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# The effective subsidence capacity concept: How to assure that subsidence in the Wadden Sea remains within defined limits?

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## Abstract

Subsidence caused by extraction of hydrocarbons and solution salt mining is a sensitive issue in the Netherlands. An extensive legal, technical and organisational framework is in place to ensure a high probability that such subsidence will stay within predefined limits. The key question is: how much subsidence is acceptable and at which rate? And: how can it be reliably assured that (future) subsidence will stay within these limits?

To address the issue for the Wadden Sea area, the concept of 'effective subsidence capacity' is used. To determine the 'effective subsidence capacity', the maximum volumetric rate of relative sea-level rise, that can be accommodated in the long term, without environmental harm, is established first. The volume of sediment that can be transported and deposited by nature into the tidal basin where the subsidence is expected, ultimately determines this 'limit of acceptable average subsidence rate'. The capability of the tidal basins to 'capture' sediment over the lunar cycle period of 18.6 years is the overall rate-determining step. Effective subsidence capacity is then the maximum average subsidence rate available for planning of human activities. It is obtained by subtracting the subsidence volume rate 'consumed' by natural relative subsidence in the area (sea-level rise plus natural shallow compaction) from the total long-term acceptable subsidence volume rate limit.

In the operational procedure for mining companies, six-years-average expectation values of subsidence rates are used to calculate the maximum allowable production rates. This is done under the provision that production will be reduced or halted if the expected or actual subsidence rate (natural + man induced) is likely to exceed the limit of acceptable subsidence. Monitoring and management schemes ensure that predicted (6-year average) and actual (18.6-year average) subsidence rates stay within the limit of acceptable subsidence rate and that no damage is caused to the protected nature. A GPS based early warning system is used for early detection of unexpected behaviour. In support of SSM (State Supervision of Mines, the government regulator), TNO-AGE (an independent government advisory group) applies an independent Bayesian statistical analysis of all data, as they become available, to calculate the probability of scenario's under which future subsidence will exceed the defined limits. It is external to the operator's annual measurement and control loop and ensures that preventive actions can be taken in time in case such scenarios emerge.

Regular communication keeps the authorities and the general public informed on the use of the effective subsidence capacity to demonstrate that the actual average subsidence rate stays strictly within the defined bounds and that, from a scientific point of view, there is no reasonable doubt that damage to the tidal system will not occur now or in the future.

***Keywords***: effective subsidence capacity, gas production, limit of acceptable subsidence, subsidence management

## Introduction

Proper management of subsidence – irrespective of its causes – is important for a densely populated country such as the Netherlands where most of the land surface is near or below sea level (Barends et al., 2002). Damage can be prevented provided subsidence is properly managed and measures to counter its adverse effects are timely taken. Without the protection of dunes, dikes and pumping, large parts of the country would be flooded. The IPCC (Intergovernmental Panel on Climate Change) predicted sea-level rise from global warming will increase the challenge (Solomon et al., 2007). Subsidence in the Netherlands has many causes. Dewatering can result in shrinkage and oxidation of peat layers, leading to subsidence of several metres (Schothorst, 1982). For land regained from the sea, like the Flevopolders, dewatering of near-surface clay layers can result in subsidence of up to a metre over a period of a few years (De Glopper & Ritzema, 1994). Man-induced artesian head changes, water production and extraction of salt, oil or gas are other causes. An example of superposition of the expected surface movements induced by natural and anthropogenic causes of the Dutch surface up to 2050 is given in De Mulder et al. (2003; see also *www.tcbb.nl/3_delfstoffen.html*).

There are more than a hundred producing mining projects in the Netherlands. Some of them have resulted in ground surface subsidence of more than ten centimetres. Examples are the Groningen, Ameland, Anjum, Roswinkel and Harlingen gas fields and several salt solution mining locations. In the Netherlands an extensive legal, technical and organisational framework is in place to ensure a high probability that subsidence resulting from oil and gas production or from salt solution mining will stay within predefined limits. It also warrants adequate preventive actions to be taken in time, in the event that measurements start to indicate a realistic risk of breaching the predefined limit in the future. To do so, a risk-based approach can be taken to distinguish those cases where the expected subsidence, including uncertainties, is at risk of exceeding the robustness limit of the area. From a water management perspective, less than five cm subsidence is often considered within the noise of the overall system. In sensitive areas such as the Wadden Sea, proper management of lower subsidence (rate) numbers can be important as the livelihood of many organisms, such as wading birds, directly depends on it.

This article starts with a general explanation of the legal, technical and organisational aspects of subsidence management in the Netherlands, including the introduction of the concept of 'effective subsidence capacity'. It is followed by a discussion on their application to prevent damage to the tidal system in the Dutch Wadden Sea area.

## Legal Frame

A mining company will have to deal with a multitude of laws and regulations before it can produce natural gas, in particular from underneath an environmentally sensitive area such as the Wadden Sea. The most important are: the Dutch Mining Act (including the mining decree and the mining regulation), the Dutch Nature Protection Act and the Dutch Spatial Planning Act. Under the Mining Act, companies involved in mining activities have to submit a Production Plan (Winningsplan), which includes potential land subsidence issues. Approval of the plan by the Minister of Economic Affairs, Agriculture and Innovation is required. The Production Plan provides maps of the extent of the predicted subsidence as a function of location and time. It also details the measures to limit subsidence and to prevent damage from subsidence. Monitoring of subsidence has to be carried out in accordance with a separate Measurement Plan, which has to be submitted for approval prior to the start of production. It has to be updated and submitted for re-approval annually. The Production Plan, other plans and license conditions are made public as part of a legal consultation process. The legal framework enables authorities or judiciary to reject a Production Plan or a proposed production profile when the risk of damage due to subsidence is considered too large.

## Technical Frame

### *Oil and gas*

Any rock layer at a given depth has to carry the weight of the overlaying strata. Prior to the start of production from a gas reservoir, the water and gas in the pores of the rock are under significant pressure. This pore fluid pressure carries part of the overburden weight. The remainder of the weight is carried by the porous rock itself, resulting in what is called 'the effective stress' on the rock. Under normal conditions, the reservoir rock and the pore fluid pressure each carry about half of the weight of the overburden (Fig. 1). For overpressured gas reservoirs, where the pore fluid pressure is much higher than hydrostatic, the fraction carried by the pore fluids is higher. In extreme cases it can be close to 100%. As the gas is produced, the pore fluid pressure drops and more and more of the weight of the overburden has to be carried by the porous reservoir rock itself. Under this increasing load, resulting in an increase in the effective stress, the reservoir rock is compressed, resulting in compaction of the reservoir layer. Pressure drop and compaction can also occur in water bearing layers (aquifers) in hydraulic contact with the gas reservoir. The deformations at depth cause a subsidence bowl to emerge at the Earth's surface in the shape of a (very) flat saucer. The lateral dimensions of the surface bowl typically exceed the lateral extent of the gas reservoir by an amount equal to its depth, usually several kilometres. Vertical deformations are very small compared to the lateral extent of the bowl. In the Netherlands, they are often only a few cm, while for a limited number of cases subsidence of up to some 50 cm has been predicted (NAM, 2010).

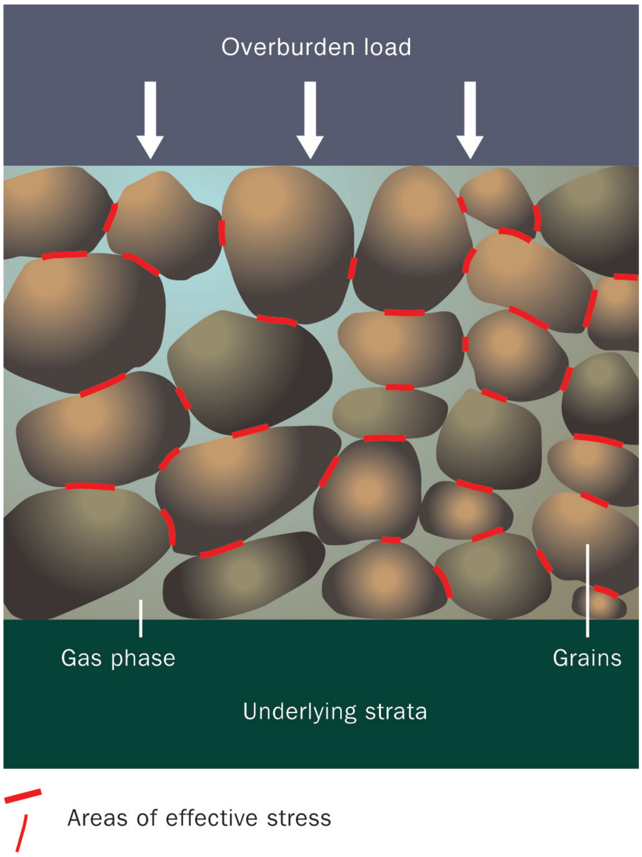


*Fig. 1. Reservoir compaction as a result of reducing gas pressure.*

## Salt

In the case of salt solution mining, salt is dissolved, creating a brine-filled downhole cavity, which deforms under the load from the surrounding salt (Fig. 2). The resulting volume reduction causes surface subsidence. The lateral extent of the subsidence bowl is of the order of magnitude of the depth of the solution cavity. The cavity remains stable, provided a mining practice is followed in which sufficient salt is left in place and the roof does not become too large. For thin roofs, the cavity volume needs to be kept limited to ensure that even in the case of cavity collapse, the resulting roof collapse cannot migrate to surface and create a sinkhole. Under these conditions deformation at surface can be kept limited (Paar & Geerts, 2008). Historically, such guidelines were not applied, resulting in larger amounts of subsidence and potentially unstable cavities that would need to be filled to avoid the need for long term monitoring and aftercare.

For ductile salts such as carnallite and bischofite and – at larger depths – halite, a different mining process is followed: after the forming of an initial cavity by dissolution, brine production from the cavity is kept at par with the rate at which the ductile salt can flow towards the cavity. This is called squeeze mining (Van Noort et al., 2009). At this stage the downhole volume reduction becomes almost equal to the volume of 'squeezed' salt while the cavity volume can be kept more or less constant. Under squeeze mining conditions, subsidence can be tens of cm while the risk of cavity collapse remains negligible.

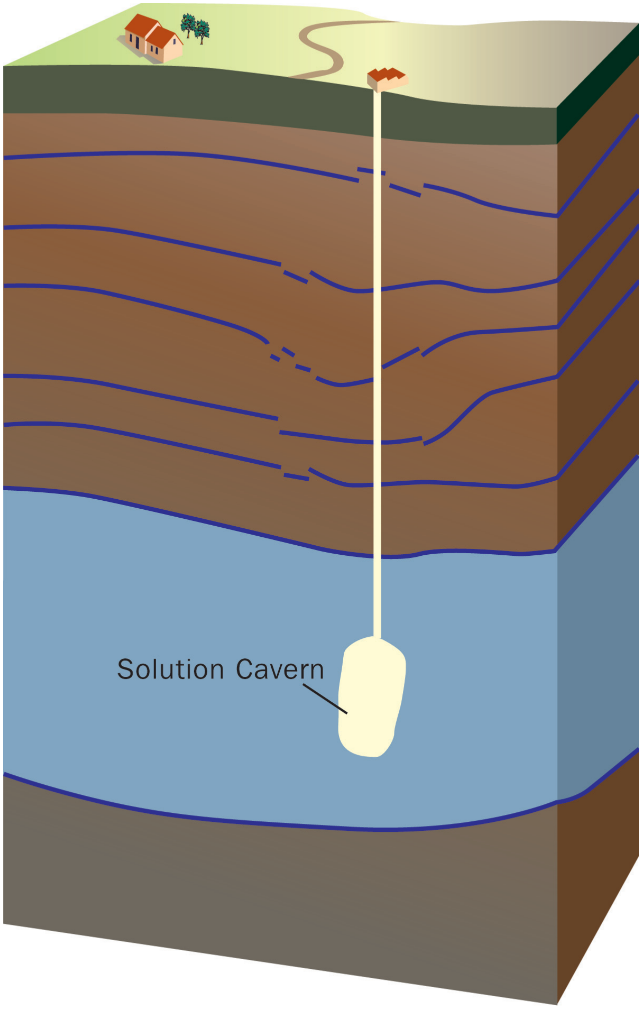


*Fig. 2. Underground salt solution cavern.*

## Modelling technology

Development of compaction and subsidence modelling for porous reservoirs started with the classical work of Terzaghi (1923). He arrived at a differential equation describing the deformation process of a compacting column by coupling the Darcy flow equation (Darcy, 1856) to a linear elastic stress-strain relation via the continuity equation. Biot extended the theory to three-dimensional systems, and showed that the deformation of a porous medium can be described as an extension of the theory of elasticity (e.g. Biot, 1941, 1956). Gassmann (1951) and Geertsma (1957a, 1973) reformulated the theory in terms of deformation constants more suitable for practical experimental determination. Lubinski (1954) and

Geertsma (1957b) pointed out that the resulting stress-strain relation is very similar to that used in the much older theory of thermoelasticity. Therefore, for many poroelastic problems an analogous but already solved thermoelastic problem exists. Care must be taken in using these solutions as the analogy between poroelasticity and thermoelasticity is not complete. The problem is greatly simplified however when the pore pressure field is known and can be used as input.

In the Dutch gas fields, the compaction resulting from declining reservoir pressures can effectively be described using a one-way coupling, especially if water influx from bottom and surrounding side aquifers is limited. This reduces uncertainties and allows for modelling simplifications. An example of particular interest is the use of the nucleus of strain concept. Analytical solutions are available for the stress and displacement fields at or below the surface from a pore pressure drop in a single point (nucleus) below the surface (Geertsma, 1973). Later (semi-)analytical extensions allow for a compressibility contrast between the nucleus and its surroundings (Gambolatti, 1972), the presence of a stiff basement at some depth below the nucleus (van Opstal, 1974) and for a layer-cake subsurface, where each layer can have its own elastic properties (Fokker & Orlic, 2006). The displacement field associated with a compacting porous reservoir of finite dimensions is subsequently obtained by integrating the nucleus solution over the total reservoir volume.

For all practical cases, the volume of the subsidence bowl does not depend on the geometry of the reservoir but only on its volume change. In contrast, the shape of the surface bowl is determined by the geometry of the problem: the ratio of the average depth and radial extent of the compacting reservoir, its shape, and additional factors such as the presence and distance of stiff or weak layers above or below the reservoir, the Poisson's ratio and the 3D distribution of geomechanical properties. Subsidence due to compaction of reservoirs with a limited lateral extent – compared to their burial depth – will spread over a larger area than the areal extent of the reservoirs. In such cases subsidence at the centre of the bowl will be less than reservoir compaction. For reservoirs with a large lateral extent, subsidence in the centre of the bowl will be more or less equal to reservoir compaction. The presence of stiff layers below the reservoir will limit the lateral extent of the subsidence bowl while stiff layers above it will bridge, thereby extending the bowl volume over a larger area (Geertsma, 1973, van Opstal, 1974, Fokker and Orlic, 2006).

The calculation of surface subsidence due to salt solution mining follows the same approach using the calculated downhole volume reduction as input.

In case of non-linear rock properties or complex subsurface geometry, finite element or finite difference numerical modelling techniques need to be used (Settari, 2002). Minimally, these must be used to check the reliability of approximate analytical calculations. Even with modern computing power, run times can be excessive, in particular for more complex 3D geometries. In such cases a combination of (semi-)analytical and numerical techniques can be applied where the analytical calculations are used for scenario screening, to investigate sensitivities and to limit the number of numerical runs (Fokker and Orlic, 2006).

### *Geomechanical behaviour of porous reservoir rock*

In the traditional approach and in the absence of significant aquifer depletion, the volume reduction of the reservoir rock is assumed to be a linear function of the change in the average gas pressure. This implies that for a given reservoir, the volume reduction and the resulting surface subsidence should be linearly proportional to the drop in the average reservoir gas pressure and thus almost linear with the produced volume of gas. In particular when the effect of the influx of water from connected aquifers into the depleting reservoir is limited, as is often the case for gas reservoirs. To derive the proportionality constant, core samples taken from the reservoir are subjected to geomechanical tests, mimicking the stress changes expected in-situ. The scatter in core compressibility values derived from laboratory experiments is often significant resulting in uncertainties in the value to be used for field application. In addition, more and more field data is becoming available indicating non-linear compaction behaviour in sandstone reservoirs (Merle et al., 1976; De Waal, 1986; De Waal & Smits, 1986; Hettema et al., 2002; NAM, 2005; NAM, 2007; Houtenbos et al., 2007 and Ketelaar et al., 2011). The reservoir initially compacts much less than expected on the basis of the laboratory measurements. As the oil or gas pressure drops further, compaction and surface subsidence gradually increase, finally reaching values much closer to those derived from (standard) laboratory measurements.

Various mechanisms or combinations of mechanisms could be responsible, varying from delayed compaction in lower permeability or poorly connected parts of the reservoir or aquifers, to intrinsic non-linear, time-dependent, rate-type or diffusive behaviour of the reservoir rock or nearby salt layers. Other causes could be a previously higher effective stress during an earlier deeper burial of the reservoir or from unloading due to an increasing reservoir overpressure over geological time. The behaviour is well known in soil mechanics and a number of models have been developed to describe it, e.g. (Bjerrum 1967, 1973; Kolymbas, 1978; Den Haan, 1994). Independent of its cause(s), the phenomenon is a point of attention when updating subsidence predictions based on early subsidence observations. It can easily lead to early under-prediction of the subsidence, later followed by the need for multiple upward adjustments as new data become available over time (Fig. 3).

Another issue to consider in this context is the large difference in loading rate – typically five to six orders of magnitude – between laboratory and field conditions. Laboratory experiments indicate that field compressibility during later stages of production could become 20-30% higher than expected on the basis of the high loading rate laboratory measurements (Teeuw, 1971; Martin & Serdengecti, 1984; De Waal, 1986; Thompson & Schatz, 1986; Pauget et al., 2002). Under most circumstances an initial prediction based on laboratory-measured compressibilities corrected for loading rate effects is considered a good initial high-case scenario for sandstone reservoirs. In particular if laboratory loading to effective stresses significantly above those expected in-situ (e.g. to +30%) does not indicate large compaction weakening (increasing compressibility with increasing effective stress).

## *Subsidence monitoring*

The Netherlands have a long tradition of geodetic and geo-mechanical expertise. High quality benchmark networks, often preceding the production period, are in place and are regularly monitored. Subsidence measurements are carried out in accordance with the Measurement Plan, which has to cover the period of production and up to 30 years thereafter. It specifies timing, locations and methods of measurement. On land it includes at least one reference measurement before the start of production. In cases where subsidence from natural causes is important, multiple 'zero' measurements over a period of several years might be required to be able to properly separate out non-mining related contributions. The Measurement Plan is annually updated by the operator and submitted to State Supervision of Mines (SSM) for approval. Measurement accuracy at cm level is required which is a major technical challenge against a background of sea-level rise, peat oxidation, noise, benchmark instabilities etc. Innovations in geodetic measurement and interpretation technology do help, but the challenge is growing with increasing and concurrent use of the subsurface for hydrocarbon and salt production, storage and geothermal projects. In particular subsidence from fields with subsidence in the cm range is difficult to separate out. Most techniques can be more easily applied on land than at sea. A particular challenge is the measurement of subsidence in a tidal area where the subsiding area is covered by a dynamic layer of sediment, which is much of the time below sea level.

New technologies include the use of temporally and permanently installed GPS stations and the rapidly increasing use of more and more sophisticated PS-InSAR measurements from satellites (Hanssen, 2005; Ketelaar, 2008; Samieie-Esfahany et al., 2009; Carreon-Freyre et al., 2010; Teatini et al., 2011). The levelling benchmark, GPS and PS-InSAR techniques each have their own pros and cons in terms of measurement frequency, resolution, accuracy, spatial coverage etc. For each particular case an optimum combination of available technologies needs to be applied to reliably establish the subsidence with sufficient accuracy.

In addition to the above techniques, the downhole volumes of solution salt mining caverns are regularly checked using sonar measurements while a material balance approach is used to determine the down-hole squeeze volume (Breunese et al., 2003).

On the interpretation side, a relatively recent development is the use of geodetic software that fits one or more parameterised subsidence bowls, honouring all available subsidence height change data in a single space-time interpretation (Houtenbos et al., 2005). Through this process measurement errors are more easily identified, while subsidence can be attributed to different causes using a-priori information, such as maximum spatial frequency and correlation distance related to each subsidence mechanism. In principle all available data can be used, including that from later installed benchmarks or later technologies, as there is no need for the use of absolute heights. The technique does not depend on the often-problematic availability of long-term stable reference points and it is therefore not influenced by the increasing error in the measured heights with increasing distance from such reference points. A-priori knowledge on the reservoir and its properties can be incorporated to constrain the inversion results and to minimise the number of free parameters (Barends et al., 2009; Muntendam-Bos et al., 2008). As with all inversion-based technologies there are serious potential pitfalls, e.g. inverting noise, potential large

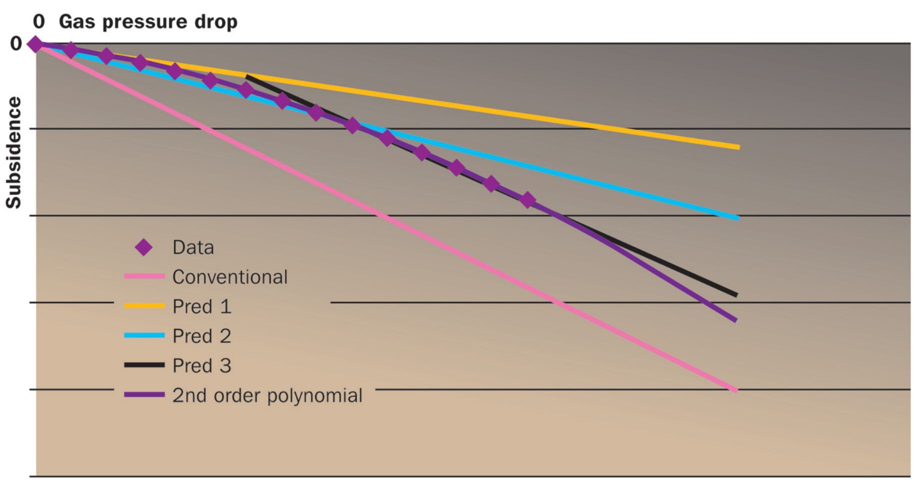


*Fig. 3. Impact of non-linear compaction behaviour of sandstone reservoir rock: conventional laboratory and field derived subsidence predictions.*

impact of outliers, and lack of control in sparse data areas. Avoiding these requires expert understanding and experience (Tarantola, 2005).

To ensure an optimal approach that meets appropriate standards under a wide range of scenarios, an industry guideline is under development (Barends et al., 2009). It covers the workflow from the design of the measurement network to the measurement technologies to be applied, the required accuracy, the measurement frequency, the processing and analysis of the acquired data, the comparison of the predictions with the measurements and the reporting standards.

### *Bringing it all together*

Subsidence predictions are the result of integrated multi-disciplinary workflows in which static and dynamic reservoir models are developed, calibrated and used to feed geomechanical models (Muntendam-Bos et al., 2008). Size and complexity of the effort are driven by the identified exposure and the available data: simple where it can be, extensive and complex where it must be. Prediction accuracy beyond a factor of two is difficult to realise at an early stage, mainly because of the scarcity of data and model uncertainties prior to the start of production. It is an iterative process in which remaining uncertainties can often be reduced over time as more subsurface, production and subsidence data become available (Fig. 4).

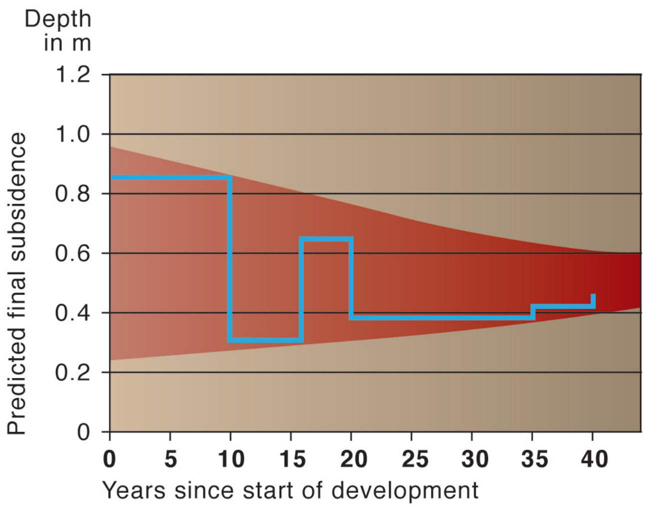


*Fig. 4. Typical changes in predictions and uncertainties over time (hypothetical example). Blue: predictions. Red: estimated uncertainty.*

Examples of major initial uncertainties are the contributions from aquifers surrounding the reservoir, the estimation of reservoir property distributions based on a limited number of wells and non-linear geomechanical behaviour of the reservoir rock (Fig. 3) and overlaying salt layers (when present). To manage this, multiple scenarios need to be developed to cover the range of possible outcomes, including a worst case. In this, care needs to be taken to avoid tunnel vision and underestimation of uncertainties. During the production period, the various scenarios need to be regularly compared with observations. Direct measurements of the subsidence bowl volume are not a good indicator to use for this. Small errors in the measured subsidence at the outer rim of the bowl are integrated over a large area resulting in surprisingly large uncertainties in the bowl volume. A better analysis is to compare predicted and measured subsidence at a number of (benchmark) locations spread out over the bowl area (Fig. 5). If these demonstrate a good fit then the calculated subsidence bowl volume can be considered reliable.

In the traditional approach, the predictions are compared with the measured subsidence using an RMS-criterion as described in attachment B of Barends et al. (2009). Where appropriate, the original approach can be extended to account for the effects of long term benchmark drift. Meeting the RMS criterion implies that the misfit between model and measurements is within the range to be expected on the basis of the estimated uncertainties in the subsidence measurements. Inconsistency between a model and observations is concluded when the misfit between the two exceeds the RMS criterion, driving the need for quality control of the data or model and scenario updates. As part of this, the subsidence data that become available during later stages can be used to adjust the subsurface model. An example is the adjustment of aquifer contributions that prove to be inconsistent with the observed subsidence pattern. In doing so, care needs to be taken not to fall into a 'curve-fitting trap'.

A more advanced, less arbitrary method to map the uncertainty in the subsidence predictions is to use an ensemble approach. Many realisations or scenarios are created, honouring the uncertainty ranges of the parameters that have the highest impact on subsidence. Propagating these models through geomechanical modelling gives a range of predicted subsidence values. Depending on the project requirements, the subsidence can be calculated at a single point, at multiple points, or integrated over the area of interest to arrive at a subsidence bowl volume. In the 'Red Flag' approach (Nepveu et al., 2010); this ensemble of subsidence outcomes is used to calculate the probability that a certain limit will be exceeded.

Improving the accuracy of the subsidence predictions requires the use of observations during the production of a reservoir. In the 'Red Flag' approach the data are used, as they become available, to update the probabilities of the modelled realisations. The realisations themselves are not changed. This is what is sometimes called an 'open-loop' approach. Fig. 6 gives an example of a synthetic study, where the subsidence from a synthetic 'real' reservoir (with fully known properties) is compared with a large number of realisations, which cover the estimated 'normal' uncertainties in the reservoir parameters. There is a large a-priori scatter in the outcomes for the resulting scenarios. The measurements (black squares) are used to update the probabilities of the fixed realisations. As a result

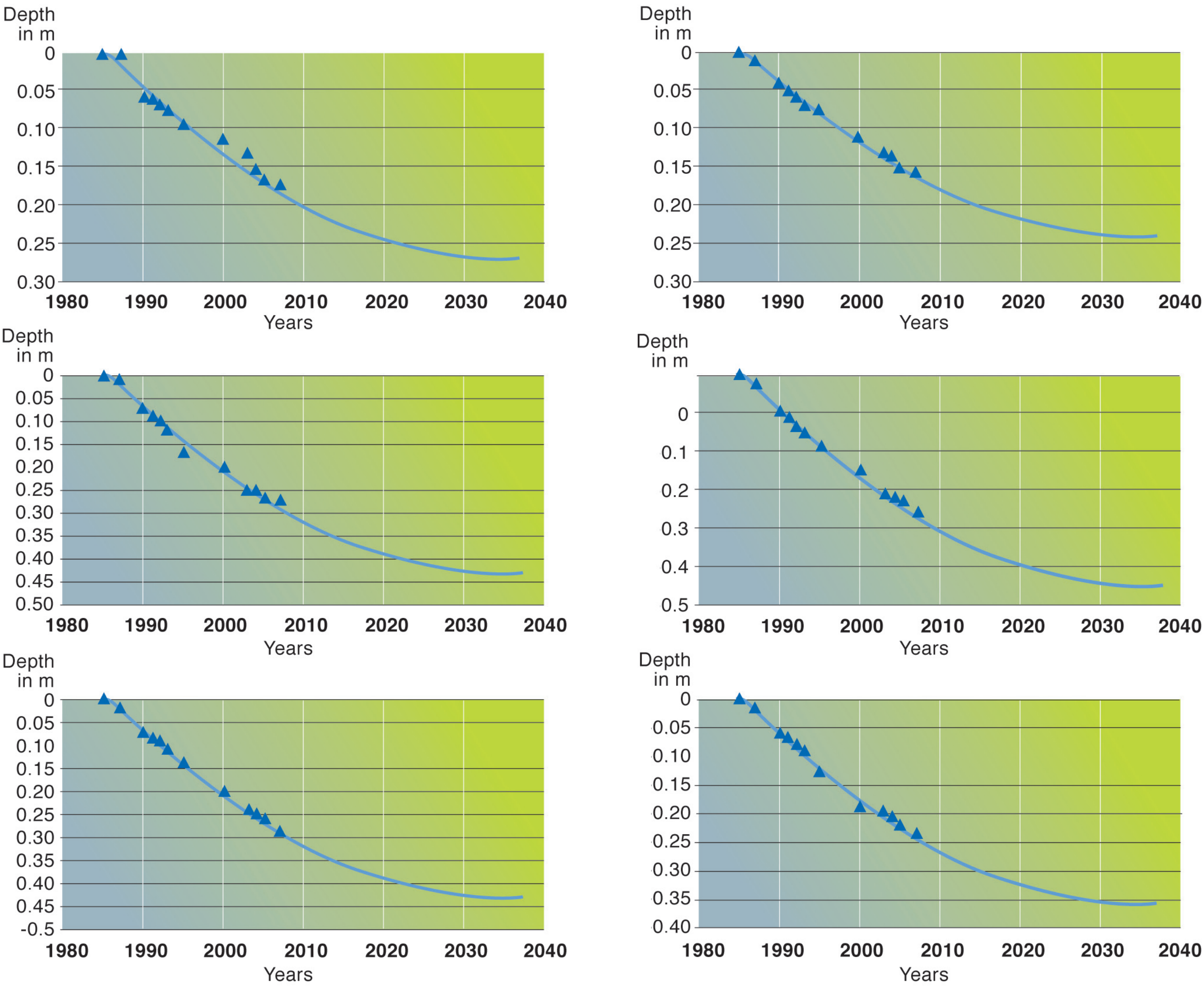


*Fig. 5. Comparison of calculated (solid lines) and measured (triangles) subsidence vs. time at a number of locations spread out over the subsidence bowl area (hypothetical example).*

the probabilities of realisations that closely follow the measurements (within the uncertainty range) increase. The probabilities of realisations that deviate from the measurements are reduced. Subsequently the renewed probabilities are used to determine the probability of exceeding a certain subsidence level. The results of this exercise are indicated in Fig. 7. Without measurements, the determination of the time at which a certain level is exceeded is quite uncertain; the incorporation of the measurements makes it much sharper.

The 'Red Flag' approach is also very suitable to design a monitoring network. Indeed, it provides an easy way to test the effectiveness of such a network without having real measurements. In real situations the approach is good as long as the measured subsidence values fall within the initial reliability range and a reasonable number of realisations predict values within the measurement error. If this is not the case, an update of the ensemble can be warranted. This is what is done in a closed-loop optimisation process. Then the existing realisations are complemented with new ones or they are updated. An example is the Ensemble Kalman Filter (Evensen, 2003; Wilschut et al., 2011), in which the cloud of total outcomes is used together with the measurements to update the ensemble of parameter realisations. Again it is essential that the scenarios are properly selected. A particular challenge is to use a sufficiently 'wide' range of scenarios that covers unexpected but possible (sometimes late) future behaviour.

## Organisational frame

Mining companies are accountable for socially and environmentally responsible production within the framework of Dutch regulation and legislation. This includes responsibility for prediction and measurement of subsidence as well as responsibility for preventing or compensating related damage. Compliance with statutory regulations is verified by SSM (State Supervision of Mines), the government regulator. The Ministry

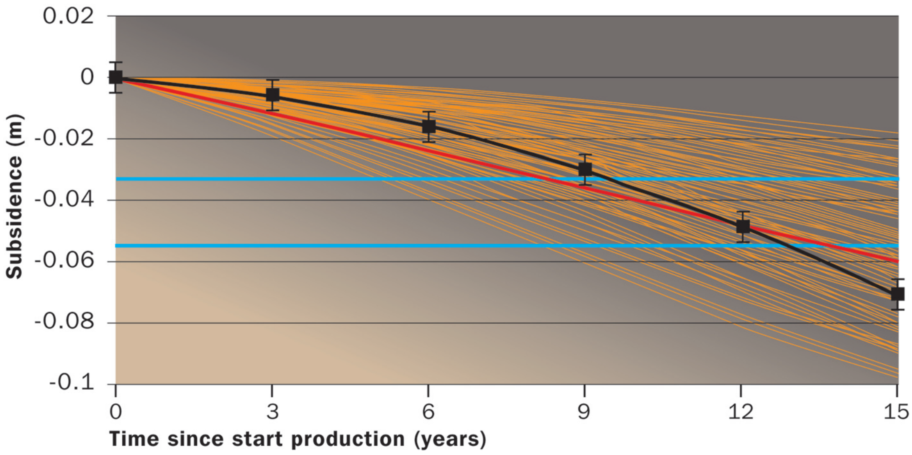


*Fig. 6. Ensemble of subsidence realisations in the centre of the subsidence bowl. Orange lines: Monte Carlo results; black symbols / solid line: measurements and their uncertainties obtained with the synthetic truth; straight blue lines: subsidence criteria: two absolute levels (horizontal lines) and a rate criterion (sloping line), (the same three subsidence criteria are used in Fig. 7).*

of Economic Affairs, Agriculture and Innovation (EL&I) authorises the Production Plan. Technical advice on soil movements is sought from SSM and from a dedicated technical advisory group at TNO working exclusively for the Ministry. Under the Mining Act, a separate institution, the 'Technical committee soil movement' (TCBB) advises the Minister on the treatment of soil movement and the prevention of damage in the Production Plan. The TCBB also advises on subsidence claims by citizens. The members are recognised professionals in the field of mining, subsidence and induced seismicity. The committee is not dealing with environmental damage. This is done under different legislation and a different institution: the 'Netherlands Commission on Environmental Assessment' (NCEA). Additional case-specific advisory bodies can be created or consulted by the government.

## The concept of 'effective subsidence capacity'

A key question for companies is: how much subsidence will be acceptable? The legal framework itself does not provide detailed answers. To address the issue and to constrain production for areas where possible subsidence is of the order of the natural robustness of the area concerned, the concept of 'effective subsidence capacity' has been developed (NAM, 2006). The effective subsidence capacity is the maximum human-induced subsidence that the affected area can robustly sustain. Depending on the characteristics of the area concerned the effective subsidence capacity can be defined in different terms: e.g. a maximum subsidence volume, a maximum subsidence at a given location, a maximum deepest point of subsidence in the centre of the subsidence bowl or a maximum subsidence rate (at a deepest point or averaged over an area. Determination of the effective subsidence capacity starts with establishing the

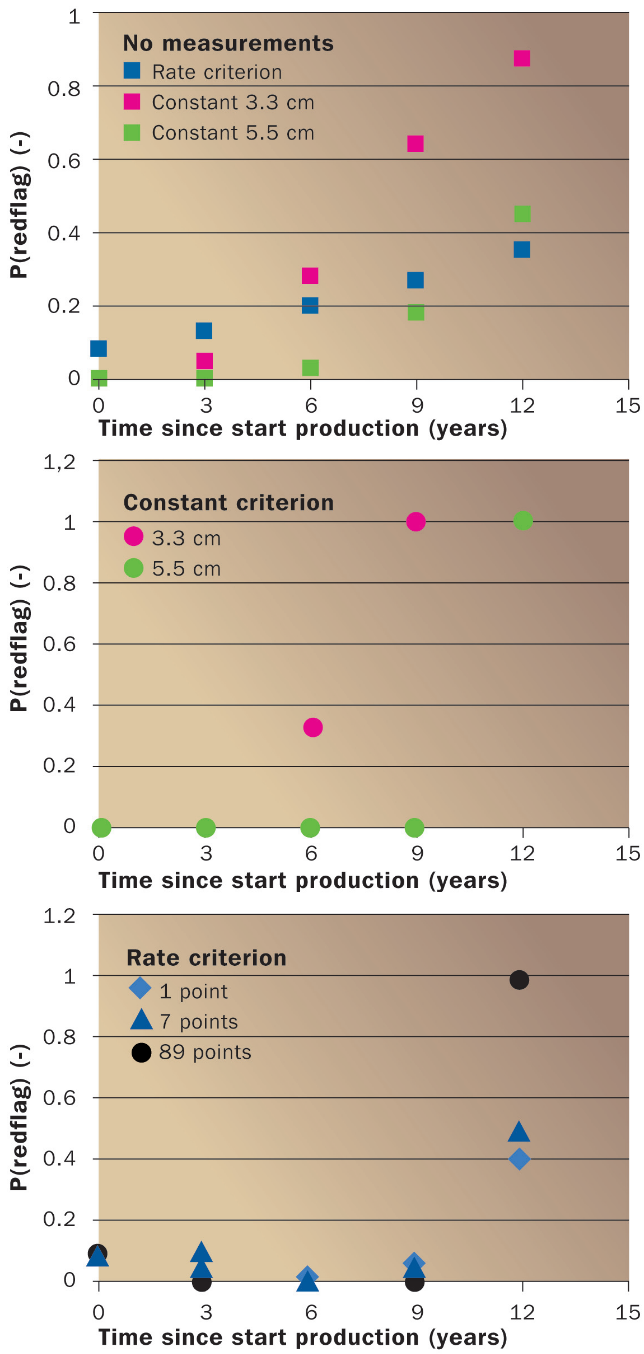


*Fig. 7. Probability that in the next campaign the subsidence criteria shown in Fig. 6 are exceeded taking account of the number of measurements. Top: Without any measurements. Bottom left: absolute-value criteria for 3.3 cm and 5.5 cm, both with 89 points. Bottom right: rate criterion with results for 1, 7, and 89 points.*

'limit of acceptable subsidence' which is the maximum total subsidence (all causes) that the area can sustainably deal with without damage to its 'environmental values'. All expected subsidence from natural causes is subtracted from the limit of acceptable subsidence. What remains is the amount of effective subsidence capacity available for human activities e.g. gas production related subsidence. The effective subsidence capacity can depend on location and time and it can change as a result of new data or new insights.

To apply the concept, the effective subsidence capacity is part of a control loop, which can contain the following elements:

1. limit of acceptable subsidence for the period relevant to the planned activity;
2. scenarios spanning the entire uncertainty range of subsidence expected from natural and human causes (including sea-level rise);
3. measurement plan;
4. agreed procedure to update expectation values of realised and predicted subsidence;
5. system to give an early warning in case predicted subsidence threatens to exceed the limit of acceptable subsidence;
6. agreed measures to adjust man-induced subsidence (rate);
7. control system to check that impact on the environment does not occur, regardless of total subsidence remaining within the limit of acceptable subsidence;
8. independent audit system to ensure compliance and to verify the technical integrity of the underlying work.

## Application to the Wadden Sea

The Wadden Sea (Figs 8, 9 and 10) is a large temperate coastal wetland system behind a chain of coastal barrier islands. It is one of the world's most important wetlands, featuring a rich diversity of flora and fauna. It is on the UNESCO world heritage list on behalf of its unique morphodynamic features as well as its wildlife values and one of the Netherlands most notable nature conservation areas protected under the European Birds and Habitats Directives. Gas production started in the mid-eighties of the previous century. The licensing process included an Environmental Impact Assessment (EIA) under the Environmental Management Act and the application for two main permits: the Production Plan, which is mostly the subject of this paper, and a permit under the Nature Protection Act.

Production is only permitted under very strict conditions. As an example, all new drilling under the Wadden Sea is done from onshore locations using deviated wells.

The natural system contains an extensive and coherent system of tidal flats, salt marshes, barriers and ebb tidal deltas. The forces of tides and waves create a complex and highly dynamic pattern of sediment displacement that dominates the morphological system on which the biodiversity thrives (Elias et al, 2012). Tide-induced currents transport large volumes of sediment – back and forth – through the tidal inlets. This sediment contains a small amount of fines brought in from other coasts. The bulk of the sediment however is sand, which is derived from the North Sea side of the barrier islands and adjacent ebb-tidal delta's. Net sand import from outside the Wadden Sea system is negligible. Yearly changes in local sediment height can be tens of cm on the tidal flats and several metres in the vicinity of migrating channels. Due to the natural transporting capacities of the Wadden Sea system there are limits to the amount of sediment from the North Sea that can be naturally imported and deposited in the Wadden Sea back-barrier area. In case of too rapid relative sea-level rise the system will eventually drown, and barrier erosion and landward migration of the ebb-tidal deltas will be enhanced (Elias et al., 2012). For Ameland, this erosion is compensated since 1990 by sand suppletions under a dynamic `hold the coast line` preservation policy (Schoeman, 2006).

The long-term survival of the Wadden Sea system depends on its ability to keep balance with the average long-term relative sea-level rise by means of sedimentation and thus maintain a dynamic morphologic equilibrium. The sea-level characteristics are strongly related to the 18.6-year lunar nodal cycle, as are probably also the morphodynamics (Hoeksema et al., 2004; Wang et al., 2005).

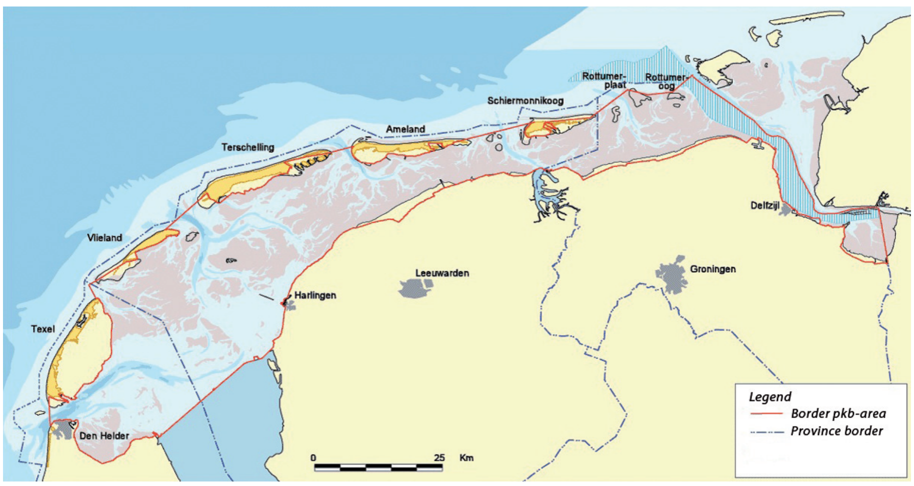


*Fig. 8. Map of the Dutch Wadden Sea area.*

*Fig. 9. View on the Wadden Sea near Moddergat.*

*Fig. 10. View on the Wadden Sea from Schiermonnikoog.*

It has thus been chosen to consider the sedimentation over periods of 18.6 years. During the decades preceding gas production the rate of relative sea-level rise was some 20 cm per century (Schoeman, 2006). The limit of acceptable subsidence 'M' is the maximum rate of relative sea-level rise that can be accommodated in the long term without impact on the geomorphologic equilibrium and the sedimentation balance. Note that a relative sea-level rise may be caused by either absolute sea level-rise or subsidence. The sedimentation balance ('the system's hunger for sand') is determined by the capability of the tidal basins to 'capture' sediment over longer time periods. It is the overall rate-determining step. This capability had to be determined from the various data available, such as geological information concerning the infill of the tidal back-barrier areas in the Holocene, the erosion of the central part of the barrier islands during the past 500 years, sediment transports through the inlet and sedimentation on shoals and tidal marshes. Since a precautionary principle in regard of nature protection is stipulated by law – when in doubt do not take risks that can be avoided – it was chosen to follow a quite conservative approach. This is particularly important in the present application since overall sedimentation rates in the Wadden Sea cannot be accurately assessed with measurements over short periods and hence they are not suitable for an early warning or control system. From all information available the lowest values were therefore chosen to determine the capability. These turned out to be the long-term rates of coastal retreat of the middle parts of the barrier islands which, on the long term, deliver the sands needed. Under a conservative approach it is estimated that Zoutkamperlaag and Pinkegat (two tidal basins in the Wadden Sea affected by gas production) can cope with a relative sea-level rise of 5-6 mm per year over a period of 18.6 years (as an average over the total tidal basin areas of respectively ca 140 and 70 $km^2$ each). This value is taken as the limit of acceptable subsidence (rate) M. Numerical modelling of sediment dynamics for the same tidal basins yields values around 10 mm per year (Wang & Eijsink, 2005). It is beyond reasonable doubt that, following the conservative approach, the resulting increases in the 'sand hunger' of the Wadden Sea is compensated by sand transport which is derived from the North Sea coast. The additional coastal erosion at the North Sea side of the barrier islands is compensated by foreshore sand suppletions.

The effective subsidence capacity available for human activities, such as gas production planning, is derived by subtracting the expected average sea-level rise from the limit of acceptable subsidence (M) discussed above. The sea-level rise scenario is updated every five years. It consists of two different parts. The short-term part, essentially covering the next 5 years, is based on the maximum rise that can be read in historical observations until the present. The long-term part, covering the period between 5 and 40 years from the present, is a time-dependent interpretation of sea-level rise from physically and socio-economically based climate models for the next century (such as models published by Solomon et al., 2007). As sea-level rise is predicted to accelerate, effective subsidence capacity shrinks over time. A historical example is shown in Fig. 11, with the junction of the two parts of the 2006 sea-level rise scenario five years from 2006, in 2011. A more recent example for the Pinkegat tidal basin has recently been published in Ketelaar et al. (2011). Note that for most sea-level rise scenario's the system will eventually start to drown, regardless of whether or not gas is being produced. Gas production profiles are adjusted such that the predicted 6-year-averaged expectation values of subsidence rate (in terms of volume over tidal basin area) – under a range of scenarios and over the full production period – will not exceed the effective subsidence capacity. Expected subsidence rates from production in all relevant gas fields (and from other human activities such as e.g. salt mining) are taken into account. Compliance with the limit of acceptable subsidence is tested in hind cast using the actual subsidence and the actual sea-level rise measured for the preceding 18.6 years. Production is adjusted or halted if the 6-year expectation average indicates a risk of exceeding the effective subsidence capacity now or in the future. The approach is known as 'Hand on the Tap'.

Operators in the area currently use a base-case scenario and additional scenarios spanning the uncertainties deemed most significant to execute the 6-year test. Latest development is to include the effects of salt creep and the effects of delays between production and reservoir compaction (Ketelaar et al., 2011).

TNO, in their supporting role for SSM, employ the Red Flag approach, described above, to calculate and update the expectation value of the subsidence over time as new data, new forecasts or new production plans become available. A suite of scenarios, all considered possible and covering a large range of outcomes, is built and the associated subsidence is calculated for each. The weighted average of these outcomes is the subsidence expectation case where the weight factors are the Red Flag derived normalised probabilities. The probability of each individual scenario is updated over time through confrontation with the latest measurements. A 'Hand on the Tap' intervention is applied based on the probability that the subsidence limit will be exceeded now or in the future.

Where possible, subsidence is measured using regular bench-marks. In the Wadden Sea special buried benchmarks have been installed on which GPS antenna's can be mounted temporarily (5-days) during measurement campaigns. Initial results indicate mm-level resolution. Measurements are repeated once additional subsidence is expected to be above noise levels.

Onshore, three continuous GPS stations are installed near subsidence bowl centres, to monitor subsidence rates. They act as an early warning system. In case of unexpected measure-ments, there is time to first check the data against additional measurements from other benchmarks and – in case the data are confirmed and require action – to timely adjust gas production. The full monitoring and control framework is depicted in Fig. 12. Extensive ecological monitoring programs are carried out to independently confirm that the natural values of the Wadden Sea are not being damaged. Under an agreed measure-ment and control protocol the operator annually reports latest results and – if needed – updates models, subsidence predic-tions, production profiles and production plans. At the request of the minister of EL&I, the formal institutional body of the

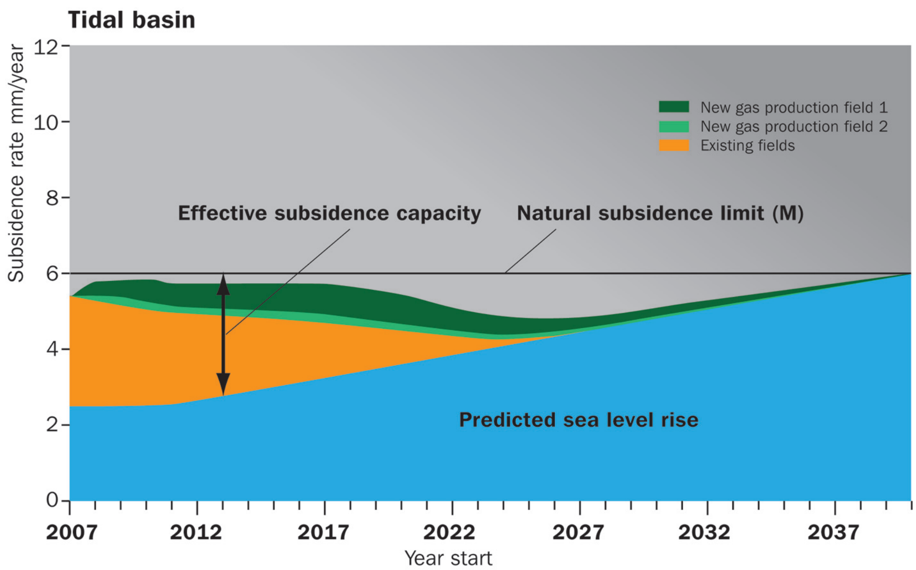


*Fig. 11. Application of effective subsidence capacity to the Wadden Sea: The predicted 6-year-averaged expectation value of subsidence rate (in terms of volume over tidal basin area) should not exceed the effective subsidence capacity.*

NCEA has put together a team of recognised experts in an audit committee. The committee evaluates the outcomes of the annual measurement and control protocol and the ecological monitoring. To date, measured subsidence has stayed within the limit of acceptable subsidence (Auditcommissie, 2010). For Ameland a separate subsidence monitoring committee overlooks progress, completeness and quality of the monitoring programs (De Vlas, 2011). The committee organises regular audits on the results of the Ameland subsidence studies, the latest of which took place in 2011 (Speelman et al., 2012).

## Communication

Annual mandatory reporting by the operator of the results obtained under the monitoring and control protocol keeps the authorities and others, inclusive of the general public, informed on use of the effective subsidence capacity (NAM, 2011). It serves to demonstrate that the actual average subsidence stays strictly within the defined bounds and that, from a scientific point of view, there is no reasonable doubt that damage to the tidal system will not occur now or in the future. The team of recognised experts put together by the formal institutional body of the NCEA annually reports to the minister of EL&I and publishes their evaluation of the outcomes of the annual measurement and control protocol and the ecological monitoring on their website (Auditcommissie, 2010).

## Future developments

In the context of gas production, the effective subsidence capacity concept and the 'Hand on the Tap' control loop are presently only applied in the Wadden Sea. The concept could be applied elsewhere, e.g. where available effective subsidence capacity has to be shared between different, competing and possibly concurrent, human activities.

## Conclusions

### *General*

1. Subsidence due to the production of hydrocarbons or salt solution mining can be predicted on the basis of subsurface models, laboratory data, geomechanical models and production forecasts. During production subsidence can be accurately measured in the field. Therefore subsidence (rate) can be regulated in a permit.
2. Predictions accurate within a factor of two (actual subsidence can be double or half of that predicted) are difficult to make prior to and during the early stages of field development, mainly because of scarcity of data and because of model uncertainties. Uncertainties related to geomechanical behaviour and aquifer depletion remain during later stages.

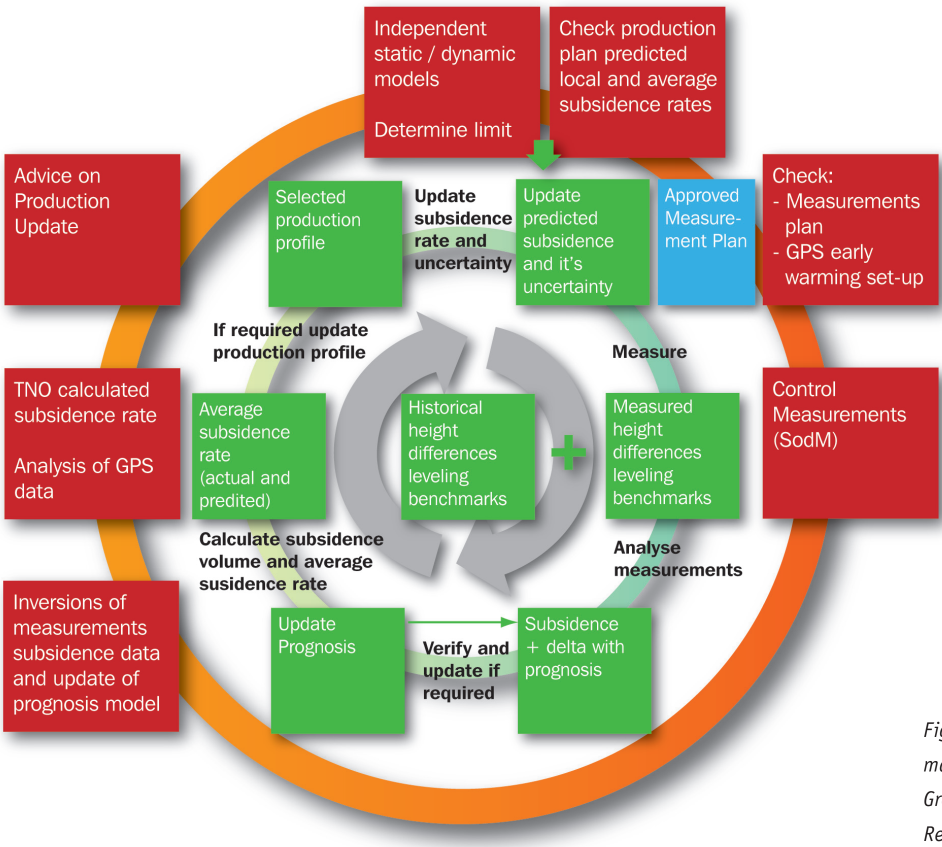


*Fig. 12. Monitoring and control framework to manage subsidence in the Wadden Sea area. Green/blue: operator activities and products. Red: SSM/TNO-AGE activities and products.*

3. To ensure that subsidence from the production of hydrocarbons or salt will not lead to unacceptable damage, an extensive legal, technical and organisational framework is in place in the Netherlands.
4. As part of the technical framework an independent (Bayesian) statistical analysis of the latest data enables to calculate the probability of all subsidence scenarios deemed possible and thereby the ensemble risk of exceeding a predefined limit now or in the future.
5. The 'limit of acceptable subsidence' is defined as the maximum (rate of) subsidence from all causes that an area can robustly sustain. The 'effective subsidence capacity' is the maximum part within this 'limit of acceptable subsidence' that is available for human related activities. Both concepts were originally developed for the Wadden Sea area but can be generalised for wider use.

### *Wadden Sea*

6. In tidal systems, subsidence leads – like sea-level rise – to a volume increase with a potential to increase flow rates and for flats to disappear. The critical rate of long-term volume increase is known for the Wadden Sea and defines the limit of acceptable (volume rate) subsidence. Subtracting the subsidence volume rate 'consumed' by natural relative subsidence (the expected average sea-level rise and the natural subsidence – under a conservative cautious scenario) from the limit of acceptable (volume rate) subsidence defines the effective subsidence (rate) capacity available for human activities.
7. Keeping subsidence within this defined limit requires 1) an operational procedure based on expectation values of subsidence rate; 2) a monitoring and control system to feed an early warning system with data; and finally 3) a protocol with preventive actions to be followed in case the early warning is confirmed, ensuring that production will be reduced or halted if the expected or actual subsidence rate (natural + man induced) is likely to exceed the permitted limit.
8. In the operational procedure for mining companies, the effective subsidence capacity concept and six-years-average expectation values of subsidence rates are used to calculate maximum allowable production rates. An annual measurement and control loop is executed by the operator to update the calculations and adjust production rates if required (Hand on the Tap approach).
9. A GPS based early warning system is used for early detection of unexpected subsidence behaviour. A linked operational procedure (Hand on the Tap) warrants that adequate actions are taken in time should such behaviour occur.
10. To date, measured subsidence and predicted future subsidence have stayed within the natural subsidence (volume rate) limit.

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