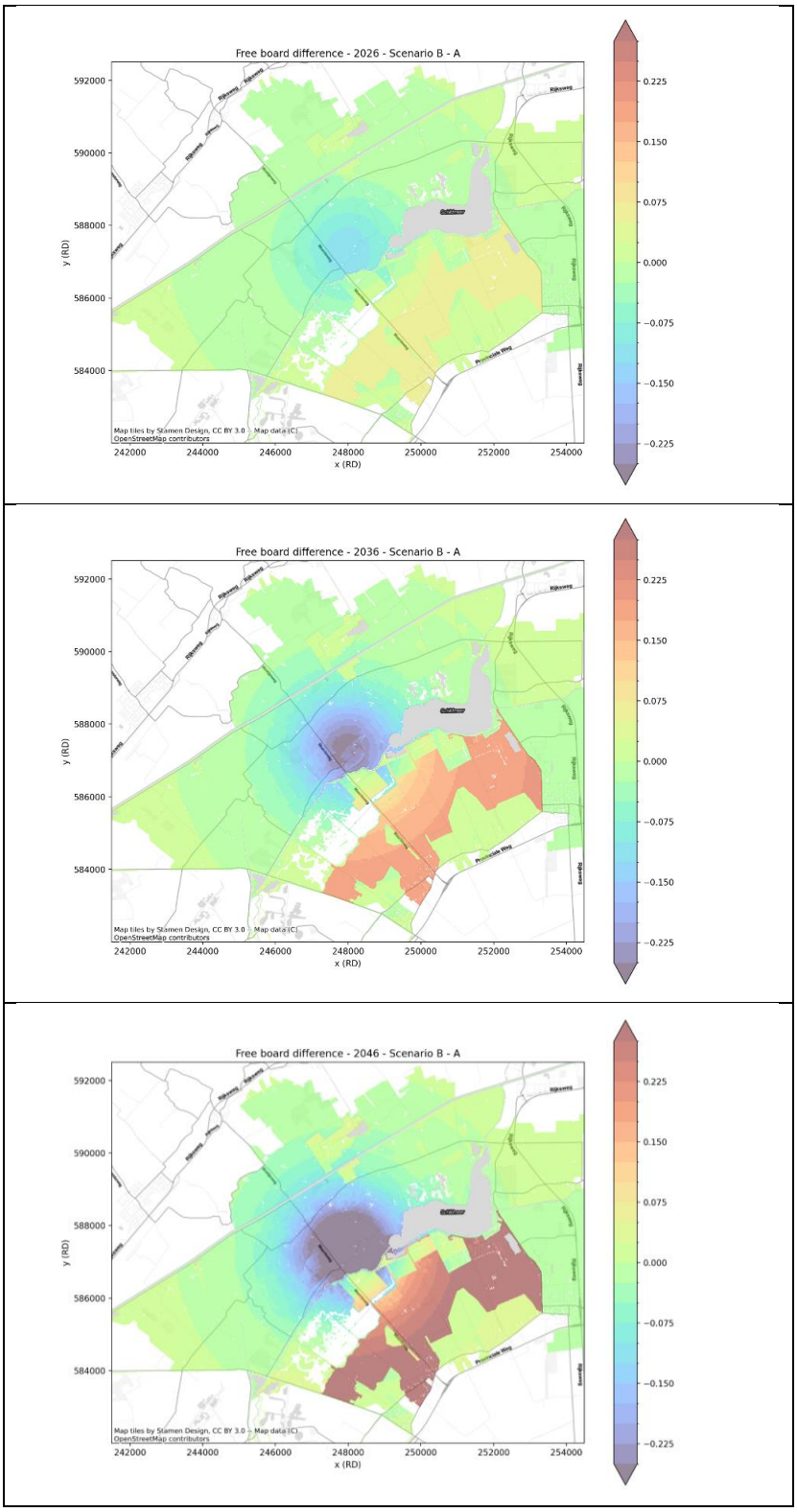

Figure 30 Deep subsidence effect on freeboard (B-A) (in m) (2026, 2036, 2046)

5.5 Discussion

5.5.1 Discussion of the graphical results

The calculated freeboard largely reflects the topography in the area (Figure 12), with lowest freeboard occurring in the central peat meadow zone which also includes lakes. The combined effects of deep and shallow subsidence cause reduction and increase of freeboard in different parts of the area (Figure 26). Reduction of freeboard predominates in the central peat meadow area. Freeboard increase is calculated for the sandy area to the southeast. The latter effect is solely related to the deep subsidence. Figure 27 shows that surface water levels decrease there. This is because the water-level controlling infrastructure of the associated fixed water level areas is located towards the centre of the subsidence bowl. Interestingly, water levels in the central and north western fixed water level areas decrease very little, reflecting that their water-level controlling infrastructure is located away from the subsidence bowl.
The independent shallow subsidence reflects the SSW-ENE zoning of predominant soils (Figure 28; top panel), with subsidence more than 0.2 m in the peat meadow area by 2046 and much less subsidence in the southeast and northwest. The relatively large shallow subsidence in the peat meadow area explains why significant freeboard reduction is also seen outside of the deep subsidence bowl in Figure 26. The deep subsidence both reduces and enhances the shallow subsidence (Figure 28; middle panel). Changes of 5 to 10 cm are calculated, which correspond to 20% to 30% of the independent shallow subsidence. The bottom panel of Figure 28 shows the changes that correspond to water management that would maintain original surface water levels (C-A). As expected, only reduction of shallow subsidence is calculated. In the centre of the subsidence bowl the changes are comparable to the values calculated for B-A (middle panel) because water levels decrease only very little there in scenario B (Figure 27).
Figure 29 compares the freeboard changes in 2046 for all three scenarios. The top panel again demonstrates that independent shallow subsidence provides a significant contribution. Figure 30 shows the separate effect of deep subsidence on freeboard for scenario B. If this were a real rather than a fictitious case, the maps could provide a useful basis to propose water management adjustments for mitigating these effects. Moreover, the tool could be used to analyse the efficacy of the proposed adjustments.

5.5.2 Comparison to the Nedmag-Veendam case

Figure 31 compares the key effects of the deep subsidence on the freeboard for the two case studies. The top panels show the total effect, including the effect of deep subsidence on shallow subsidence. The bottom panels show the separate effect of deep subsidence on shallow subsidence. Note that, in contrast to what the legend colours may suggest, the latter effect contributes as a reduction of freeboard change in the maps shown in the top panels.

The differences in the two top panels are apparent. In the Nedmag-Veendam case freeboard change is much less in the centre of the subsidence bowl. In the fictitious case, freeboard increase is more pronounced in parts along the rim of the subsidence bowl. These differences are mainly caused by the differences in the size and positioning of the fixed water level areas relative to the deep subsidence bowl and of the positioning of the locations of their water-level controlling infrastructure. The bottom panels illustrate that the contribution to freeboard change by the effect of deep subsidence on shallow subsidence – this is the indirect effect - is negligible for the Nedmag-Veendam case (but a few centimetres, corresponding to several percent) and locally more pronounced for the fictitious case (between 5 and 10 centimetres, corresponding to about 25% of the freeboard change). The generic meaning of the latter result is not fully explored at this stage. For instance, the spatial

extent of the shallow subsidence contribution shown in the bottom right panel still is rather limited due to the predominance of sandy soils in the south-eastern part of the area affected by deep subsidence.

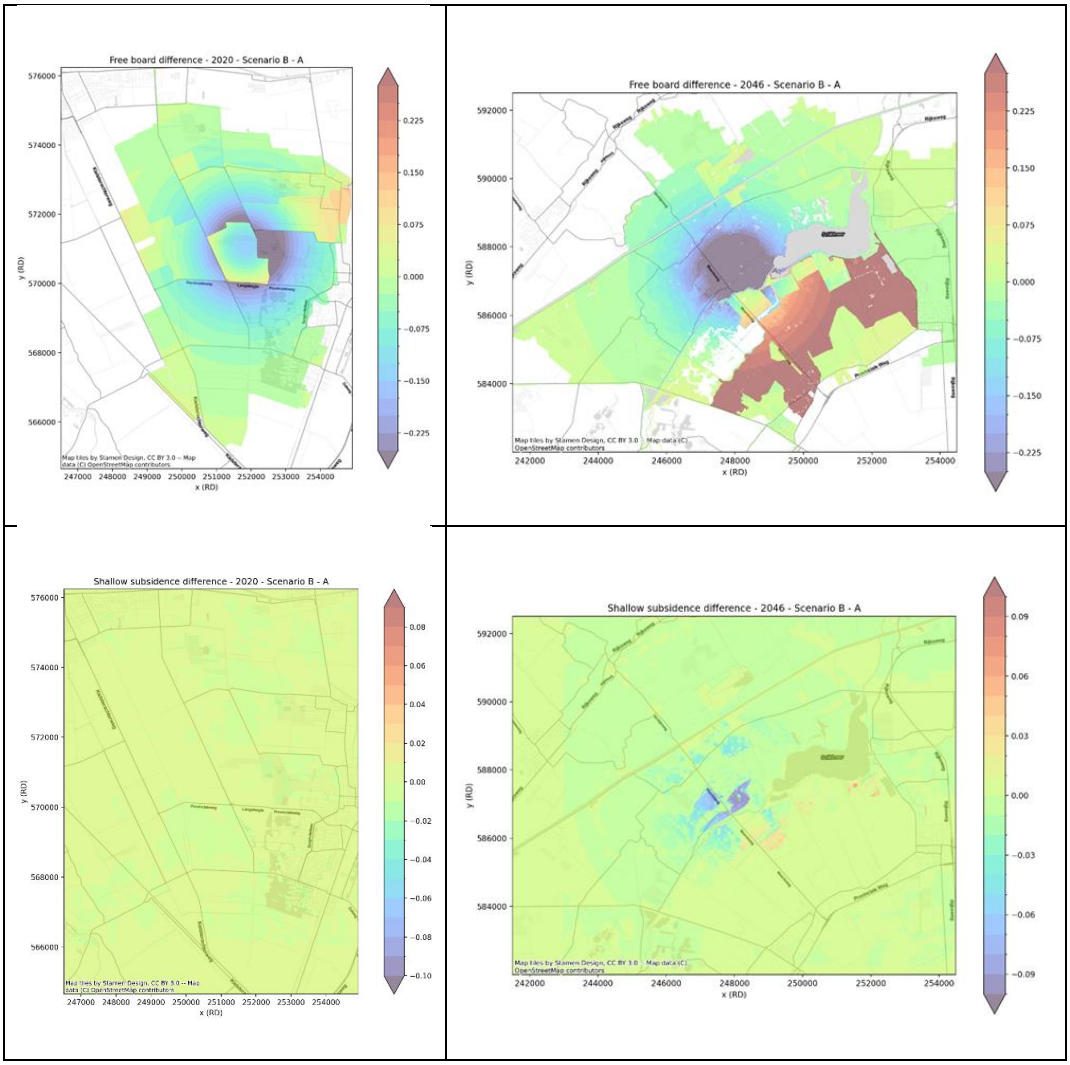

Figure 31 Comparison of the case 1 (Nedmag-Veendam, left panels) and case 2 (right panels) results (26 years after onset deep subsidence). Top panels: the effect of deep subsidence on freeboard (including the effect on shallow subsidence). Bottom panels: the effect of deep subsidence on shallow subsidence. Values are metres.

5.5.3 Remarks

- Less laborious. Compared to the hindcasting application of the tool for the Nedmag-Veendam case, the forecasting application of this second case study is considerably less laborious. The ‘actual’ voxel model does not need to be corrected for historic subsidence. Moreover, digital datasets for the actual conditions can be also be used without modification/reconstruction and are generally readily available.

- Less concerns regarding accuracy. The previous remark implies that several risks of bias that apply to hindcasting/reconstruction applications (4.5.3) need not be considered.

- Although not demonstrated here, the tool can be used in a design mode in which the efficacy of water management design options is quantified.

6 Discussion and recommendations

A tool has been developed which allows stakeholders to perform calculations to separate the effects of (1) deep (mining) subsidence, (2) water management interferences, (3) independent shallow subsidence, and (4) combinations thereof, on the temporal development of freeboard in fixed water level areas. Freeboard is a parameter that is of central importance in water management in the Dutch coastal plain. Two unique features of the tool are that (i) the impact of (1) and (2) on shallow subsidence are included and can be quantified separately; (ii) complex temporal scenarios can be efficiently analysed. The tool can be applied to analyse historic development (hindcasting) but can also be used in a predictive sense (forecasting). The latter can be useful to evaluate impacts of planned new mining activities.

This result goes a long way towards to goal of the project as formulated in 1.2. Below, first two practical aspects of the project goal are discussed. Then tool availability is briefly elucidated, and several recommendations are made.

6.1 Attribution of water management measures to deep subsidence

Does the tool allow to determine which part of water management measures is due to mining-induced deep subsidence?

The Nedmag-Veendam case included implemented water management measures. The tool allows calculation of the separate effect both of deep subsidence (B-A; Figure 18), and of the management measures (D-B; Figure 19) on freeboard, where:

Scenario A: Independent development in the absence of salt mining and water management, solely shallow subsidence.
Scenario B: Development with deep subsidence, but no interference by the water board since the start of the salt mining.
Scenario D: The actual historical development.

However, this does not suffice to unambiguously answer the posed question.

One path that could be pursued is to define the part of the water management measures due to deep subsidence in terms of the negative of the freeboard change induced by the deep subsidence: (A-B). The rationale is that if measures were taken that produce these freeboard changes – this cannot be perfectly achieved in practice -, these measures would nullify the effects of the deep subsidence (B-A). The residual freeboard change, that would then be unrelated to deep subsidence, would be (D-B)-(A-B) = D-A. A practical problem then remains to translate A-B freeboard change into concrete management measures. The simplest approach would be to infer the optimal surface water level change required at the times the actual water management measures were taken (e.g., 2001, 2006, 2012, 2021 for the Nedmag-Veendam case) and for the fixed water level areas and infrastructure at those times. These required ‘water level changes due to deep subsidence’ could then be compared to the actual water level changes that were implemented. This comparison could indicate that at a certain time x% of the implemented water level change was required to address the effects of the deep subsidence. However, this approach does not allow judgement which part of the reorganization of fixed water level areas and infrastructure was required to mitigate the effects of the deep subsidence.

A second path that can be envisaged, is that the tool could be used in a 'redesign' mode in which, in hindsight, water management measures are sought that are optimised in some sense, for instance both in terms of freeboard and costs. To redesign solely for deep subsidence effects, the calculated freeboard development would have to be corrected for independent subsidence (scenario A). This path would provide an approach to come up with a minimal cost-estimate that may be associated with the deep subsidence that could be related to the costs of the actual measures taken.

6.2 Authoritativeness

Is the tool authoritative?

Authoritativeness of the tool is something that cannot and should not be determined by its producers. Stakeholders such as EZK, the water boards (or STOWA), and possibly other knowledge institutes like TNO could be more appropriate parties to assign such a qualification formally or informally. In practice, the qualification may be applied when a tool becomes (widely) used for decision making, without being challenged. None of these aspects are currently at issue. However, the following can be said that bears on a potential judgement about authoritativeness.

Atlantis is a key component of the tool. Existing products generated with Atlantis, such as the national subsidence prognosis maps that are published by the Climate Adaptation Services foundation in The Netherlands, can be regarded authoritative in the sense that the products meet the quality requirements of the various users (predominantly provinces) for their decision making. Authoritativeness is primarily assigned in the trust that the products are based on knowledge, and datasets based on open source data, that are state of the art and progressively improved. The products are not 'truth', but the best possible estimates. For the present tool, stakeholders together with the experts need to judge if this suffices for the application for which the tool is used and for the decisions that are to be made.

Shallow subsidence predictions with Atlantis are not formally validated due of lack of independent historic subsidence records of sufficient accuracy and associated records of groundwater conditions. The only pertinent monitoring data are from a few locations in the peat meadow region in the provinces of Utrecht and Zuid Holland. These data were used to calibrate the subsidence component due to peat oxidation (Erkens et al., 2021). The validity of the compaction calculation[9] associated with the small load changes due to groundwater level changes is currently addressed in the framework of the research program 'Regio Deal Bodemdaling Groene Hart'. Also, sensitivity analyses are performed to get a better handle on the uncertainty of the overall predictions. Otherwise, the validity and accuracy of the subsidence predictions basically rely on expert judgement of (shallow) subsidence experts. Presently, an overall guideline value of 50% is deemed appropriate for uncertainty of prediction (Erkens et al., 2021). Although this uncertainty of modelled shallow subsidence is rather high, the significance of this uncertainty for the present tool is limited. Focus of a validity and accuracy judgement for outcomes of the present tool would concern the estimates of effects of deep subsidence in terms of freeboard change. Shallow subsidence (Atlantis) is but a relatively small part of that effect. Although not directly mapped in the case studies, the contribution of shallow subsidence (due to coupling) in the effect is estimated to be on the order of several percent for the Nedmag-Veendam case and up to about 25% for the second, fictitious case. The 'direct' contribution to the freeboard change via surface water level change – this is handled by the pre- and post-processing (Figure 8), therefore, deserves

[9] Authoritative methodology used in Dutch geotechnical practice

greater attention. The validity of the approach is deemed very high. The validity and accuracy of the calculation outcomes as a representation of what happened in the real world (scenario D in the Nedmag-Veendam case), strongly depends on the validity and accuracy of the inputs used in the calculation, and of judicious/careful tool use. Options for validation of calculated results are not obvious. However, checks on plausibility/consistency of outcomes are possible and essential ensure meaningful results.

6.3 Tool availability and expected use

The tool consists of Atlantis and a set of pre- and post-processing scripts.
Atlantis is available through Gitlab (https://gitlab.com/deltares/subsidence/atlans.jl)[10]. The pre- and postprocessing scripts of the new tool can similarly be made available on request. Availability applies to all interested parties.

The tool and preliminary results of the Veendam case were presented to the northern waterboards September 14, 2022. The waterboards expressed interest in the tool and the outcome of the case study. In response to the question if they would also be interested to apply/use the tool themselves, the waterboards indicated that they would be more inclined to ask knowledge institutes or qualified consultancies to perform desired analyses with the tool.

6.4 Recommendations

The following recommendations are made.

1. The following aspects merit further documentation:
   - The relative contribution of shallow subsidence in the effect of deep subsidence on freeboard change. The two case studies that were conducted thus far are insufficient to support generic conclusions.
   - The sensitivity of effect(s) for the positioning of the deep subsidence relative to the positioning of fixed water level areas and infrastructure (case study 2).

2. It is recommended to organize one or more workshops with stakeholders to (further) discuss and clarify the merits of the tool. Key topics would be:
   - Correctness of and explanations for the inference for the Nedmag-Veendam case that effects of water management substantially differs from effects required to offset the deep subsidence effects.
   - Approaches to attribute parts of implemented water management measures to deep subsidence via freeboard calculations (6.1).
   - Usefulness of the tool for impact assessment and water management design.
   - Possibilities for validation
   - Further potentially interesting case studies.

   The first topic would have to be discussed with the relevant water board. For the other topics a broader range of water boards, STOWA, and the Commissie Bodemdaling would be valuable stakeholders to consult.

[10] A comprehensive user manual is not (yet) available.

7 References

Arcadis (2021). Toelichting peilbesluit 1e schil Electraboezem. https://www.noorderzijlvest.nl/_flysystem/media/toelichting_peilbesluit_elecrtraboezem_1ste_schil.pdf

Bootsma, H., H. Kooi, G. Erkens (2020). Atlantis, a tool for producing national predictive land subsidence maps of the Netherlands. Proc. IAHS, 382, 415–420, https://doi.org/10.5194/piahs-382-415-2020

[1] Erkens, G., M.J. van der Meulen, H. Middelkoop (2016). Double trouble: subsidence and CO2 respiration due to 1,000 years of Dutch coastal peatlands cultivation, Hydrogeology Journal, https://link.springer.com/article/10.1007/s10040-016-1380-4

Erkens, G., H. Kooi, R. Melman (2021). Actualisatie bodemdalingsvoorspellingskaarten. Deltares report 11206724-002-BGS-0001.

Grontmij (2005) Bodemdaling waterschap Hunze en Aa's; Beleid en Techniek. Report provided by the water board.

Kooi, H., J.C. Landwehr, R.J. Stuurman, J.J. van Meerten, O. Levelt, M. Korff (2021) Indirects schade-effecten van diepe bodemdaling en -stijging bij het Groningen gasveld en gasopslag Norg. Deltares report 11207096-002-BGS-0001.

van de Ven, G.P. (1993) Leefbaar laagland, geschiedenis van de waterbeheersing en landaanwinning in Nederland, uitgeverij Matrijs, 4e druk (1996).

Witteveen en Bos (2004). Onderzoek waterhuishoudkundige maatregelen naar aanleiding van bodemdaling NEDMAG. Report VDM20-1.