Deltares

Deltares Capacity Statement on dealing with Land Subsidence

Our Vision and Integrated Approach

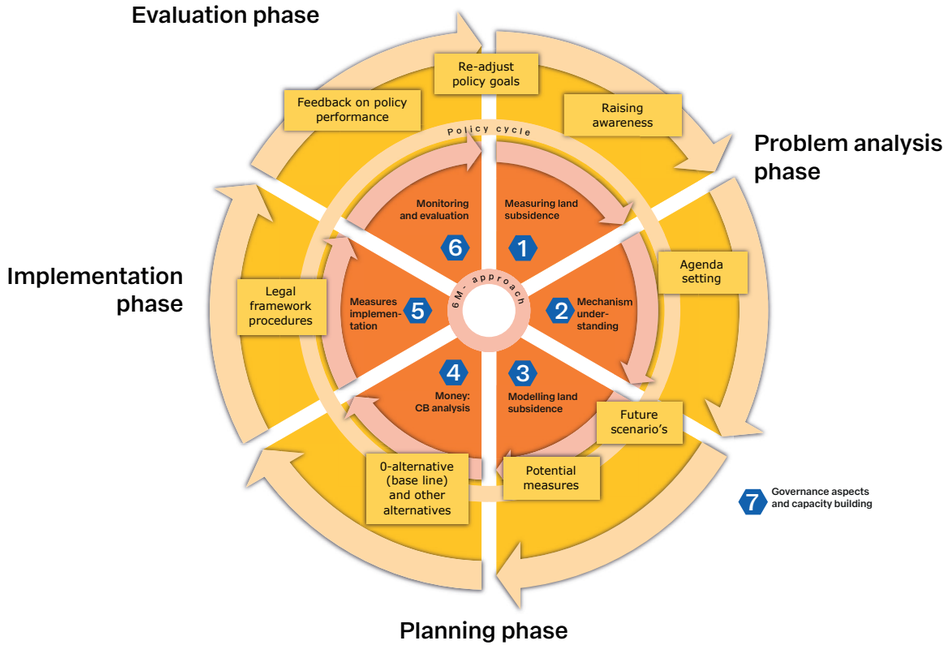
Land subsidence – much of which is caused by human activity – exceeds absolute sea-level rise by up to a factor of ten in many coastal zones worldwide (including mega-cities). Without mitigation, parts of Jakarta, Ho Chi Minh City, Bangkok and numerous other coastal cities will sink further below mean sea level. One of the major causes is excessive groundwater extraction in combination with rapidly increasing demand for water because of urbanization and population growth. The loading and draining of soft soils is another major factor. The phenomenon can exacerbate flood risk and damage essential infrastructure and buildings, with economic damage in the order of billions of dollars per year. The costs of adaptation measures to address these impacts far exceed the costs of mitigation.
Land subsidence is literally a “hidden” issue, taking place out of sight, sometimes at a slow pace. Its complex, cross-sectoral nature means it is usually not fully recognized (or acknowledged), especially in the domain of governance and institutional mandates and responsibilities. Furthermore, large amounts of long-term data are necessary to monitor, assess and predict its causes, progress and risks. These data are often lacking, even though they are crucial for the development of effective, tailor-made, adaptation or mitigation strategies.
If proper attention is paid to developing the required technical, administrative, and institutional capabilities, the negative impacts of human-induced land subsidence can be mitigated, and the process largely stopped. A comprehensive and integrated (step-wise) approach is therefore needed, preferably in pro-active form.

Our stepwise integrated approach has been elaborated in line with the stages of the policy cycle, with clear steps that need to be taken towards a comprehensive policy strategy for land subsidence. On the technical side, we identified six steps – collectively referred to as the 6M approach – that are crucial to tackle land subsidence: Measuring, understanding Mechanisms, Modelling, Money (making a cost-benefit analysis), Measures and Monitoring. Governance aspects and capacity-building in all those steps are also addressed.

Our work is focused on supporting our clients with methods and tools in each step, resulting in products and services for reducing the impact of land subsidence and establishing more options for mitigation. This is further illustrated below. With our in-depth knowledge of water and the subsurface, we can make a difference in important challenges facing society, especially through our applied research programs and related ‘moonshots’.

Our clients and networks

Our national and international clients include government authorities, policymakers and administrative authorities responsible for operational and strategic management (particularly in the domain of water). In the private sector, our clients include consultants, contractors and insurance companies. Financing agencies such as national development aid agencies, the European Commission, the World Bank and the Asian Development Bank are also regular clients.



Deltares is an active participant in a range of networks and joint research programs in the Netherlands and abroad. In addition to being involved in various joint research projects with universities (such as 'Living on Soft Soils'), we are a partner in the Dutch public-private cooperation program on dealing with Subsidence (Regio Deal Bodemdaling Groene Hart) and the Dutch National Research Programme on Greenhouse Gases in Peatlands (NOBV) to improve the action perspective of all stakeholders. Deltares is also active in the Unesco IHP Land Subsidence International Initiative. This working group has endeavored to improve and disseminate knowledge on land subsidence since the 1970s through international symposiums on land subsidence, collaborative projects and publications.

Our products and services

Deltares offers support for the implementation of a multi-sectoral and multi-stakeholder approach that addresses the 6M steps (see above) and the cross-cutting issue of governance. This results in the following products and services:

- Setting up networks for measuring and monitoring subsidence and groundwater resources;
- Analyzing and identifying subsidence trends and causes over time (natural and human-induced);
- Predicting subsidence, and risk and damage analysis, in a range of socio-economic and climate change scenarios (modelling and visualization);
- Decision-support tools for cost-benefit analysis, and the assessment and selection, of appropriate measures;
- Supportive actions on the vof subsidence, and capacity-building and training. This is further explained below and illustrated in the project examples.

1 Measuring

Measurements are made in order to establish a picture of the current status of land movement in terms of spatial and temporal trends but this activity also extends into the governance domain and the legal framework relating to land subsidence. More specifically, the focus is on the physical elements (system analysis: what causes land subsidence?) and governance elements (raising awareness, problem owners, who bears responsibility?).
Accurate measuring techniques are also essential to validate models for predicting land movement. Measuring techniques include GPS and conventional leveling, the extensometer technique, LiDAR (Light Detection And Ranging) and InSAR (Interferometric Synthetic Aperture Radar).

Deltares ambition:

- To integrate different data sources in order to establish a holistic view of spatial and temporal trends of land movement and related factors such as (dynamic) groundwater levels.
- To use the best available measuring techniques for each case.

See project examples A, B, C and D of monitoring in the Netherlands, a quick scan of subsidence in Lagos and Douala and a generic adaptive monitoring framework.

2 Understanding Mechanisms

Multiple processes, either natural or anthropogenic, often contribute to land subsidence at a given location. Discriminating between these different sources by understanding the underlying mechanisms is important in order to take effective measures (mitigation measures to reduce anthropogenic subsidence, adaptation measures for natural subsidence). For example, extensometers can be used to derive point measurements of vertical movement in different subsurface levels at mm-scale accuracy, and to determine the contribution of different soil layers, and in some cases processes, to total land subsidence.

Deltares ambition:

- To enhance knowledge about the different processes that contribute to vertical movement in soft soils, allowing for a better understanding and the unraveling of the causes of long-term land subsidence (through lab research, for instance).
- The application of inverse modelling to constrain the available knowledge about the geology and hydrological dynamics of a system quantitatively with land subsidence observations.

See project examples E and F for projections of subsidence in the Mekong Delta and in New Orleans.

3 Modeling and visualization

Once the causes of land subsidence have been established, predictions can be made through numerical modelling to acquire an insight into future land subsidence and the effects of adaptation and mitigation measures under different climate scenarios. Model outcomes for historical scenarios (including eras predating measurements) provide spatially resolved insights and may be used in conjunction with InSAR and LiDAR results to make predictions. Deltares has extensive experience with combining hydrological (groundwater) models (MODFLOW, USGS) with a one-way coupled geo-mechanical land subsidence model (SUBCR) and with the modelling of shrink and swell, as well as peat oxidation.
Numerical models are available for soft-soil-related land subsidence as a result of drainage or loading. They calculate the rate of organic matter degradation and compaction. Modelling land subsidence generates important added value by comparison with relying on measurements alone, as it makes it possible to address missing data, the spatial heterogeneity of the subsurface and variability in the hydrogeological situation (including groundwater extraction). More refined modelling can provide the required spatially resolved land subsidence predictions (maps and figures) under a range of possible and actual conditions.

Deltares ambition:

- To be able to provide well-tested and developed numerical models in order to understand spatial and temporal trends for different scenarios, providing a realistic estimate of the uncertainty of model outcomes, and possible ways to reduce uncertainty.

See project examples H and I for a global subsidence map and mapping deep peat carbon stocks with LiDAR in Sumatra.

4/5 Cost-benefit analysis /and implementation of measures

The main financial risks and costs/benefits should be assessed in subsidence-prone areas, including damage prevented by adaptive measures and the maintenance of assets. This can lead to improved design options, the programming and prioritization of investments, feeding into asset management, and the inclusion of spatial and temporal scales as well as public and private responsibilities. Deltares can perform cost-benefit assessments and develop decision-support models and tools in order to select the most appropriate and sustainable adaptive measures for the short and long terms.
The implementation of measures follows cost-benefit analyses and informed decision-making. It often includes governance and legal aspects (who is responsible?) and financial aspects (who is paying for the measures, and who benefits?). Deltares can advise about technical aspects, as well as the governance measures and institutional arrangements needed to facilitate and accelerate the implementation of measures.

Deltares ambition:

- To include damage values based on modelled future subsidence rates in order to estimate direct subsidence damage for different climate and socio-economic scenarios, and adaption and mitigation pathways.
- To combine damage estimates with the benefits of damage prevented in subsidence mitigation scenarios.
- To assess impacts on a range of ecosystem services.

See project examples J and K for a quick-scan cost-benefit analysis in Gouda and a roadmap for the mitigation of land subsidence in Jakarta.

6 Monitoring

Systematic monitoring requires sound organization: data should be reliable and easily accessible in order to provide feedback on the effectiveness of policy and measures. Monitoring plans should be drawn up to describe which measurements are needed, how often and at which locations. The answers to these questions will differ in each case depending on local physical and socio-economic conditions (such as subsoil composition and variation, natural and anthropogenic hydrological situation, policies and political interests). Deltares has developed an adaptive monitoring framework with feedback loops to assess the effectiveness of measures and to support adjustments to policies and measures if needed.

Deltares ambition:

- To support the development of frameworks for monitoring land subsidence in coastal areas worldwide.
- To integrate different data sources and store data in transparent and easily accessible databases.

See project examples A, B, C and D.

7 Governance and capacity building

Multi-sectoral cooperation, joint policy development, and the coordination and participation of all relevant stakeholders is needed for good governance and institutional arrangements in the domain of land subsidence. A clear policy framework and appropriate legislation for land subsidence issues will support agenda-setting, planning and implementation of interventions and enforcement from the local to national levels. Deltares can support the governance process with a range of methods and tools for participatory stakeholder involvement, such as serious games and collaborative modelling. This approach is being elaborated in several multi-sectoral 'delta plans', notably in the Netherlands, Vietnam and Bangladesh. Particularly in the problem and planning phase, policy- and decision-makers, and experts, from the national to the local level need awareness-raising and capacity-building for land subsidence issues. This may involve need assessments, training programs, workshops, seminars and conferences. Moreover, exchanges of knowledge and best practices are important to prevent the recurrence of the same problems and the duplication of activities (in research and elsewhere). Deltares has extensive experience with capacity-building for land-subsidence issues in many international and national projects covering technical and governance aspects. This effort is supported by our Deltares Academy https://www.deltares.nl/en/academy-courses/.

Deltares ambition:

- To have a generic approach to governance issues in subsiding areas that is implemented in ways tailored to specific area characteristics.
- To build a database of best practices for coping with land subsidence with examples from around the world.

See project examples K and L for a mitigation roadmap for subsidence in Jakarta and an international comparison of governance systems addressing subsidence.

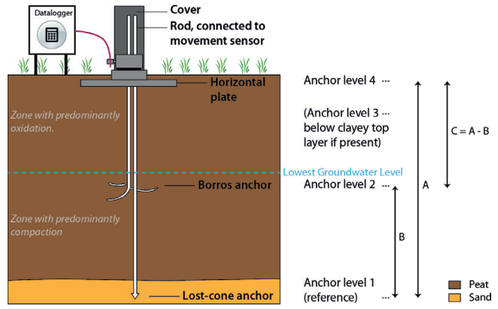
Project examples

A. Rouveen monitoring site: systematic measurements required for effective technical and policy measures

Deltares is using four different measuring techniques at this site to measure land movement: extensometers, conventional spirit levelling, LiDAR and InSAR. Moreover, conventional and large incremental load tests are being performed on samples obtained by the Deltares Large Diameter Sampler (DLDS). The objectives are: to optimize techniques for measuring land movement, to quantify short-term and long-term land movement dynamics in a cultivated peatland, to understand and unravel processes contributing to land movement, to determine and understand the effects of submerged drains. This site is the first step on the road to a national monitoring network that will produce systematic and frequent measurements of land movement and related conditions. The comprehensive monitoring of land subsidence helps to determine the effectiveness of mitigation measures. It also provides a picture of the rate of land subsidence, the mechanisms involved and how they vary in time and space.

B. Extensometer measurements

Deltares has designed an extensometer specifically for application in soft soils in order to make hourly measurements of land movement at up to five levels in the subsurface with mm-scale accuracy. We have installed more than twenty extensometers in peat(y) soils around the Netherlands. The measurement results show spatial and temporal trends in land movement associated with variations in environmental conditions (such as drought) and under a range of land subsidence mitigation measures. They also show the contribution of processes in different soil layers to land movement. These data are important for the calibration and validation of numerical land movement and settlement process models, and for optimizing the assessments of land movement at regional scales with full spatial coverage using radar images (InSAR). Deltares makes those assessments in partnership with the Delft University of Technology.

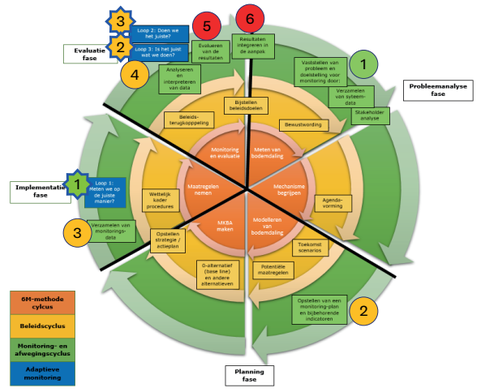


C. Quick scan for Lagos & Douala

African coastal cities are vulnerable to climate change effects such as sea level rise, more intensive storm surges and rainfall. Recently, the World Bank monitored land subsidence in eighteen African coastal cities with InSAR. InSAR analysis allows for the remote detection of deformations of the Earth's surface. The observed deformation may be due to a mix of different phenomena that are difficult to identify without further analysis. Low subsidence rates are a poor indicator of subsidence risk/vulnerability and may lead to the underestimation of the importance of subsidence in studies of coastal urban resilience in the future. Deltares is developing a quick scan to assess vulnerability to subsidence by combining the global data with local groundwater use and geological/hydrogeological data.

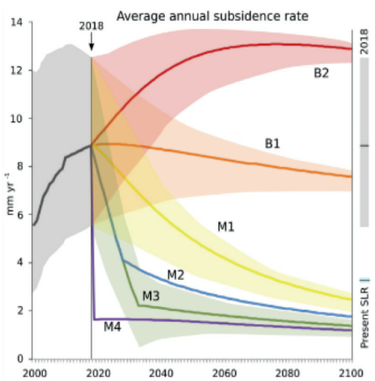
D. Adaptive monitoring framework of spatial interventions addressing land subsidence

Deltares has developed a framework for the adaptive monitoring of spatial interventions that serves as a bridge between the physical aspects of monitoring and the more social and governance side, which may also affect decision-making and implementation. The proposed method also includes the notion that changing circum stances may affect the purpose for which the measures are taken, the measures themselves, or what exactly is monitored. This framework can be used to strengthen the implemen tation of adaptive measures for land subsidence. The framework is being applied for several cases, notably in Gouda (the Netherlands) and Semarang (Indonesia). Feedback from stakeholders will be incorporated to develop this approach further.



E. Projections of subsidence in the Mekong delta induced by groundwater extraction

Projections of subsidence induced by groundwater extraction are presented as well as the resulting delta elevation loss for this century in line with six mitigation and non-mitigation extraction scenarios using a 3D hydrogeological model with a coupled geotechnical module. Results reveal the long-term physical response of the aquifer system through different groundwater extraction pathways and show the potential of the hydrogeological system to recover. If groundwater extraction is allowed to increase continuously, as has been the case in recent decades, extraction-induced subsidence alone could lead to the submersion of the Mekong delta before the end of the century.

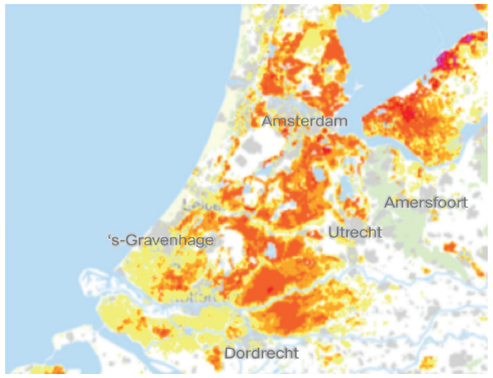


F. Towards Resilient Groundwater and Surface Water Management in New Orleans

Land subsidence in New Orleans exacerbates flood risk and it may cause damage to buildings and infrastructure, and the loss of protective coastal wetlands. To make New Orleans more resilient to flooding, a new approach to groundwater and subsurface management will be needed there. Deltares was involved in the development of an approach of this kind that encompasses the collection of high-quality and high-resolution subsurface and groundwater information as part of the monitoring of groundwater and subsidence in order to better understand and quantify shallow land subsidence in New Orleans. Moreover, a subsidence vulnerability map was drawn up based on geological field work, and iMOD was used for the numerical modelling of groundwater and subsidence. Eventually, such information will be needed for the effective design of tailor-made measures to limit urban flooding and subsidence.

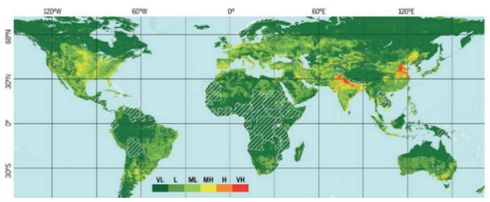
G. Maps for the prediction of land subsidence in the Netherlands

In 2021, Deltares provided updated maps predicting land subsidence in the Netherlands for the Dutch Climate Impact Atlas, which brings together and displays information about the impact of climate change in the Netherlands. It is used by local and regional government for climate stress tests. The Deltares modelling tool Atlantis was used to produce land subsidence projections for two markedly different scenarios: a future with significant climate change and the continuation of the current water management practices that lead to land subsidence and a future with limited climate change and mitigation measures taken to limit land subsidence. Deltares developed Atlantis for large-scale projections of shallow land subsidence based on existing information about subsurface lithology and hydrology. The maps provide a nationwide picture of the extent of land subsidence to be expected until 2050 and 2100, and they can help to determine the scope and extent of land subsidence issues and to compare different regions.



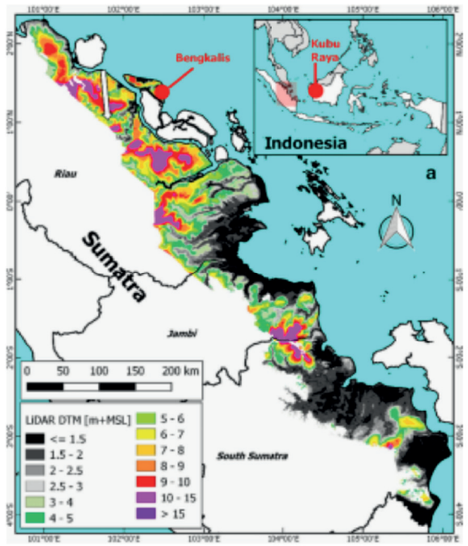
H. Global Subsidence map

A new global map published in *Science* (*https://science.sciencemag.org/content/371/6524/34.full*),shows that land subsidence as a result of the depletion of our groundwater resources is a global anthropogenic hazard that produces relevant environmental, social and economic impacts. According to the authors, nineteen percent of the global population and twelve percent of the global gross domestic product are at risk because of the high probability of land subsidence in the regions concerned. Eighty-six percent of the exposed global population lives in Asia and subsidence could increase the flood risk for 635 million inhabitants by 2040. The aim of the global map and the underlying research is to raise global awareness and inform public authorities about this subsidence hazard. The research could enhance our understanding of land subsidence, identify new subsiding areas and guide mitigation efforts. Deltares and Utrecht University are now improving this map by supplying a modelling framework that can be used to predict global land subsidence under different scenarios.



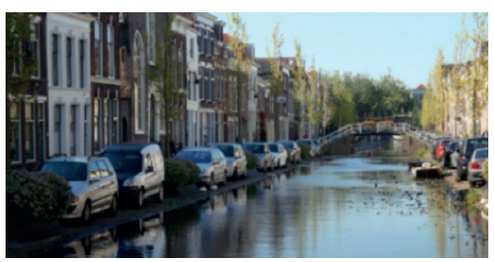
I. Mapping deep peat carbon stocks using a LiDAR-based DTM

In Indonesia and most of Southeast Asia, accurate maps of deep peat are still crucial for correct estimates of peat carbon stocks and to facilitate appropriate management interventions regarding peatland subsidence and carbon emissions. Deltares developed a rapid and cost-effective approach to deep (>3 m) peat mapping in the eastern Sumatra lowlands using a LiDAR-based Digital Terrain Model (DTM) in an area where the peat thickness was limited. Peat thicknesses in the field were measured by creating perpendicular transects from the rivers, streams, and canals, using an Edelman auger going up the peat dome slopes. A high correlation between surface elevation and peat thickness was found, confirming that the peat bottom is often relatively flat and correlates with the surface height in the LiDAR-based DTM. The LiDAR-based DTM itself was created using an elevation model derived from interpolated, partial-coverage, airborne LiDAR data with an estimated overall vertical accuracy of between 0.25-0.61 m.



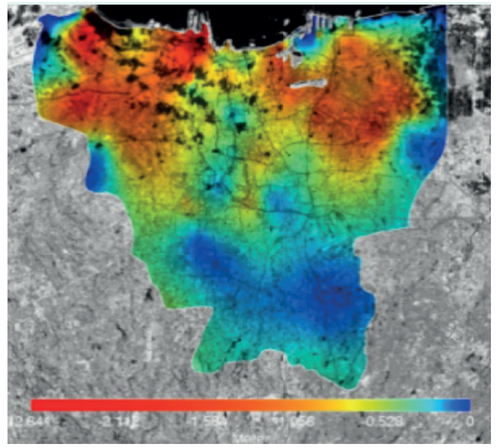
J. A quick-scan cost-benefit analysis of two 'extreme' future policy perspectives in Gouda (the Netherlands)

The cost-benefit analysis contributed valuable new insights to the decision-making process: in addition to a general idea of the feasibility of an action perspective (in terms of cost), it also provided a picture of the economic rationale from a welfare perspective to take action. The municipal authority of Gouda believes the quick-scan CBA is a genuine game-changer and a valuable instrument to develop strategies further and supply analytical support for the decision-making process.



K. Jakarta - Integrated Coastal Development Roadmap for the Mitigation of Land Subsidence in the National Capital

The aim of the Roadmap for the Mitigation of Land Subsidence is to analyze the existing information and the progress of activities to accelerate mitigation measures in a SWOT analysis and to identify the steps and activities needed to stop deep groundwater extraction, assess the mitigation scenarios for the future and possible future rates as the basis of design for floo.d risk management measures, and measures to accelerate mitigation strategies.



L. International comparison of governance systems for land subsidence

In this comparison two urban and two rural case studies were compared: Shanghai and Jakarta (urban), New Orleans and The Netherlands (rural). For each case a brief introduction is given regarding the natural system characteristics and the cultural perspective (Hofstede dimensions: Power distance, Individualism, Masculinity, Uncertainty Avoidance, Long Term Orientation, Indulgence), followed by a description of the current situation regarding governance aspects related to land subsidence, i.e. organisation, communication, interaction/involvement, decision-making process, legal and regulatory framework, finance and policy. Based on these analyses conclusions and recommendations were drawn regarding governance aspects.

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Deltares is an independent institute for applied research in the field of water, subsurface and infrastructure. Throughout the world, we work on smart solutions, innovations and applications for people, environment and society. Deltares is based in Delft and Utrecht.

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