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Subsidence

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ABSTRACT

Subsidence is a complex problem, both in a technical sense and in governance. This is particularly the case in the Netherlands, which is a low-lying and densely populated country where various causes of subsidence interfere with each other. Coping with subsidence in the Netherlands started already 1000 years ago. This long history of subsidence, however, along with its slow manifestation, has resulted in a tendency to adaptation rather than mitigation. There is a growing awareness that this focus on adaptation is actually excluding alternative solutions. Potentially cheaper or more effective options may be unknown and not even considered. At the same time, Dutch society is becoming more aware of the severity of human-induced subsidence as it is one of the most prominent current geological hazards. What is needed therefore, is a sound knowledge base facilitating the exploration of solutions outside the traditional way of thinking. Here we present the different knowledge and governance issues at stake. We start with the description of the natural processes that cause subsidence, and the human-induced causes like groundwater management and exploitation of deep geological resources. Then we elaborate how subsidence can be estimated from measurements. We pay specific attention to the utilization of modern ensemble-based techniques to integrate multiple models and data. The objective is to avoid deterministic predictions and instead produce a range of subsidence forecasts with confidence intervals that are in agreement with observational data and their uncertainties. Finally, we describe how technical knowledge can be integrated in decision making by estimating the costs and benefits of different scenarios, thereby offering an array of options for decision makers. Subsidence will keep playing a role in shaping the future of the Netherlands. Human-induced subsidence will continue with new subsurface activities directed towards the energy transition. Incorporating the grim sea level rise predictions, the issue becomes even more serious. It is therefore of paramount importance to maintain and further develop the current knowledge position and to develop proactive mitigation activities.

<< A row of houses built at the end of the 19th century along the Oostsingel in Schiedam (west of Rotterdam). The deformed facades are caused by subsidence. Photo: Vincent Basler Fotografie.

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Introduction

The Netherlands is a country in the delta of Rhine and Meuse, with low elevation, dense population, and intense surface use. A movement of the surface downward with respect to the ever rising sea level therefore poses considerable risks for flood safety and has economic repercussions. Some places in the Netherlands are moving upward by both natural and anthropogenic processes, but in many parts of the country the surface has been, and still is going down. Subsidence as a result of human activities commenced locally as early as the Late Iron Age (Vos, 2015). Extensive and systematic human-induced subsidence started roughly 1000 years ago with intensifying land cultivation. The population was forced to react to subsidence with innovative measures: canalization, embankments, wind-driven and mechanical artificial drainage, giving up land, changing land use, and reconstruction of infrastructure in cities (Fig. 23.1). These interventions were focused on short-term adaptation to the consequences of subsidence. The interventions never resulted in decreasing subsidence rates. In fact, some interventions, for instance those that enabled drainage of soft soils, even increased the subsidence.

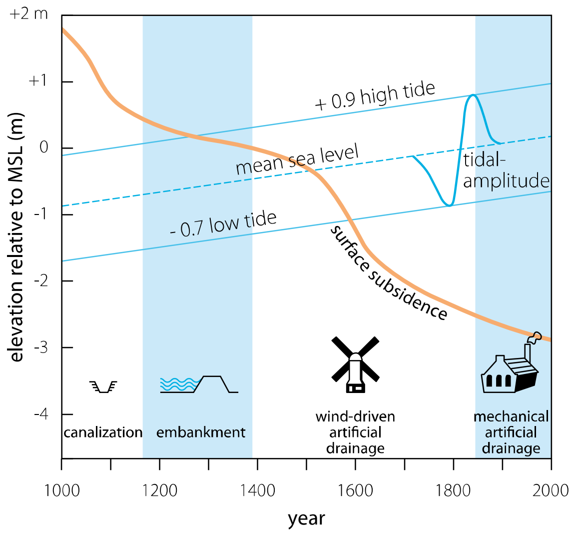

Figure 23.1. Cartoon of 1000 years of subsidence in the coastal zone of the Netherlands showing the response of the Dutch to ongoing subsidence since drainage of the coastal and deltaic areas started (modified after Van de Ven, 1993). Some of these responses, e.g. the construction of windmills and mechanical drainage, have prolonged and further intensified subsidence.

The impact of subsidence in the Netherlands is slowly being unravelled and quantified (Van den Born et al., 2016). At the same time, over the last decades scientific research has contributed to an increased understanding of the processes leading to subsidence. Technological development in measuring techniques and the ongoing development of numerical predictive models have further enhanced the capability to quantify subsidence. As an example, it has become clear that the greatest contribution to subsidence in the Netherlands is human-induced and thus could theoretically be avoided. Subsidence will therefore continue until an effective policy to reduce the rates has been developed and deployed. These developments have sparked a discussion in the Netherlands on whether the traditional adaptive approach to ongoing subsidence is still the most optimal one. There is a societal demand for conscious decision making and a long term subsidence strategy.

A successful subsidence strategy requires a broad societal support and a justified confidence in its outcome. It is important to understand the processes leading to measured subsidence and to be able to quantify them. A critical check in this regard is, of course, the agreement between modelled surface movements and the movements estimated from measurements. Moreover, movement measurements need to be used to improve the knowledge of the subsidence processes and the model parameters. Such knowledge is required to define economic and effective governance. Finally, to close the loop, feedback is required by monitoring the policy results and incorporating lessons learnt in an ongoing process. Such a policy cycle is essential to ensure continual learning and improve the effectiveness of measures to counter subsidence.

This chapter summarizes the current state of knowledge about subsidence in the Netherlands. The processes causing subsidence, both natural and human-induced, are at the basis of this knowledge. Therefore, we start with a summary of the next two sections. Natural causes of surface movement are compaction, isostasy and tectonics. The most important human-induced causes of subsidence in the Netherlands are groundwater regulation and extraction of deep natural resources like gas and salt. Besides subsidence, uplift also occurs locally. The largest uplift is observed in Limburg, where the hydraulic heads are increasing since the abandonment of the coal mines. The fourth section explores the ways surface movement can be estimated from measurements. The classical levelling methods are described as well as modern satellite techniques. The next section presents the methods that combine data and models to increase the quality and accuracy of understanding. Stochastic methods are at the core of many such methods, since they provide efficient ways to not only provide best estimates, but also confidence ranges of parameter values and model predictions. Such knowledge is critical input for decision making, and we subsequently outline the current practice and effective ways forward. We consider a policy cycle that integrates measurements, understanding, models, economic considerations, governance and monitoring in a large feedback loop as the optimal approach. The final section presents a panoramic view on what is currently available and what we can still expect to come.

Natural subsidence processes

Natural subsidence occurs independently of human influence and is an expression of geological deformation processes. With its location on the southern margin of the North Sea Basin with its thick succession of Mesozoic and Cenozoic sedimentary deposits, natural land motion has played a central role in the geological history of the Netherlands. *Tectonic*, *isostatic* and *compaction* contributions are commonly distinguished (Kooi et al., 1998; Fokker et al., 2018). Tectonic subsidence is the expression of faulting and folding within the crust and cooling of the lithosphere. Isostatic subsidence is caused by changes in buoyancy equilibrium of the lithosphere-mantle system and involves the flow of mantle rock. Compaction refers to compression and porosity reduction of sedimentary layers. Long-term (2.5 Ma-present) average subsidence rates for the individual components were inferred by Kooi et al. (1998) using backstripping of Cenozoic stratigraphy, yielding low subsidence rates on the order of 10^{-2}-10^{-1} mm/yr (Fig. 23.2). These rates are presumed to be relative to the centre of mass of the earth.

Figure 23.2 provides a reasonable estimate for the long term, but magnitudes and spatial patterns of historic or present-day tectonic subsidence could be quite different over shorter time periods. To assess the rates over shorter, more recent time periods, other methods and considerations are generally needed. Tectonic deformation, for instance, tends to be irregular in space and time when faulting is involved. Studying detailed stratigraphic records in the Roer Valley Rift System, Houtgast & Van Balen (2000) recognized periods of high and low relative displacement rates on parts of the Peel Boundary Fault and the Feldbiss Fault zones during the Quaternary. The 1992 'Roermond-earthquake' further attests to natural fault activity in the Netherlands in very recent times.

To estimate present-day natural compaction in the western coastal provinces, Kooi (2000) modelled delayed pore-water expulsion and associated compaction (consolidation) of low-permeable Cenozoic clay layers in response to Holocene sediment loading. This process differs from the backstripping technique used for the long-term subsidence which assumes equilibrium compaction based on porosity-depth relationships. The latter approach neglects Darcian flow and thus implies that only present-day sediment loading would cause present-day compaction. Inferred current rates generally are higher than the long-term compaction estimates of Figure 23.2, of up to 0.12 mm/yr to the west of Rotterdam. The younger dune system represents a geologically recent prominent load. Kooi (2008) calculated that a current subsidence rate of 2 mm/yr could theoretically exist in parts of the western coastal provinces.

The long-term isostasy component obtained by backstripping assumes equilibrium of the lithosphere-mantle

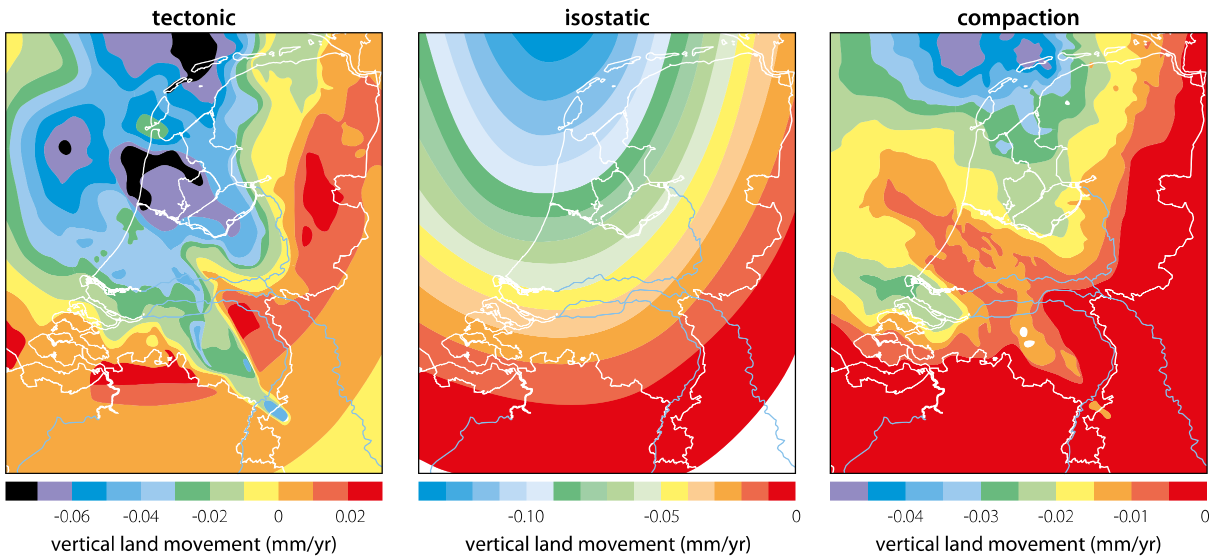

Figure 23.2. *Separation of tectonic, isostatic and compaction contributions to vertical land movement for the Quaternary (ca. 2.6 Ma – present) constructed by 3D back-stripping of Cenozoic stratigraphy of the Netherlands and the Southern North Sea Basin (modified after Kooi et al., 1998). Negative values indicate subsidence.*

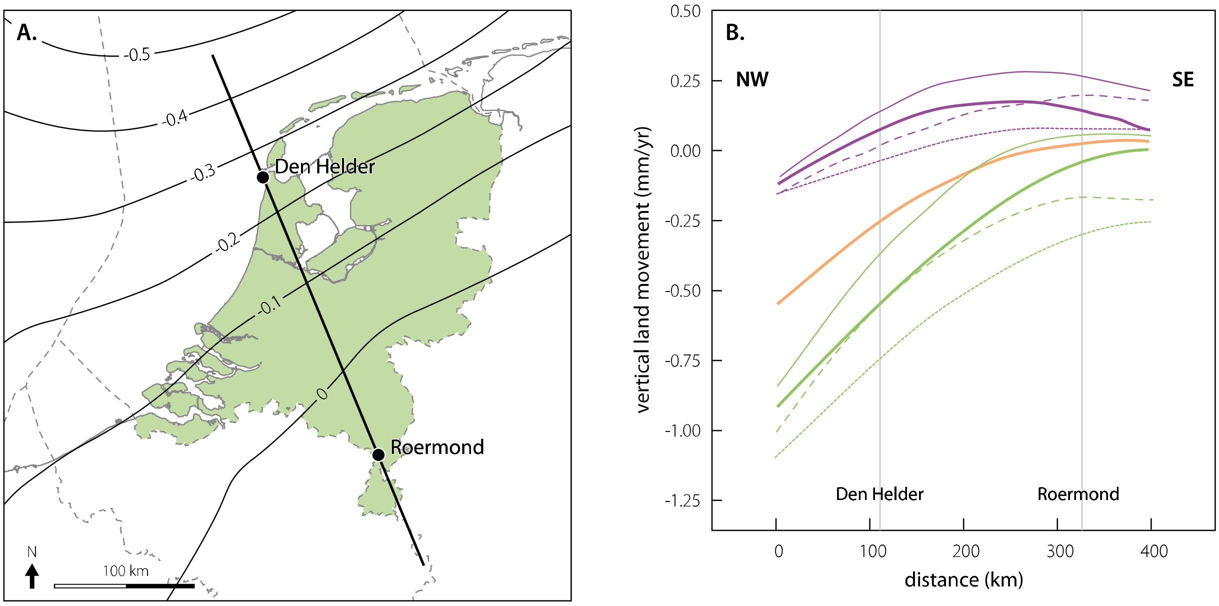

Figure 23.3. Current isostatic vertical land movement (in mm/yr) from GIA modelling of relative sea-level data (modified after Kooi et al., 1998). a) Result from the best-fit earth model. b) Results for the profile in the left panel for the best-fit earth model (orange line) and other earth models that provide a good fit to Fennoscandian relative sea-level data.

system in response to the load of Quaternary deposits. By contrast, current isostatic vertical land movement in the Netherlands is dominated by the dynamic response to changes in ice and water mass on the surface of the earth since approximately the Late Glacial Maximum, ca. 20 ka BP (Kooi et al., 1998; Vermeersen et al., 2018). Various Glacial Isostatic Adjustment (GIA) models that describe the dynamic lithosphere-mantle system response to mass changes on ice-age timescales (resolution ~1 kyr), and that are constrained by relative sea-level data in the central and northern North Sea, indicate that the present isostatic subsidence component includes a tilting of the onshore part of the Netherlands in a northwest to northerly direction (Fig. 23.3; Kooi et al., 1998; studies discussed by Vermeersen et al., 2018). This is consistent with independent Holocene relative sea-level reconstructions from Belgium to the Wadden Sea (Koster et al., 2017; Meijles et al., 2018) which show subsidence rates that increase towards the north. However, the predicted present-day tilting rate and the absolute vertical movement rates are rather uncertain and vary significantly within and between studies, depending on the adopted ice-sheet reconstruction, lithosphere rigidity and mantle viscosity (Kooi et al., 1998; Vermeersen et al., 2018). Riva et al. (2017) showed that post-1900 melting of glaciers and the Greenland and Antarctic ice sheets cause an additional elastic vertical uplift of several tenths of mm/yr. This component of land movement, which varies temporally over timescales less than a decade is not included in the GIA models.

Human-induced subsidence processes

Human-induced subsidence (and uplift, which we regard as ‘positive’ subsidence) processes are primarily related to the extraction and injection of subsurface substances and the results are largely irreversible. Subsidence can be considered as an unwanted side effect, as these processes themselves are not intended to cause changes in surface elevation.

Human activities that cause subsidence can in general be divided into deep (ca. >500 m), middle-deep (ca. >20 m and <500 m) and shallow activities (ca. <20 m). The deep and middle-deep depths are roughly corresponding to depth intervals of hydrocarbon extraction, geothermal production and salt mining, groundwater pumping and heat storage (Fig. 23.4). Near-surface activities can be many: phreatic groundwater lowering, excess overburden by man-made ground, peat mining, and others.

While subsidence is the accumulation of effects of different origin, both anthropogenic and natural, it is the total effect of surface movement that is of interest to the societal stakeholders. In the following, we will discuss deep, middle-deep, and shallow sources of subsidence.

Deep sources of subsidence

Hydrocarbon extraction

Gas or oil production involves the extraction of hydrocarbons from a reservoir. As a result, the pore pressure drops. The net forces between the sand grains constituting the matrix increase, and the rock will compact. This mechanical response is propagated to the surface and causes subsidence (Geertsma, 1973; Fokker & Orlic, 2006; Fjaer et al., 2008). Models are deployed to quantify this behaviour. Such models start with assessing the pressure distribution of the reservoir fluid, which is controlled by the production profiles and the reservoir flow properties. The outcomes are fed into geomechanical models that describe the mechanical response upon pressure changes. Here, the complete subsurface must be considered: the reservoir compaction, the overburden response as well as the basement properties influence the resulting subsidence. Compaction at a certain location at the reservoir level is distributed over distances at the surface comparable to the depth of the source. Complications can occur due to several factors. When aquifers that are connected to a reservoir are also depleted, they also compact and cause subsidence (Fokker et al., 2018). Furthermore, the mechanical behaviour of the subsurface may be nonlinear or viscoelastic, which results in a time-dependent effect and the persistence of the subsidence even when the activity that caused compaction has ceased (Marketos et al., 2016). This time dependence is difficult to isolate when production is still ongoing. In addition, other processes like water or gas injection can interfere (Hettema et al., 2002). Modelling and forecasting the subsidence, therefore, is not trivial. An important step in quantifying subsidence causes is the matching of modelled subsidence and subsidence estimated from measurements. A section is dedicated to this later in this chapter

Geothermal energy production

Geothermal energy production also involves pumping of

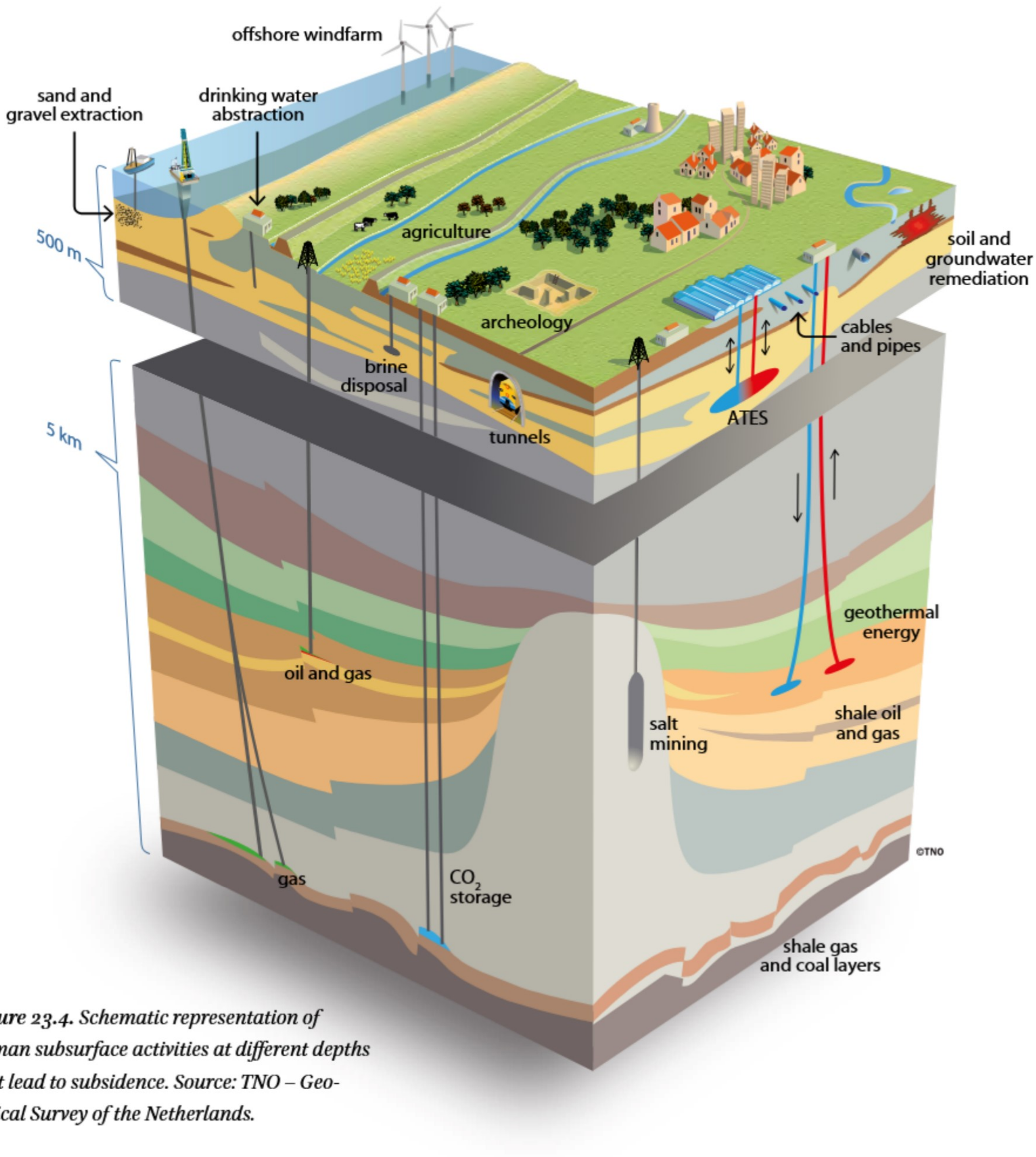

Figure 23.4. Schematic representation of human subsurface activities at different depths that lead to subsidence. Source: TNO – Geological Survey of the Netherlands.

fluids, viz. water or steam into and out of the subsurface. This may also be accompanied by pore pressure changes, compaction and associated surface movement. An additional subsidence effect of geothermal energy production is caused by the heat that is extracted. Even if the pressure is kept constant by injecting as much water as is being produced, progressive cooling around the injector wells may cause substantial thermoelastic stresses resulting in compaction of the subsurface strata and associated subsidence (Grant & Bixley, 2011). Modelling the subsidence effect of geothermal energy production proceeds along similar lines as modelling the effect of hydrocarbon production, with the addition of thermoelastic effects.

Salt mining

The process of salt mining is described by Groenenberg et al. (2025, this volume). Water is injected into the rock salt layers, salt dissolves and a cavern filled with brine develops, from which the saturated brine is produced. The visco-elastic mechanical behaviour of the rock salt causes cavern convergence as the pressure in the cavern is smaller than the stress in the formation around it. The cavern boundaries move inwards, and the surface subsides. Even after cessation of the salt production, this driving force may cause continued subsidence. In addition, the temporal behaviour of the surface subsidence and the shape of the subsidence bowl may be complicated functions of time and space, due to the complex constitutive rock salt behaviour (Breunese et al., 2003). In the recent past, shallow salt mining has also resulted in accelerated subsidence leading to overburden collapse, with sinkholes as a result (see Groenenberg et al., 2025, this volume and references therein).

Coal mining

In the south of the province of Limburg, mining activities caused local depressions above the mined coal seams, 50 to 200 m in diameter and 0.5 to 10 m deep. Most of these depressions were formed during the peak of coal mining in the 20th century. After closure, when the groundwater was allowed to rise, land rising has been observed (Caro Cuenca et al., 2013; Zhao & Konietzky, 2021). However, also some depressions were formed in the decades after the closing of the mines (Vis et al., 2020). A quantitative description based on first principles is not available, but it is clear that their formation is due to sinkholes related to coal mining that are formed by a combination of rock deformation, groundwater- and sediment flow and collapsed mine roofs. In urban areas this form of subsidence is hazardous, because the formation of sinkholes can suddenly accelerate, resulting in foundation instability and therefore collapse of buildings. This is exemplified by a near-collapse of a shopping mall in the city of Heerlen in 2011 (Chang & Hanssen, 2014). Natural sinkholes in Upper Cretaceous chalk are discussed in Van Lochem et al. (2025, this volume).

Middle-deep sources of subsidence

Groundwater abstraction

Sandy aquifers at depths between tens to hundreds of meters below the surface are an important source of freshwater supply for the Netherlands. These aquifers are confined by clayey and sometimes peaty aquitards. Aquifer water pressure drops if more groundwater is extracted than is being replenished by inflow into the aquifer. These pressure drops prograde into bounding aquitards, resulting in aquitard compaction by increasing effective stress and creep processes, and consequently in subsidence. Due to a lack of dedicated subsidence monitoring, knowledge of groundwater-abstraction-induced subsidence in the Netherlands is extremely poor and mostly based on theoretical calculations. By using InSAR data, Kooi (2018) found that subsidence rates in the surroundings of De Lier (province of South Holland) may have locally increased by about 5 mm/yr in the period 2003-2011 due to groundwater abstractions that supplied greenhouses with irrigation water. The same study also showed that model predictions of the subsidence are fraught with uncertainty since the subsidence depends not only on the distribution of compressible clay and peat layers in the Holocene cover layer, but also on the details of the vertical permeability distribution within the Holocene strata. Both of these are variable and uncertain. Another example, using forward modelling of subsidence rates based on groundwater abstraction data and geomechanical schematization of stacked sandy aquifer systems at Nijverdal and Boerhaar (province of Overijssel), reported subsidence rates of 0.2 to 1.6 and 0.4 to 2.3 mm/yr respectively (Valeda, 2021). The upper 100 m of both sites primarily consist of sand, however at Boerhaar a fine-grained aquitard is present at 40 m below the surface. Compaction of this aquitard explains the difference in compaction rates between the two sites.

Subsidence by aquitard compaction is local and could lead to damage to infrastructure and the built environment when groundwater abstraction sites are located within or near domestic areas. This form of subsidence can be mitigated or even partly reversed with managed aquifer recharge, i.e. by pumping water back into aquifers. Water injection coeval with abstraction, for instance, is commonly used during construction works in the Netherlands. Furthermore, subsidence by groundwater abstraction partly reverses when an abstraction site is abandoned, and natural water pressures are restored. Such elastic rebound is currently being monitored in the northern part of Delft, where century-long industrial groundwater abstraction was progressively reduced and even terminated in recent years.

Aquifer Thermal Energy Storage

Aquifer Thermal Energy Storage (ATES) refers to temporary warming of aquifer groundwater at depths less than 500 m by residual heat from e.g. industry, solar thermal collectors, and geothermal systems. The storage is primarily conducted during the summer season, whereas the warm water is being used to heat-up buildings during the winter season. Furthermore, during the winter season, cold water is stored in aquifers to cool buildings during summer. Conventional ATES involves temperature changes in the subsurface typically ranging from 5-10°C to 15-18°C (Rostampour et al., 2019). Efficiency considerations are currently leading to the development of storage at higher temperatures, up to 90°C (Drijver et al., 2019). The associated thermal contraction and expansion of aquifers, which potentially lead to measurable subsidence or uplift at the location of the injection well and surrounding areas are currently subject of investigation.

Shallow sources of subsidence

Phreatic groundwater-level lowering

The coastal plains and inland peaty and clayey areas of the Netherlands are subsiding on a regional scale because of lowered phreatic groundwater levels. Surface level oscillations are superimposed on the net subsiding trend, as seasonal fluctuations in phreatic groundwater level and soil moisture cause stress changes and hence elastic responses in the upper part of peat layers. Phreatic groundwater levels have been kept at artificially low levels for centuries to enable agriculture and urbanization, and to prevent the area from inundation in general. In pristine conditions groundwater levels in coastal plains gradually grade towards mean high sea level or just above, keeping the substrate waterlogged. But when areas are drained, groundwater levels are artificially low and the exposure of peaty and clayey substrates to the atmosphere make them vulnerable to oxidation and shrinkage processes, while lowering of hydrostatic pressures induces various mechanical processes.

Aeration of peat or organic substrate causes the breakdown of its organic material by microbial communities of bacteria, archaea, and fungi (Stephens & Johnson, 1951). This results in degradation of peat layers, greenhouse gas emissions, and subsidence by volumetric loss (Neller, 1944). This process is irreversible. Van den Akker et al (2008) calculated an average emission of 2.26 t CO_2 $ha^{-1}yr^{-1}$ for each mm of subsidence in the Zegveld area. This is a general number for peat in the Netherlands and it only addresses degradation of organic carbon above the groundwater table. The number has since been used in greenhouse gas emissions reporting (e.g. Arets et al., 2019).

Aeration of clayey substrate results in shrinkage by loss of water captured between platy clay particles. In submerged conditions, the negatively charged surfaces of the clay particles adsorb water by attracting dissolved cations (Barciela-Rial et al., 2020). This water is expelled during periods of evaporation, resulting in shrinkage of the clay and thus strong volumetric loss. This is mostly irreversible, but may be partly countered by swelling processes if a clayey substrate is saturated again. An example of this process is the reclaimed province of Flevoland. There, shrinkage of the clayey substrate caused a surface elevation lowering of 1 to 2 m (Fokker et al., 2019).

Hydrostatic pressure lowering in peaty and clayey substrates leads to consolidation by increasing effective stress, consequential pore space reduction, volumetric loss and subsidence. This process is partly reversible when the effective stress decreases again through an increase of the hydrostatic pressure. Furthermore, these stress changes result in creep processes that compact clayey and peaty substrates superimposed on the compaction related to hydrostatic pressure reduction. Creep comprises the visco-plastic rearrangement and flow of soil particles.

Quantification of expected surface movement can be achieved using soil-mechanics models similar to those used for the quantification of subsidence due to deep causes. Using an estimate of the groundwater level development they calculate a volume loss. In comparison with the deep-seated sources, a simplification is that the connection to surface movement is immediate. The soil-mechanics models, however, are rather complicated. They contain an elastic contribution, but also irreversible, non-elastic compaction and creep, shrinkage, and oxidation. Models for these phenomena often depend heavily on laboratory results and field tests of short duration or tests with different goals than long-term predictions. As a result, it is often difficult to interpret data in the context of modelling results (Fokker et al., 2019).

Anthropogenic brought-up soil

Anthropogenic brought-up soil has been used for centuries in the Netherlands to increase the load bearing capacity of peaty and clayey strata, in order to make these soft substrates suitable for supporting infrastructural works and construction activities in general (Van Laarhoven, 2017; Van Asselen et al., 2018). In historic times, brought-up soil consisted of locally derived sods and debris. Initially, the emplacement of anthropogenic brought-up soil on peaty and clayey substrates induces compaction of underlying strata by increasing effective stress, which results in subsidence (Fig. 23.5; Koster et al, 2016). Therefore, such areas needed the periodic addition of anthropogenic soil to compensate for experienced subsidence (Koster, 2016) and, consequently, many historic urban centres in the coastal plains have meters thick strata of anthropogenic brought-up soil that have been compacting underlying

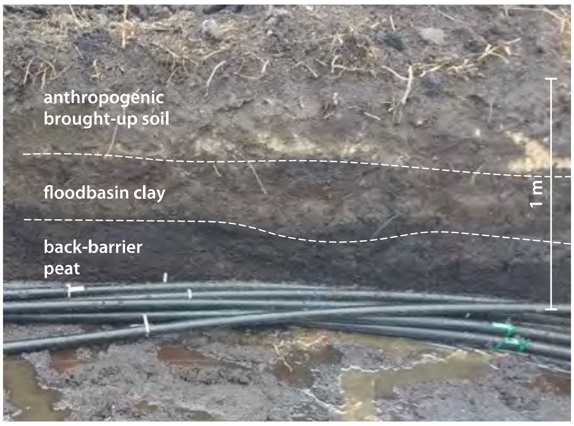

Figure 23.5. *Example of anthropogenic brought-up soil in the urbanized area of Amsterdam (from Koster et al., 2018). The overburden of the brought-up soil causes underlying peaty and clayey substrate to compact and leads to subsidence.*

peaty and clayey substrates. However, a complex interplay results: effective stress changes by additional overburden have pushed the peaty substrates sometimes meters below local phreatic groundwater levels, thereby hampering oxidation and shrinkage processes, and thus protecting soft substrates from further deterioration (Koster et al., 2018).

Since the industrial revolution, sand is the prime aggregate used to increase load bearing capacities of natural deposits, especially in areas with a peaty substrate (Van der Meulen et al., 2007). Sand has a relatively high specific weight and causes substantial surface elevation lowering when brought-up. Depending on the spatial variability of the substrate this could cause strong differential subsidence on a local scale, potentially resulting in damage to buildings and infrastructure (Nicodemo et al., 2020).

Peat mining

Substantial surface elevation lowering took place between the 12th and late 19th century due to mining of peat bogs for fuel (Van Dam, 2001). Approximately 34% of the volumetric loss of the natural Holocene peaty substrate is due to these activities (Erkens et al., 2016). This lowered the coastal plain substantially and created lakes, which were then partly drained, resulting in shrinkage of their often clayey substrates. Although these activities were terminated more than a century ago, their legacy of a strongly differentially elevated coastal plain and resulting local inundation risk is still a prime cause of the present day strict Dutch phreatic groundwater level management that is the mechanism behind most shallow subsidence processes.

Sinkholes

A relatively new phenomenon in built-up areas in the Netherlands are sinkholes that are formed in man-made ground due to erosion by excess waterflows caused by several processes including burst water pipes. The formation of such sinkholes may result in sudden collapse and instabilities of buildings and infrastructures (e.g. Venmans et al., 2020).

Combined effects of shallow subsidence

For the Netherlands a shallow subsidence prediction map (Fig. 23.6) was published by Erkens et al. (2021). It is based on a combination of results from different forward models targeting the various sources of shallow subsidence for a priori defined scenarios. The map shows that a continuation of the current strategy, the so-called adaptation strategy, will result in up to several decimetres of additional subsidence up to 2100. In the 'Governance' section we show how an alternative strategy can be underpinned with data and information in the form of a scientifically informed policy cycle.

Detecting and monitoring subsidence

Subsidence processes form a subset of all the movements (horizontal and vertical) occurring at the earth's surface and in the objects on it. Such movements exhibit a wide range of variability, both spatially as well as temporally. For example, a small depression in a pavement and a large subsidence bowl due to gas extraction may have the same shape but different dimensions and impact (see Fig. 23.7). Temporally, a surface depression may precede a sinkhole collapse by a few hours, while surface motion due to salt mining will take a long time to develop a significant expression at the surface. The dynamics of peat areas are even more time-variable and can significantly and abruptly vary spatially, e.g. between polders (Morishita & Hanssen, 2015). Some processes even lead to uplift (Hanssen et al., 2008, 2020; Fokker et al., 2016; Conroy et al., 2022).

Surface deformation in real life is usually the combined effect of many processes. The diversity of the earth's surface itself translates almost inevitably into a diversity in subsidence and movement signals.

The consequence of this complexity is that to detect and monitor subsidence using geodetic techniques, (i) the sought 'subsidence' signal needs to be defined specifically for the particular objective at hand, i.e. *'what do we want to know?'*, and subsequently (ii) the most optimal strategy for detecting and monitoring must be selected, i.e. *'how do we measure it?'*. As a consequence, for a particular area of interest one could generate many different subsidence maps, using different techniques, and with different objectives.

The signal of interest

To select an optimal monitoring strategy for the subsidence signal of interest, specific a priori information needs to be established. Obviously, this should include the location of interest as well as the time interval of interest. However, this is not sufficient; the expected extent and smoothness of the signal of interest need to be given both spatially as well as temporally, i.e. how much relative subsidence do we expect between two locations as a function of their distance (see the example in Fig. 23.7). With reference to the smoothness it should be stated whether breakpoints or other spatiotemporal inhomogeneities can be expected. Finally, there needs to be an expectation of the magnitude and type of the signal. This set of expectation parameters is necessary to define the next steps: sampling and parameterization.

Sampling

Subsidence is always estimated as a *double-difference* signal, i.e. it concerns the 3D spatial position of one point relative to another (single spatial difference), as well as changes in time from one epoch to another (single temporal difference). The differences combined are referred

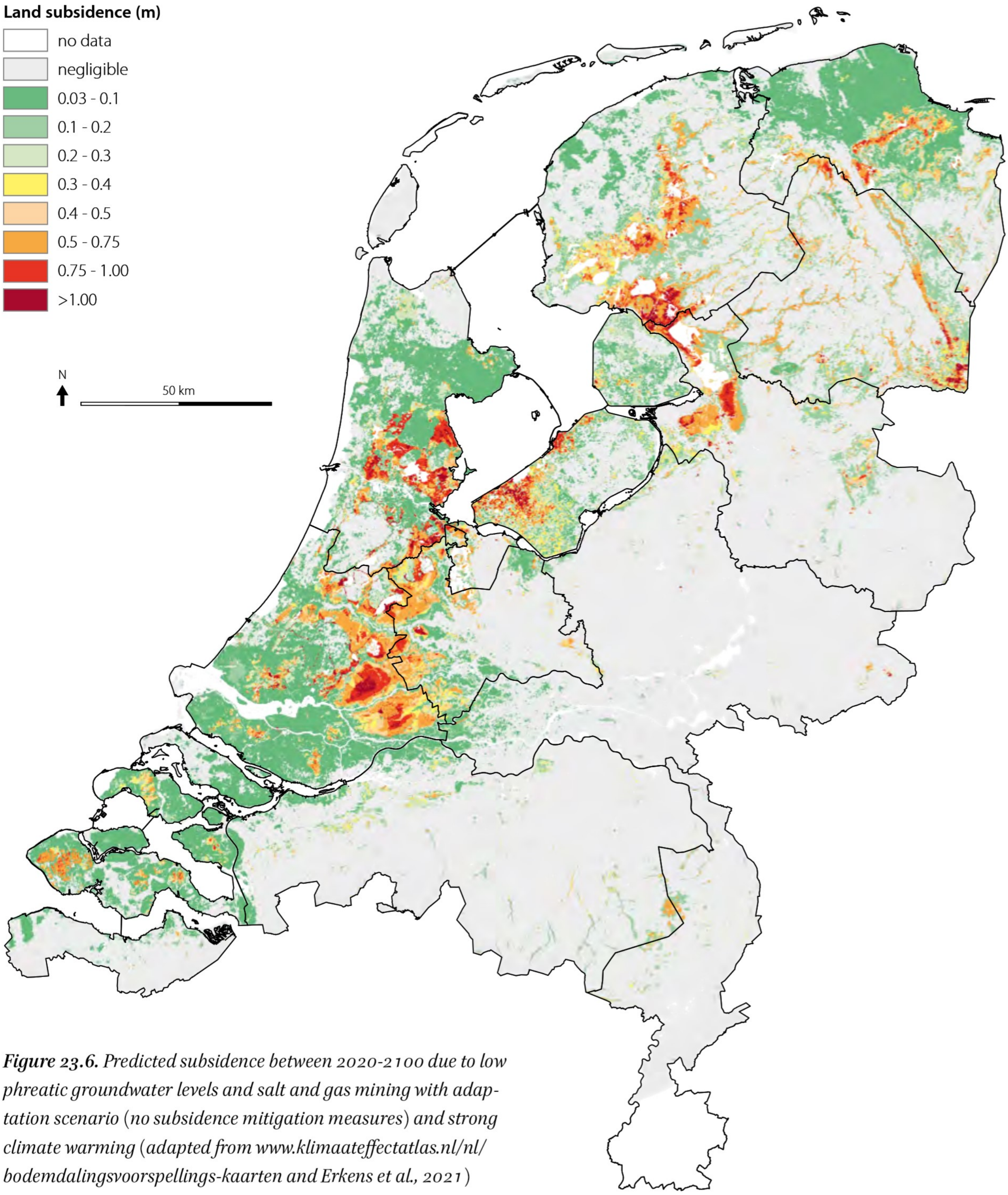

Figure 23.6. Predicted subsidence between 2020-2100 due to low phreatic groundwater levels and salt and gas mining with adaptation scenario (no subsidence mitigation measures) and strong climate warming (adapted from www.klimaateffectatlas.nl/nl/bodemdalingsvoorspellings-kaarten and Erkens et al., 2021)

Figure 23.7. Subsidence occurs in many shapes and sizes. a) Subsidence bowl in a pavement. b) Subsidence bowls in the Groningen area, showing the cumulative subsidence between 1992 and 2007.

to as double difference. Once the expected spatial extent of the signal of interest is known, the full area of interest needs to be at least a factor of two wider, in order to incorporate areas that are not affected by the subsidence signal as reference. The expected smoothness drives the spatial sampling. A smooth deformation signal, e.g. due to deep hydrocarbon production, requires a less dense set of measurement points than a deformation signal with very localized characteristics, such as the subsidence preceding a sinkhole collapse. Due to the typical superposition of subsidence contributions, the spatial sampling should also consider the variability of the other signals that will be present in the observations. These can either be disentangled later, or they can be treated as noise in the data. Unless tailor-made benchmarks for a specific driving mechanism are used, the spatial sampling should be sufficiently dense to observe the signal with the highest spatial variability. Expected spatial inhomogeneities need to be considered in the sampling pattern as well.

In addition, the period of interest needs to be defined. This can be related to subsidence processes that are expected in the future, occurred in the past, or are ongoing. Obviously, this choice significantly limits the type of surveying techniques that can be deployed, ranging from advanced electronic systems to information inferred from proxy data. The temporal smoothness of the expected double difference subsidence signal drives the temporal sampling. A subsidence signal that varies smoothly over time, e.g. due to gas production, requires a less frequent sampling than a signal that varies within weeks or days, e.g. the dynamics of organic soils. The temporal sampling should take the potential superposition of signals into account, as the measurements may be susceptible to various components of the superposed signal, including the ones with a higher temporal variability.

Apart from the spatial and temporal characteristics of the subsidence the expected magnitude of the signal is also important to consider, as it influences the choice of geodetic technology that is most suitable.

Parameterization

Parameterization refers to the definition of the parameters of interest and is strongly dependent on the original objective. In some cases the parameter is simply $z(\mathbf{x}, t)$, referring to the elevation of a location with horizontal coordinates $\mathbf{x}=(x, y)$ at an epoch t, expressed in a suitable geodetic datum. This is a so-called 'undifferenced' parameter that gives no information on temporal or spatial changes and for that reason is usually rather meaningless. For example, the actual elevation of a levelling benchmark installed in a wall (see Fig. 23.8), estimated at time t, is of no physical importance for land dynamics even though it is of high importance for several practical procedures in civil engineering. Single-differences are defined either in time as $\Delta_t z(\mathbf{x}, \Delta t)$ or in space as $\Delta_x z(\Delta\mathbf{x}, t)$ with $\Delta t = t_2 - t_1$ and $\Delta\mathbf{x} = \mathbf{x}_p - \mathbf{x}_q$, respectively and with p and q presenting two different locations. These single differences are equally meaningless, because the vertical movement of a single point over a particular time interval, or the elevation difference between two points at a particular epoch does not qualify as subsidence. Only for the *double-difference* parameters $\Delta_{t,x} z(\Delta\mathbf{x}, \Delta t)$ we obtain a physically interpretable variable.

We then parameterize the signal preferably by a minimum number of unknown parameters, for example by a vertical subsidence rate $v_z(\Delta\mathbf{x}_{p,0}, \Delta t_{i,0})$ at every sample point, where $\Delta\mathbf{x}_{p,0} = \mathbf{x}_p - \mathbf{x}_0$ and $\Delta t_{i,0} = t_i - t_0$, and where $\mathbf{x}_0$ and t_0 represent an (arbitrary) reference location and reference epoch, respectively. More elaborate parameterizations, using e.g. seasonal periodicity, acceleration, or higher-degree polynomials, are possible as well, but should only be used when physically plausible. The parameterization can be performed solely on the measurement benchmarks, interpolated to a predefined grid, which would introduce additional interpolation errors, or via a spatiotemporal analytical function. In addition, for satellite techniques there are nuisance parameters that need to be estimated, such as integer ambiguity numbers, atmospheric delays, or scaling parameters (Hanssen 2001).

Absolute and relative deformation

Irrespective of whether the subsidence signal is expressed in terms of a spatially variable velocity or in a more elaborated parameterization, its double-difference nature implies that it is always a *relative* deformation. In fact, the term 'deformation', i.e. a change in 'form', underlines this relativity intrinsically. As such, an *absolute* deformation does not exist, since 'form' is position invariant. Nevertheless, assuming a predefined reference benchmark in the network and a reference epoch in time, and assuming that the position of the reference benchmark is known in a common geodetic datum at time of the reference epoch, it is possible to integrate all double-difference displacement estimates to this spatiotemporal reference system. This effectively yields time series of benchmark positions in the geodetic datum, which are sometimes referred to as quasi-absolute positions.

Benchmarks

After the signal of interest is defined and the sampling and parameterization of the observation system are derived, the next important decision refers to the choice of the benchmarks. This choice is important to ensure reliable, representative, and repeatable observations with sufficient precision and is even more critical than the choice of the surveying technique. There are three options: physical benchmarks, virtual benchmarks, and benchmark-free observations. The first two are Lagrangian, as they follow a physical particle (the benchmark) over time, whereas benchmark-free observations are Eulerian, only reporting the vertical coordinate corresponding to a specific geographic location.

Physical benchmarks are the optimal choice regarding reliability, repeatability and interpretability. Examples are presented in Figure 23.8 and include brass levelling bolts installed in sturdy infrastructure, piles driven down into presumably stable deep strata, masts or buildings carrying antenna, radar reflectors and transponders and integrated geodetic reference stations (IGRS; Hanssen, 2017). Whilst optimal for repeatability and reliability, physical benchmarks are expensive and are often insufficient in terms of spatial sampling. Moreover, they are representative only for the displacement of the monument (object) on which they are placed and not for displacements occurring in strata above the lowest point of the monument, which are often significantly more dynamic. Another drawback is that these benchmarks are subject to loss over time, which is problematic if very long time series are required.

Virtual benchmarks satisfy the condition of repeatability but cannot be pinpointed physically. Such benchmarks are the product of satellite or airborne radar interferometry and are dependent on the earth's scattering conditions. Although such virtual benchmarks have less optimal characteristics compared to physical benchmarks, their advantage lies in their sheer number. There are ~35.000 physical levelling benchmarks in the Netherlands compared to billions of virtual radar benchmarks. This has pros and cons: more benchmarks are favourable for the spatial sampling density and for redundancy, but they are of varying nature and quality, and therefore often harder to interpret unambiguously. Whereas physical benchmarks are installed or selected before measurements take place, virtual benchmarks can only be selected a posteriori, given a set of observations. This enables the estimation of parameters over areas based on archived data.

Benchmark-free subsidence estimates stem from, for instance, repeated airborne laser scanning surveys or from bare-soil levelling campaigns. In these cases the land is

Figure 23.8. *Physical benchmarks. a) the Amsterdam Ordnance Datum NAP ('Normaal Amsterdams Peil') at Noordeinde, Delft. b) A corner reflector for InSAR satellite data. c) Integrated geodetic reference station (IGRS) with GNSS antenna on the mast, airborne laser scanning horizontal platform, levelling benchmark, and two corner reflectors.*

surveyed repeatedly, but typically observations from subsequent campaigns are made at different locations and under different environmental circumstances, which reduces precision and repeatability. Moreover, while the Lagrangian physical or virtual benchmarks guarantee capturing real motion of an object or surface, the Eulerian benchmark-free estimates cannot distinguish between subsidence of the surface and extraction or suppletion of material, e.g. by digging a hole.

Geodetic techniques and observables

Explicit identification of the objectives and of the a priori understanding of the subsidence signal of interest allows for the choice of preferred benchmark types, which leads to a limited set of options for geodetic surveying techniques: (i) spirit or hydrostatic levelling, (ii) continuous or campaign style GNSS (Global Navigation Satellite Systems), (iii) satellite InSAR (Interferometric Synthetic Aperture Radar), (iv) airborne laser scanning, and (v) relative or absolute gravimetry.

Levelling requires a levelling instrument, mounted on a tripod, and operated manually. The principal observable is a spatial single difference in orthometric elevation between two benchmarks (Torge & Müller, 2012). The required double-difference subsidence variable is derived by differencing spatial single-differences between epochs. For high precision and reliability it requires (i) the a priori installation of physical benchmarks (see Fig. 23.8a) representative of the subsidence signal of interest and (ii) manual in-situ land surveying. Cost increases with the area of interest and the temporal sampling.

Using a system of satellites orbiting the earth, GNSS (Global Navigation Satellite Systems) determine the position of a local GNSS antenna. The principal observable of GNSS is the 3D position of the GNSS-antenna reference point, acquired at one position and one epoch (Teunissen & Montenbruck, 2017). The required double-difference subsidence variable is a derived quantity, obtained by differencing either the spatial single-differences between epochs (campaign style), or the temporal single differences between positions (continuous). It requires the a priori installation of physical benchmarks representative of the subsidence signal of interest (see Fig. 23.8c).

Satellite radars emit signals towards the earth and record their subsequent reflections. Using interferometric techniques (InSAR) the change in position of a large number of these reflections can be estimated. For InSAR, the principal observable is the double-difference displacement in the line-of-sight to the radar instrument, derived from the interferometric phase (Hanssen, 2001). The selection of representative virtual benchmarks is performed a posteriori based on the observations. The modulo ambiguity in the phase measurements results in a non-unique solution, which can only be solved by conditioning the parameter estimation using prior knowledge.

Airborne laser scanning is performed from an airplane that sends laser pulses to earth and records the travel time to receive their reflections. The principal observable is the 3D position of a location on the earth's surface (Carter et al., 2007). The required double-difference variable is a derived quantity, obtained by differencing the elevation of two positions for one epoch, and subsequently subtracting two epochs. This results in Eulerian differences.

Gravimetry requires a gravimeter instrument and is operated manually, most often in campaigns. The principal observable is the gravitational acceleration acquired at one position and one epoch (absolute gravimetry), or the spatial single-difference between gravitational accelerations at two positions at one epoch (relative gravimetry; Timmen, 2010). The required double-difference elevation variable is derived by spatio-temporal or temporal differencing, respectively, assuming that there are no mass movements between the epochs, only geometric changes.

Subsidence Estimation

Given that the objectives, benchmarks, and a priori understanding of the signal are known, a set of subsidence parameters can be estimated from various sets of geodetic observations. This involves a mathematical model, consisting of two parts. The functional model describes the relation between the parameters and the observables, while the stochastic model describes the stochastic characteristics of those observables. The choice for these two models is based on the a priori information and assumptions and influences the outcome, as different choices will result in a different product. For example, in a levelling campaign the implicit assumption is that the benchmarks used only exhibit motion that is due to the subsidence signal of interest. For InSAR the implicit assumption is that the phase ambiguities have been successfully resolved.

This dependency on prior knowledge to estimate a subsidence signal introduces a sequential *reciprocity* between the models and the observations, which demands a continuous interaction between physical and observational disciplines.

Extensometers

In-situ observations, obtained for instance with extensometers, may be used to unravel the total subsidence signal. Extensometers are used to measure compaction worldwide (e.g. Poland, 1984). They derive point measurements of vertical movement at various (sub)surface levels at mm-scale accuracy. As such, the contribution of individual layers, and in some cases processes, to the total subsidence can be determined. Traditionally, in the Netherlands, extensometers have been used in geotechnical investigations, for instance for the determination of the subsidence after a building mound has been constructed. With the increasing demand for accurate monitoring of shallow subsidence and for a better understanding of the observed subsidence, extensometers are now also applied in the Dutch (agricultural) peat meadows area. Van Asselen et al. (2020) described the first application of extensometers that are capable of capturing shallow subsidence in peatlands with average rates in the order of mm yr^{-1} and even rates of cm $week^{-1}$, occurring on shorter timescales. Since late 2018, four extensometers at two livestock farms in Rouveen, Overijssel have hourly measured vertical movements of (sub)surface levels. Preliminary results show vertical movements (up and down) in the order of centimetres on the timescale of weeks (Van Asselen et al., 2020). These movements seem to be related to groundwater-level fluctuations, but evapotranspiration is expected to contribute to additional subsidence during the summer period.

Dutch Ground Motion Service (*Bodemdalingskaart*)

An information service containing ground motion has been made publicly available online (Hanssen et al., 2020). Using satellite InSAR data, the displacement time series of 200 million virtual benchmarks have been estimated and the results presented in an interactive portal

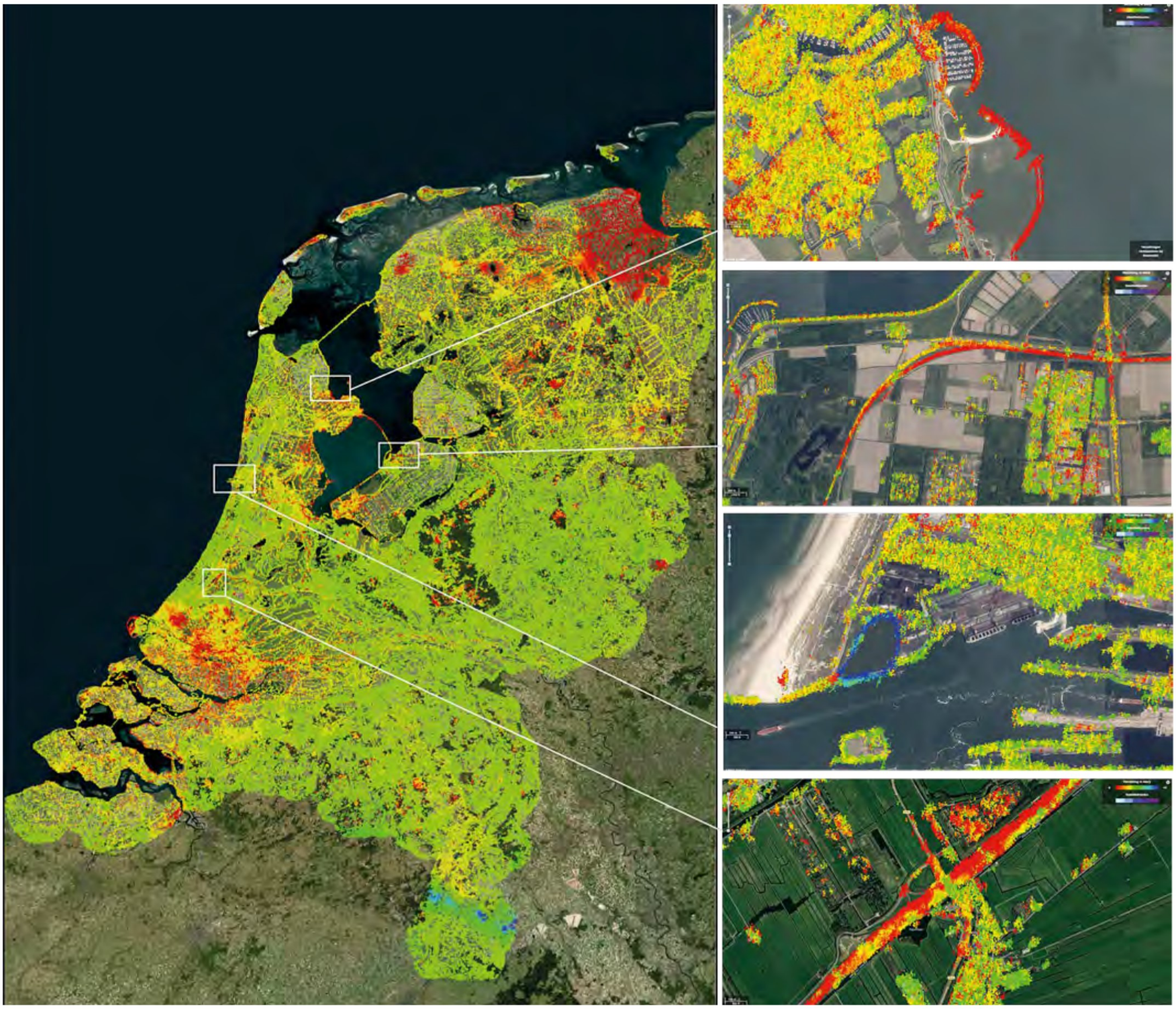

Figure 23.9. *Displacement time series of 200 million virtual benchmarks using satellite InSAR data. The data are presented in an interactive online portal (bodemdalingskaart.nl). Green colours indicate relative stability, blue colours indicate upward soil movement and orange and red colours indicate downward soil movement. Reflections are mainly collected from hard surfaces as illustrated by the inset maps. For a European-scale InSAR viewer: egms.land.copernicus.eu.*

(bodemdalingskaart.nl, see Fig. 23.9). The estimates are based on generic settings and are not optimized for a particular application. Based on the statistical properties of the data, a differentiation has been made between processes in the shallow and the deep subsurface.

Integration: combining detected and modelled subsidence

As outlined in the previous sections, the surface movement constitutes a measurable signature of the processes in the subsurface, which can thus provide information about the subsurface (Maury et al., 1992). This is beneficial, since subsurface parameters are usually associated with large uncertainties. Typical uncertainties include the spatio-temporal distribution of the pressure and temperature changes at depth (e.g. Fokker et al., 2012; Candela et al., 2017), the amount of depletion of aquifers connected to a gas field (Fokker et al., 2016), the value of the compaction coefficient of the reservoir rock and its dependency on porosity and pressure (Van Thienen-Visser & Fokker, 2017), the time dependence of compaction (Fokker et al., 2019), the geomechanical response of the reservoir surroundings up to the surface (Marketos et al., 2016) and other interfering causes such as deep and shallow expressions of compaction (Kroon et al., 2009). These uncertainties immediately propagate into uncertainties in subsidence estimates when forecasting models are deployed.

Inverse modelling or data assimilation can be employed to constrain subsurface knowledge and parameters with

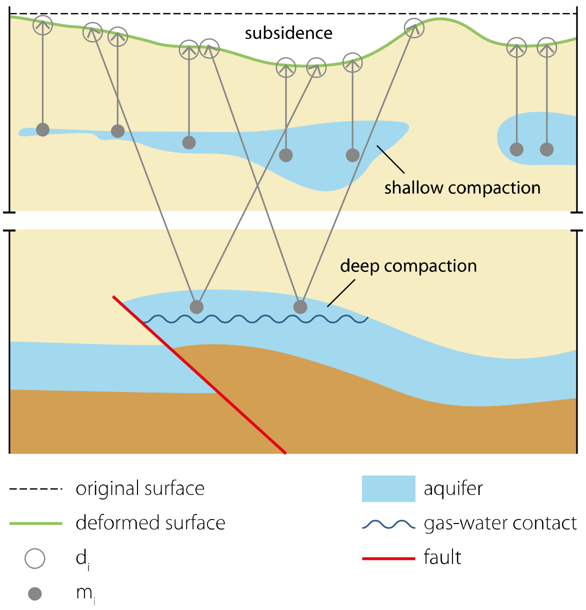

Figure 23.10. Demonstration of compaction sources leading to a cumulative and smoothed subsidence expression.

surface movement data (Tarantola, 2005), although this is not straightforward. It is especially difficult for cases where there is a combination of a spatially distributed source of compaction such as a depleting gas field and a heterogeneous shallow subsurface, where there are strongly nonlinear forward models or interfering causes of subsidence and where there are highly correlated data (see Fig. 23.10). A direct application of inverse models often results in non-unique or unstable solutions. Additional information in the form of prior knowledge is required. We will briefly sketch how inverse modelling of subsidence can be approached in such a way that the result is useful for forecasting and governance.

Linear inversion can be employed if the relationship between driving parameters and estimated surface movement is linear. This is, for instance, the case if the compaction is the unknown parameter and the subsurface response is linearly elastic. The prior knowledge then can be a prior estimate of the compaction estimate (Marchina, 1996; Fokker et al., 2012). The forecast uncertainty for the estimate forms an automatic output of the procedure if the data and model uncertainties are correctly known (Menke, 2018).

A more complicated inversion is usually required. The unknowns may be the subsurface elastic or visco-elastic behaviour or the reservoir permeability that controls the pressure distribution. Classical history matching methods employ a trial-and-error methodology; these may, however, miss important regions of the parameter space (Vasco et al., 2000). When few parameters need to be estimated, an iterative least-squares approach may be appropriate (Vasco et al., 2010). These methods, however, do not result in an automatic estimate of the confidence range of the forecasted subsidence.

Modern estimation algorithms frequently employ an ensemble approach: a large number of model realizations is used. Such models originated in weather forecasting (Mackenzie, 2003) but quickly also found applications in the subsurface domain (Evensen, 2009). One example of an ensemble approach is the particle filter (Van Leeuwen, 2009; Nepveu et al., 2010). Many models are created with limited prior knowledge of the driving parameters, so the ensemble of all realizations should highlight the prior uncertainties of the model parameters in a range of subsidence predictions. The model outcome then is compared with the data and the models that fit the data best are favoured by giving them larger weights than others. A posterior model estimate is finally constructed by means of a weighted average of all prior forecast realizations. The elegance of this approach is that model realizations do not have to be updated: the prior models are used to construct an improved model forecast. However, the problem with the method is that with many measurement points, a tendency towards divergence or ensemble collapse emerges: one single model collects virtually all the weight and the prediction coincides with that model only. This behaviour also renders the calculation of a posterior uncertainty range impossible. An unrealistic number of model realizations would be required to obtain a reasonable number of non-zero posterior weights (Van Leeuwen, 2009).

Current state-of-the-art procedure is to employ data assimilation, whereby both the model forecast and the parameter space are modified in adapting the model ensemble. In data assimilation, the complete ensemble is used to construct an update step. Crucial ingredient in this update step is the correlation between model parameters, model predictions and data. This correlation is used to construct an updated ensemble of model parameters and model predictions that honours the measured data.

Many brands of data assimilation exist. The most common one is the Ensemble Kalman Filter. Every time that new data are collected, the Ensemble Kalman Filter (EnKF) procedure is applied, and the model parameters and predictions are updated. A progressively developing forecast mean and bandwidth are created. The Ensemble Kalman Filter has proven to be very effective in weather forecasting, but also in reservoir engineering approaches (Evensen, 2009; Katterbauer et al., 2014). For subsidence modelling, the Ensemble Smoother has been used more frequently (Baù et al., 2015; Fokker et al., 2016; Zoccarato et al., 2016). This method constructs the new ensemble in a single step (Baù et al., 2015). When applied with nonlinear forward models or non-Gaussian statistics, however, results are inferior to those obtained using EnKF (Tavakoli et al., 2013). Publications by Emerick & Reynolds (2013a,b) and Tavakoli et al. (2013) compare different ensemble techniques and conclude that an Ensemble Smoother with Multiple Data Assimilation (ES-MDA) is a good alternative: computational cost is like that of EnKF but the result of ES-MDA agrees better with the 'true' model in their synthetic cases.

An example application of ES-MDA was given by Fokker et al. (2019) for the case of surface subsidence in the southern Flevopolder. The combined knowledge (data, models, and data assimilation technology) gave a new insight into the processes at work in this reclaimed area. Here, subsidence was mainly the result of clay shrinkage after its first exposure to air. An example of employing a particle filter is NAM's approach to subsidence in the Wadden Sea. All uncertainties present in geology, reservoir dynamics, geomechanical behaviour and subsidence data are stochastically integrated in a large set of models (Van Thienen-Visser et al., 2015; NAM, 2017; TNO, 2017). The forecasts, updated with the modified weights for the various model realizations, were used to assess the subsidence in the Wadden Sea in conjunction with the expected sea level rise and the Wadden Sea morphodynamical development (Van der Spek, 2018; Vermeersen et al., 2018; Wang et al., 2018).

Estimates which are used in inverse models should be as close as possible to the original measurements. An example where this turns out to be important is when Persistent Scatterer InSAR data (PS-InSAR) are employed. These measurements result from the projection of the 3D displacement vector onto the line of sight of the satellite. Using ascending and descending satellite orbits, the displacement vector can be decomposed further, albeit still insufficiently for full decomposition in the east, north and vertical directions (Klemm et al., 2010; Janna et al., 2012; Rucci et al., 2013). The decomposition into vertical and east-west movements, however, introduces the need for a spatial interpolation, because the persistent scatterers identified for ascending and descending satellite orbits are not identical. Thus, such decomposition is allowed only when the deformation signal is sufficiently smooth and sufficiently well-sampled. Interpolation can be avoided by using the line-of-sight data directly in the parameter estimation procedure, as is common practice in the assessment of volcanic activity and earthquakes (Jónsson et al., 2002; Anderssohn et al., 2009; Fokker et al., 2016). Estimates of the purely vertical movement can be made with the updated model ensemble.

Governance

Subsidence is a complex problem. There are many stakeholders with different interests, whilst their level of awareness of the issue is often limited. This may be related to the fact that damage cannot unambiguously be attributed to subsidence, nor to low levels of knowledge and insight into the root cause and possible mediation strategies (Erkens et al., 2015). As a result, as with many problems that root in earth sciences, the process of formulating a subsidence strategy or implementing appropriate measures is often problematic, leading to particularly difficult decision making.

Land subsidence: adaptation or mitigation

In developing coping strategies, there is the option of reducing subsidence (mitigation) or reducing the negative consequences of subsidence (adaptation). Most likely a combination of both will be optimal (Erkens et al., 2015). In coastal areas, where subsidence quickly leads to increased flooding, adaptation often forms the initial hazard management strategy. Adaptation measures may for instance target the increased flood risk. In the Netherlands, the response to human-induced subsidence over the last ca. 1000 years is a prime example of a subsidence adaptation strategy. The stepwise raising of embankments has traditionally been the response to lowering land elevations and the consequently increasing flood risk (Fig. 23.1). Similarly, subsidence that reduced drainage capacity of the surface water and overall wetter conditions have often been addressed by the installation of pumps, which led to further subsidence (e.g. Van de Ven, 1993; Erkens et al., 2016). Even though these actions were mitigation measures to address the increased flood risk, for subsidence they may be considered as adaptation measures. In case of damage to structures by land movement, the traditional approach was to adjust the structure, or completely rebuild. Over the last centuries, the increasing application of pile foundations in the Netherlands also forms an adaptation strategy to cope with the soft soil conditions.

Mitigation measures need to target the root cause of subsidence. For the Netherlands, where there are multiple causes of subsidence (see the previous sections on natural- and human-induced subsidence), this means that, for instance, in case of deep-rooted subsidence, rates could be reduced by diminishing the extraction of hydrocarbons, groundwater or salt. In case of shallow subsidence, measures need to target either the load (weight) on the soft soil or the shallow groundwater level. In both cases, the aim of the mitigation strategy could be to avoid acceleration of subsidence after an intervention or even to actively reduce the current rates. For instance, when applying a load on soft soil with low bearing capacity in the building process, mitigation of subsidence would consist in limiting the processes of consolidation and creep. This can be achieved by using lighter building material, or even by striving to achieve no net increase in loading. Similarly, preventing the temporary lowering of shallow groundwater levels (e.g. during droughts) would limit subsidence, so that on the longer term rates would slowly reduce. Permanently raising groundwater levels would actively reduce subsidence rates, but completely bringing human-induced subsidence to a halt at present is not achievable in the Netherlands. This results from the omnipresence of soft soils combined with the need for groundwater management, in addition to disturbances that cannot be prevented.

The history of coping with subsidence in the Netherlands and lock-in conditions

It is only over the last couple of decades that interest in subsidence mitigation measures has increased. The historically grown dominance of experiences with adaptation measures has led to an optimization of subsidence adaptation strategies. This applies to the technical aspects (for example the building of embankments for flood protection and pumping stations that drain the land), but also to the institutional and financial aspects. Institutions that have implemented these adaptation measures and strategies have strengthened as they have acquired the requisite technical skills and knowledge and the necessary financial resources (Seijger et al., 2018). As a result, over time it has become increasingly easy to implement an adaptation strategy to subsidence problems. This development of a single strategy to manage subsidence problems can be viewed as a path-dependent process (Sydow et al., 2009), where managerial discretion in terms of choices or options depends on the choices made in the past (Fig. 23.11). The end stage of path dependency, when managerial discretion is limited and a single management option fully dominates, is called a lock-in. The Netherlands can thus be regarded as trapped in a dual lock-in condition as the dominating adaptation strategy in terms of the applied technologies and the principal institutions act as constraints to move toward a more long-term sustainable strategy (Seijger et al., 2018) – one that also may include measures to mitigate subsidence (Erkens & Stouthamer, 2020).

The urgency to deal with subsidence with a sustainable long-term strategy is growing. As subsidence continues and cumulative land-level lowering increases, new problems arise and existing problems worsen. Also, subsidence

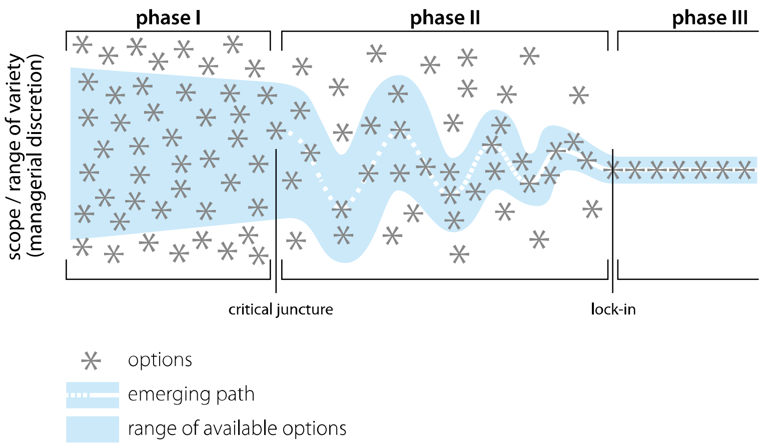

Figure 23.11. Visualization of a lock-in caused by path dependency. This is currently the situation for subsidence in many coastal areas where an adaptation strategy is preferred over a mitigation strategy (from Sydow et al., 2009; reproduced with permission).

and the increasingly grim predictions of future climate warming-induced global sea-level rise are interconnected, as they contribute both to relative sea-level rise. In many coastal areas, including the Netherlands, land elevation is increasingly viewed as an asset (Koster et al., 2020), and therefore losing elevation puts the value at risk (Erkens & Stouthamer, 2020). At the same time, exposure to subsidence is increasing, as population growth, ongoing urbanization and economic growth continues in the Dutch coastal zone, which largely consists of soft soils. As a result of increasing damage to buildings and infrastructure, societal awareness on subsidence and its consequences in the Netherlands has increased. There is a growing awareness that much of the subsidence is in fact human-induced and that it thus can be actively reduced by human action. An additional negative effect of subsidence by peat oxidation is the associated emission of CO_2. In order to comply with legally binding international treaties, the Netherlands is obliged to reduce these greenhouse gas emissions, including those from the drained peatlands and organic soils. This forms an extra incentive to review the current subsidence rates in these peatlands.

Because of the increased urgency, questions arise whether the current subsidence strategies are durable and in fact, these strategies are challenged by stakeholders. The lock-in condition makes it difficult to choose alternative management options, however, as they conflict with existing interests and break with the long-standing traditional approach to managing the subsidence using an adaptation approach. If the societal and financial benefits of alternative management approaches would be fully known a different action perspective could be offered to decision makers. For such alternatives a sound and shared knowledge, based on in-depth understanding of the physical problems, the financial perspectives (what are the costs and benefits of different options?) and governance and legal capabilities (who is responsible and are there sufficient capabilities to implement the management measures?) is required. Only when these conditions are satisfied, will the threshold to act on an alternative management strategy become lower.

Getting out of the lock-in using a sound knowledge base

Realising that in order to emerge from lock-in a sound and shared knowledge base is required to facilitate decision making, it is important to establish which elements must be included in the knowledge base. Based on experience and reviewing best practise cases, Erkens et al. (2015) gathered crucial research elements to facilitate decision making with scientific knowledge. This framework has evolved into the 6M approach to subsidence (Erkens & Stouthamer, 2020), which is a step-wise approach that elaborates along the stages of the policy cycle, with six distinct steps that need to be taken: Measuring, understanding Mechanisms, Modelling, Money, Measures and Monitoring. The policy cycle is a tool that is used to analyse the development of a policy item and has been used for decades in political sciences. In this approach, each of the steps consists of questions that need to be addressed and data that need to be gathered and interpreted. Furthermore, there are governance aspects that often need to be considered in order to answer questions such as regarding the responsibility of parties to act and the ownership and storage of data. In real life short-cuts are often taken, for instance, where measurements from the first step show the urgency of the situation and measures are directly implemented.

In this contribution we have summarized the state-of-the-art concerning the measuring and monitoring of subsidence, the understanding of subsidence mechanisms and the modelling of subsidence in the Netherlands. For policy making and decision making, these steps form the knowledge base (Erkens & Stouthamer, 2020). Here we also argue that policy making and conducting science are coeval activities: it is not recommended to wait with vision and policy forming until the first three steps have been finished and reported. In fact, immediate input from the first three steps will help shaping policy. It is important that lessons learnt are readily available. Preferably, the monitoring data and analysis results should be stored in a central database and freely accessible information platform (Van Daalen et al., 2020; Erkens et al., 2021). Another example of relevant information on the physical system for policy making that needs to be available relatively early in the process is the discrimination of different processes that contribute to subsidence. Often there are both natural and human-induced causes at the same location. For policy development this distinction is important: while it is worthwhile to implement mitigation measures to reduce human-induced subsidence, for natural subsidence only adaptation measures can be taken (Erkens et al., 2015). The proposed measure will often specifically target a single subsidence driver and cause.

While inverse modelling or data assimilation is targeted at the reduction of uncertainty in parameter values and subsidence forecasts, there will always be remaining uncertainty. The great advantage of the ensemble-based methods is that this uncertainty is quantified. It can thus also be propagated into the model forecasts for different governance scenarios. A scientifically underpinned decision making must incorporate the confidence range of the model outcomes in the process.

With subsidence predictions for different management scenarios available, the next step is to perform a cost-benefit analysis for each scenario. Estimating subsidence-related costs (damage) is notoriously complex. Subsidence is a 'hidden threat' because in practice, the actual costs appear on financial sheets as ad hoc investments or planned maintenance schemes but typically are not identified as damage costs related to subsidence and thus remain hidden (Erkens et al., 2015). Dedicated damage estimates can help to raise awareness among policymakers and initiate policy development. For subsidence, being a gradual process, mitigation measures are usually costly in the short term, but cost-effective in the long term (Erkens et al., 2015). Cost-benefit analyses could provide insights into the hidden costs and potential benefits of mitigation measures (usually avoided damage or costs) in a quantitative way. They can also provide a rationale for upfront investment in measures that realize long-term benefits. Often, with subsidence, costs and benefits are different for different stakeholders. This may lead to demands for financial compensation measures or mitigative measures to reduce costs for a certain stakeholder group.

In Gouda, a city in the western peatlands in the Netherlands, Kok and Hommes-Slag (2020) showed that the adaptation strategy that has been followed over the last centuries may be the most beneficial economically, despite the continuation of subsidence. In this scenario, costs made to avoid, reduce and repair the future subsidence-related damage to the structures were calculated at 7-16 M€, but the damage prevented (reducing damp conditions and groundwater nuisance) was approximately 13-20 M€, making this the economically most rational option. This example shows how cost-benefit analyses, based on subsidence model outcomes, may inform decision makers, helping them to unlock the lock-in.

Implementation of measures should follow cost-benefit analysis and informed decision making, with the consequences of remaining uncertainties incorporated. This will often include governance and legal aspects (who is responsible?) and financial aspects (who is paying for and who benefits from the measures?). For various examples around the world, Erkens et al. (2015) showed that the costs of the measures are always high, regardless of the strategy followed. If nothing is done, costs of repairing the subsidence damage (flooding, tilting of structures) are also high. An adaptation strategy is costly, because as subsidence continues adaptation measures need to be taken continuously. A mitigation-focused strategy is costly also because the implementation of measures must be accompanied by investing in development of databases containing measurement data and predictive model outcomes to break out of the lock-in.

The step-wise 6M approach mentioned above is a structural way of facilitating decision making using scientific knowledge prior to, during, and after the decision-making process. Moreover, it is a scheme that offers a framework to exchange best practises and approaches between different subsiding areas around the world.

Summary and outlook

Subsidence is a complex phenomenon and a complex problem to tackle, both in a technical sense and in governance. This is particularly the case in the Netherlands, a low-lying and densely populated country in which various causes of subsidence interfere. The long history of slowly manifesting subsidence in the Netherlands (more than 1000 years) has resulted in a tendency to adapt rather than to mitigate. This 'lock-in' situation is suboptimal, since potentially cheaper and more effective governance options may not be considered. What is needed is a sound knowledge base and a mindset to explore solutions outside the traditional way of thinking. To facilitate this, we have presented several knowledge and governance issues of concern. First, we have described the natural processes that cause subsidence, and the human-induced causes like groundwater management and exploitation of geological resources. After that we have elaborated on how subsidence is detected and monitored. However, well-founded decision making requires quality forecasts for different governance options, and these can only be achieved if data and models are integrated. To this end, modern ensemble-based techniques are available that combine detected and modelled subsidence. An essential element in these methods is the fundamental incorporation of expectation values and expectation bandwidths (or confidence intervals) of the ensuing model parameters and model outcomes. These can then be propagated to forecasts based on management decisions, and with the application of monetary evaluation, the right measures can be proposed and executed. This policy cycle needs to be closed through continuous monitoring and model updating.

The subsidence situation will change in the Netherlands. For the coming decades, it may be expected that subsidence resulting from gas and oil extraction will decrease as greenhouse gas emission mitigation force these activities to diminish or shut down. Conversely, we expect a continuation of surface movements induced by salt production, gas storage (methane or hydrogen) in depleted gas fields or in salt caverns, and geothermal operations including high-temperature thermal storage. In rural areas, greenhouse gas emission reduction targets will no longer allow for substantial CO_2 emissions and the associated shallow subsidence from drained peatlands by 2050. The rate and intensity of peat oxidation must therefore be reduced strongly. This implies the need for a strong reduction in subsidence in these areas as well. For the urban area, a clear aim of subsidence reduction is currently lacking and it is questionable to what extent subsidence will be reduced, if at all. In the longer term, by 2100, following the grim sea level rise predictions, the effects of subsidence may be magnified by absolute sea-level rise, increasing flood risks in the Netherlands. Subsidence will keep playing a role in shaping the future of the Netherlands for decades to come. It is therefore crucial to have a freely accessible central database and information platform for monitoring data and analysis, and to maintain and further develop the current knowledge position.

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here: https://doi.org/10.5117/aup.28164749.

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