Sinking cities

An integrated approach towards solutions

In many coastal and delta cities land subsidence exceeds absolute sea level rise up to a factor of ten. Without action, parts of Jakarta, Ho Chi Minh City, Bangkok and numerous other coastal cities will sink below sea level. Increased flooding and other widespread impacts of land subsidence result in damage totalling billions of dollars per year. A major cause of severe land subsidence is excessive groundwater extraction due to rapid urbanization and population growth. A major rethink is needed to deal with the 'hidden' but urgent threat of subsidence. Deltares presents a comprehensive approach to address land subsidence from the perspective of more sustainable and resilient urban development.

There is abundant evidence that land subsidence causes major problems worldwide:

- In many coastal megacities around the world land subsidence increases flood vulnerability (frequency, inundation depth and duration of floods), with floods causing major economic damage and loss of lives. Land subsidence results in significant economic losses in the form of structural damage and high maintenance costs. This effects roads and transportation networks, hydraulic infrastructure - such as river embankments, sluice gates, flood barriers and pumping stations -, sewage systems, buildings and foundations. The total damage worldwide is estimated at billions of dollars annually.
- Because of ongoing urbanization and population growth in delta areas, in particular in coastal megacities, there is, and will be, more economic development in subsidence-prone areas. Consequently, detrimental impacts will increase in the near future, making it necessary to address subsidence related problems now.
- The impacts of subsidence are further exacerbated by extreme weather events (short term) and rising sea levels (long term).
- Subsidence is an issue that involves many policy fields, complex technical aspects and governance embedment. There is a need for an integrated approach in order to manage subsidence and to develop appropriate strategies and measures that are effective and efficient on both the short and long term. Urban (ground)water management, adaptive flood risk management and related spatial planning strategies are just examples of the options available.

The figure below illustrates the current subsidence problems related to socio-economic development and climate change.

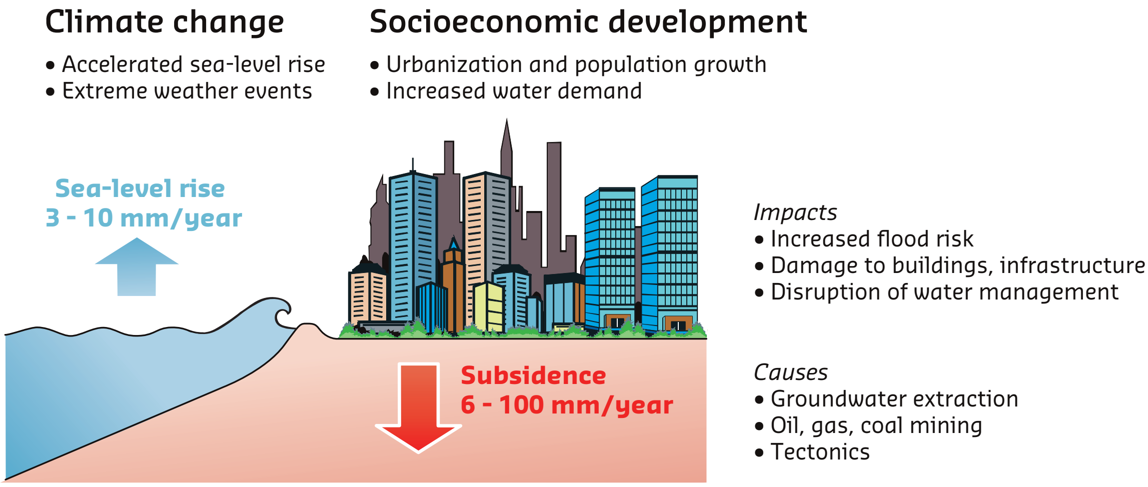


Figure 1. Land subsidence from a multi-sectoral perspective

Current global mean absolute sea level rise is around 3 mm/year and projections until 2100 based on IPCC scenarios expect a global mean absolute sea level rise in a range of 3-10 mm/year. However current observed subsidence rates in coastal megacities are in the range of 6-100 mm/year and projections till 2025 expect similar subsidence rates, depending on future measures. This is illustrated in figure 2.

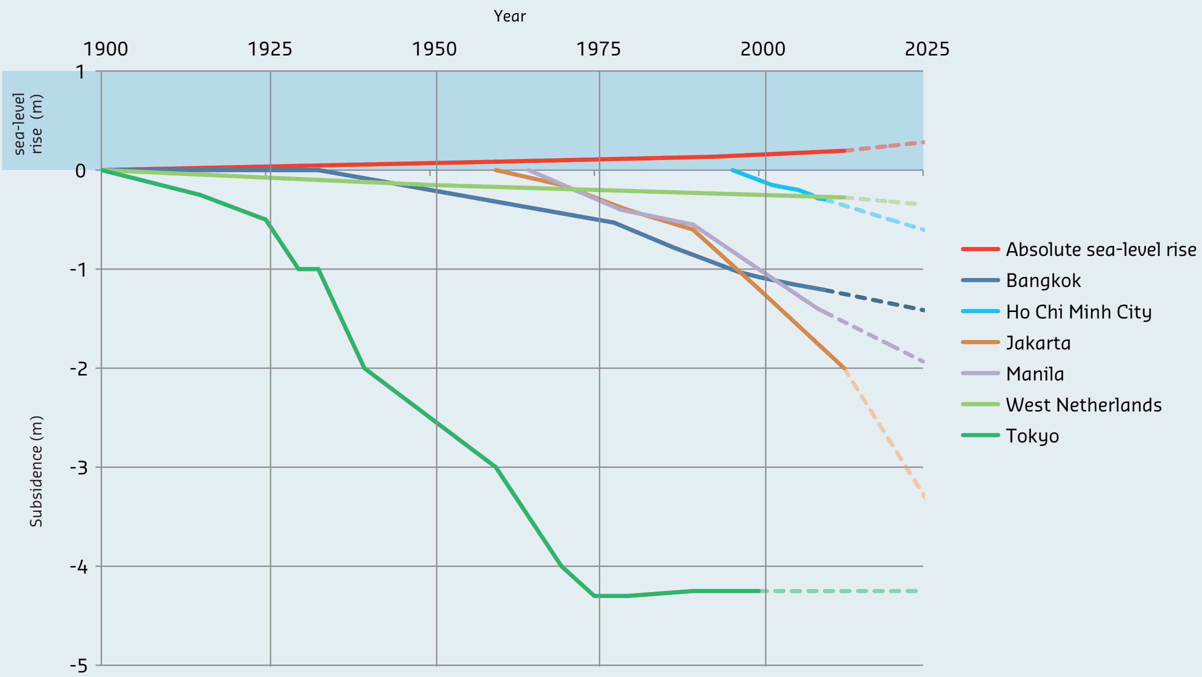


Figure 2. Global sea level rise (SLR) and average land subsidence for several coastal cities (please note that subsidence can differ considerably within a city area, depending on groundwater level and subsurface characteristics)

Subsidence in Sinking Cities

	Mean cumulative subsidence in period 1900 - 2013 (mm)	Mean current subsidence rate (mm/yr)	Maximum subsidence rate (mm/yr)	Estimated additional mean cumulative subsidence until 2025 (mm)
Bangkok	1250	20-30	120	190
Ho Chi Minh City	300	Up to 80	80	200
Jakarta	2000	75-100	179	1800
Manila	1500	Up to 45	45	400
New Orleans	1130	6	26	> 200
Tokyo	4250	Around 0	239	0
West Netherlands	275	2-10	> 17	70

Sea level rise (SLR)

	Cumulative mean SLR in period 1900 - 2013 (mm)	Current rate (mm/yr)	Maximum rate (mm/yr)	Possible additional future SLR until 2025 (mm)
Worldwide mean	195	3	-	86

Sources: Bangkok: MoNRE-DGR 2012; Ho Chi Min City: Le Van Trung & Ho Tong Minh Dinh, 2009; Jakarta: Bakr 2011; Manila: Eco et al 2011; West Nederlands; Van de Ven 1993; Tokio: Kaneko & Toyota 2011; Church and White, 2011, Slangen et al., 2013

Monitoring

To determine land subsidence rates, accurate measuring techniques are required. These are also essential to validate subsidence prediction models. Ongoing subsidence monitoring provides the necessary insight into minor to very significant changes in the topography of the urban area. This could be used for a so-called "dynamic Digital Elevation Model (DEM)". This is not just a static, one-time only recording of the local topography (preferably high resolution) in a DEM, but an elevation model that can be corrected and updated from time to time, and used in hydraulic models for flood prediction and urban water management.

The following observation methods are being used:

- Optical leveling
- GPS surveys
- Laser Imaging Detection and Ranging (LIDAR)
- Interferometric Synthetic Aperture Radar (InSAR) satellite imagery
- Field observations (ground truthing on buildings and infrastructure, including the use of extensometers)

Following early work with systematic optical leveling, nowadays GPS surveys, LIDAR and INSAR remote sensing techniques are deployed with impressive results. In contrast to surveys, LIDAR and INSAR images give a spatially resolved subsidence signal. INSAR images date back to the nineties, but an aplication of this technique is currently limited to the urban environment.
Periodic and systematic surveys remain essential for ground truthing of remote sensing derived subsidence rates and for validation of subsidence prediction models.

Causes

Subsidence can have natural as well as anthropogenic causes. The natural causes include tectonics, glacial isostatic adjustment and natural sediment compaction. Subsidence from anthropogenic causes occurs as a result of compression of shallow layers (0-20 m) by loading (with buildings), or as a result of drainage and subsequent oxidation and consolidation of organic soils and peat. This is related to the physical characteristics of alluvial sediments (alternating layers of sand, clay and peat), making low-lying coastal and delta areas very prone to subsidence. In deeper layers subsidence is caused by extraction of resources such as oil, gas, coal, salt and groundwater.

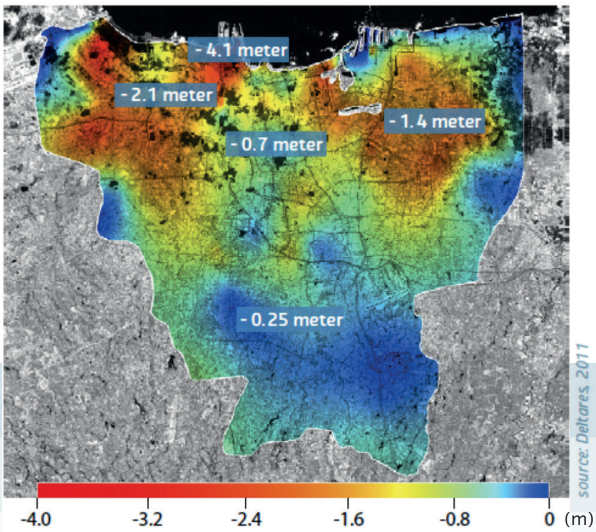


Figure 3. Cumulative land subsidence over the period 1974 – 2010 in Jakarta, Indonesia (Deltares, 2011)

In most of the large delta cities, severe land subsidence is mainly caused by extraction of groundwater (Jakarta, Ho Chi Minh City, Bangkok, Dhaka, Shanghai and Tokyo). Rapidly expanding urban areas require huge amounts of water for domestic and industrial water supply. This often leads to over-exploitation of groundwater resources, especially when surface waters are seriously polluted (Jakarta, Dhaka). In Dhaka continuous large scale extractions cause groundwater levels to fall by 2-3 meters per year.
Moreover in many developing cities, multiple large construction activities require site dewatering for foundation excavations. This causes lowering of the groundwater level as well, resulting in soil compression and land subsidence.

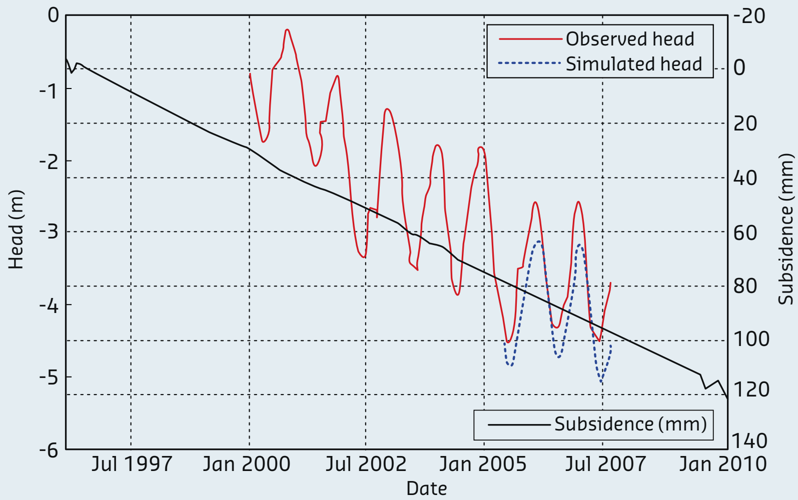


Figure 4. Distinct relation between falling groundwater level (head) and subsidence in Ho Chi Minh City (Deltares, 2013)

Studies in many cities have revealed a distinct relation between falling groundwater levels and subsidence. The resulting spatial pattern of subsidence and its progress over time, is strongly related to the local composition of the subsurface and the number and location of groundwater wells.

New Orleans (USA) is a prominent example of a city where shallow drainage causes subsidence. After draining the organic rich soils, they start to oxidize adding to the overall subsidence rate of 6 mm/year. This process will go on as long as organic material is available and it contributes to the sinking of the already low lying coastal city.

State of the art subsidence modeling

Land subsidence modeling and fore-casting tools are being developed that enable Deltares to quantitatively assess medium- to long-term land subsidence rates, and distinguish between multiple causes. Modeling tools are used as part of our inte-grated approach and complemen-ted with monitoring techniques (i.e. GPS leve-ling, the use of InSAR moni-toring techniques). Preferably, the required primary monitoring data and analytical results (of various modeling tools) are stored in a central database.

As land subsidence is in many places closely linked to excessive groundwater extraction, Deltares has developed modeling tools that calcu-late land subsidence - vertical com-paction - in regional ground-water flow models. These models enable us to make predictions for land sub-sidence under different scenarios of groundwater usage and contribute to develop integrated water resources management including its environ-mental and socio-economic impacts.

The subsidence modeling approach uses changes in groundwater storage in subsurface layers (aquifers and aquitards) and accounts for temporal and spatial variability of geostatic and effective stresses to determine layer compaction.

The modeling tool is a modified ver-sion of the groundwater flow model (U.S. Geological Survey). The mode-ling tool has been used in several studies (Jakarta, Ho Chi Minh City) to assess the adverse consequences of groundwater extraction and to determine medium to long-term land subsidence trends and consequences for urban flood management and vulnerability.

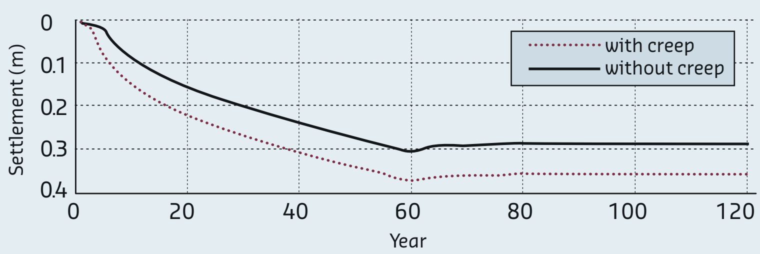


Figure 5. Deltares' new subsidence model now also includes the calculation of creep, the slow and largely irreversible component of subsidence. Specifically in aquifers with many fine-grained interbeds, creep clearly adds to the total amount of settlement over time and may not be neglected.

Impacts

Some major impacts of subsidence are:

- Increased flood risk (frequency, depth and duration of inundation) and more frequent rainfall induced floods due to ineffective drainage systems

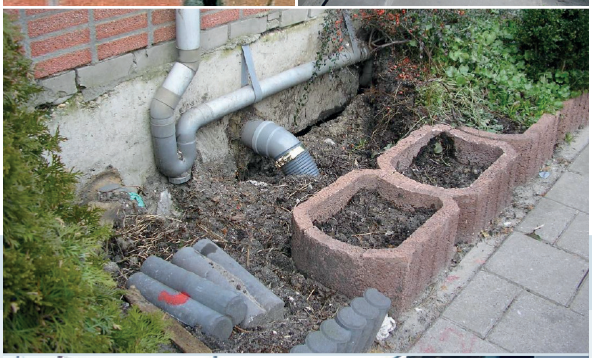
- Damage to buildings, foundations, infrastructure (roads, bridges, dikes) and subsurface structures (drainage, sewerage, gas pipes etc.)

- Disruption of the water management and related effects (changing gradient of streams, canals and drains, increased salt water intrusion, increased need for pumping)

Moreover, as a result of limited available space, housing, industrial estates and infrastructure are increasingly situated in subsidence-prone (marginal) lands, such as floodplains and coastal marshes (Jakarta, New Orleans) with obvious consequences.
These impacts are aggravated on the long term, by future climate change impacts, such as sea level rise, increased storm surges and changes in precipitation.

Subsidence leads to direct and indirect damage. Direct effects are for instance loss of functionality or integrity of structures like buildings, roads and underground utility networks (critical infrastructure). The most common indirect effects of damage are related to changes in relative water levels, both groundwater levels and surface water levels.
The estimation of associated costs is very complex. In practice operational and maintenance costs are considered in several short and long term policies and budgeting. The costs appear on financial sheets as ad hoc investments or planned maintenance schemes, but not as damage costs related to subsidence.

In China the average total economic loss due to subsidence is estimated at around 1.5 billion dollars per year of which 80-90% are indirect losses. In Shanghai, over the period 2001-2010, the total loss cumulates to approximately 2 billion dollar. In Bangkok many private and public buildings, roads, pavements, levees and underground infrastructure (sewerage, drainage) are severely damaged by subsidence, but proper estimates of the costs of damage are not available.
In 2006, the total costs of subsidence related damage in The Netherlands was estimated at over 3.5 billion Euro per year. The majority of these costs will not be recognized directly as damage due to subsidence. Also the construction site preparation and construction costs in soft-soil areas should be considered as subsidence-related costs, as these are mainly incurred to prevent consolidation.
Moreover due to economic and urban development the potential damage costs will increase considerably, especially in subsidence prone areas such as flood plains.



Responses

In pristine deltas, the naturally occurring subsidence is compensated by the sediment delivered by the river. However, nowadays, many river systems deliver much less sediment to their deltas, because sediment is trapped by upstream dams or is extracted for building material. With limited sediment supply, natural subsidence remains inadequately compensated, let alone the larger anthropogenic subsidence. Hence deltas start to sink. This is noticeable in delta cities like Jakarta, Ho Chi Minh City, Bangkok, New Orleans, Shanghai and in The Netherlands.

Measures to counteract anthropogenic subsidence are in most cases initiated only when the detrimental impacts become apparent, in the form of flooding or serious damage to buildings and infrastructure. Responses till now have been largely focused on restriction of groundwater extraction and some spatial planning adjustments or locally raising the level of the land. A comprehensive and integrated (multi-sectoral) approach is often lacking.

In the Greater **Jakarta** area, metropolitan authorities and technical agencies are advocating the reduction of groundwater extraction in vulnerable areas by completely phasing out the use of groundwater and taxing groundwater consumption. This would include the development of alternative water supply for large industrial users or relocation of large groundwater users, outside the 'critical zones'. The number of 'unregistered' users is still a problem. Ongoing economic development and city expansion, lead to the filling of low-lying and flood prone lands with mineral aggregates and often waste materials. To some extent, spatial planning measures were applied to avoid subsidence-prone areas, but fast growth of informal settlements has made many of these plans obsolete. Recently the Jakarta Coastal Defense Strategy (JCDS) programme integrated the results of various subsidence studies and tried to obtain reliable figures for current and future subsidence. This subsidence prognosis is regarded as an extremely vital component for an integrated flood management and coastal defense strategy.

In **Bangkok** extreme land subsidence by groundwater extraction was successfully reduced by regulations and restrictions for groundwater extraction. A specific law (Groundwater Act) was enacted in 1977. Most severely affected areas were designated as Critical Zones with more control over private and public groundwater activities. Groundwater Use Charges were first implemented in 1985 and gradually increased. In Bangkok currently about 10% of the total water use is from groundwater extraction, however subsidence is still ongoing but at a much slower pace than before.

Although land subsidence in **Ho Chi Minh City** has been observed since 1997, there is still considerable disagreement about its causes and impacts. This is partly due to poor monitoring data on land subsidence and groundwater extraction. Restrictions on groundwater extraction have been initiated but it is too early to observe effects. Besides the registered exploitation, which draws mainly from the deeper aquifers there is a large amount of unregistered extraction for domestic water supply. Hence, the total drawdown rate shows no sign of decreasing. Possibly, this can also be attributed to the fact that recharge is hindered by the reduction in infiltration area due to urbanization.

In **New Orleans** and the Mississippi delta, there is as yet no coordinated strategy on mitigating subsidence. The extraction of oil and gas is of great economic importance for the region and will be stimulated, rather than limited. The debate on groundwater use in New Orleans has only recently started, as its contribution to subsidence is so far unknown. The recently published water management strategy for New Orleans, however, recommends raising water levels in areas with organic rich soils, reducing oxidation of organic matter, and

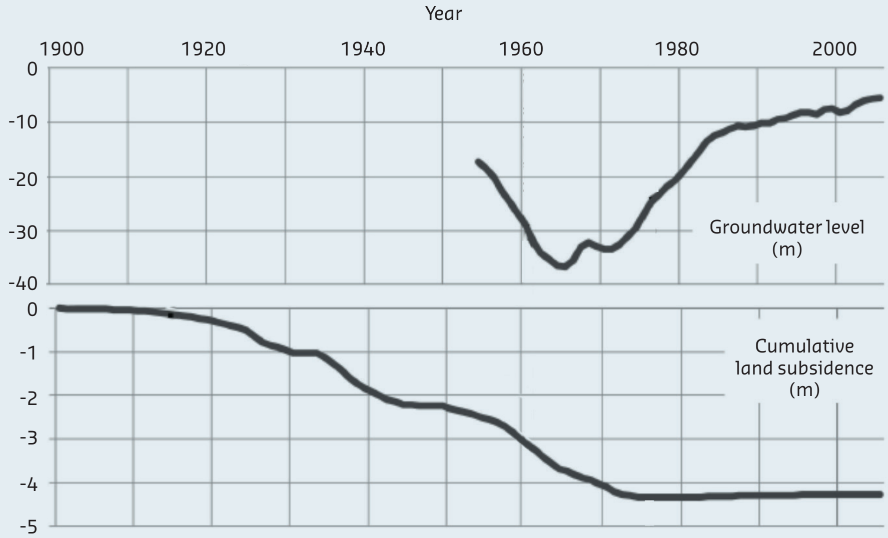


Figure 6. Land subsidence and groundwater level in Tokyo area (Kaneko & Toyota, 2011)

mitigating subsidence. The Mississippi delta is starved of sediment because of constructions of dams and erosion-prevention measures upstream in the catchment. In the Coastal Master Plan for the Mississippi Delta include plans to reintroduce sediment-loaded floodwaters to the delta once more.

In **Tokyo**, after taking regulatory measures on restriction of groundwater use in the early sixties, the groundwater levels increased again and after around 10 years the subsidence was stopped (see figure 6).

With increasing insight in the relationship between groundwater extraction and land subsidence, techniques were developed in **Shanghai** to restore groundwater levels with active or passive recharge. Although this approach reduced the further lowering of groundwater tables and limited subsidence, it did not solve immediate problems, notably the effect of subsidence on infrastructure, roads and buildings. Further developments in Shanghai have shown that active and substantial recharge makes sustainable groundwater use possible, without severe subsidence, provided that average yearly pumping rates are in balance with the average yearly recharge.

In **Dhaka**, increasing problems with flooding and water supply are resulting in more attention to excessive groundwater extraction and subsidence. In this rapidly expanding city many areas are subsidence-prone but there is currently a lack of data on subsidence and its impacts. At present 87% of the supplied water is from ground water extraction and it has been acknowledged that a shift is necessary to using surface water. However, treating surface water is much more technically complex and expensive than using groundwater, in part because the large rivers nearest to Dhaka are polluted by the economically important textile industry, among others.

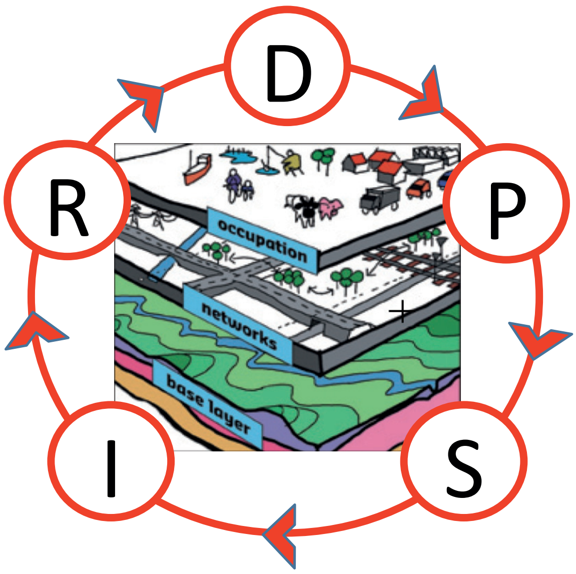
A flood event can lead to more attention for subsidence. This happened in November 2007, for example, when the northern part of Jakarta, which is heavily subsided and below sea level, was flooded by the sea during an extremely high tide. For a long time, land subsidence was not really seen as one of the root causes of flooding. Nowadays, there is increasing awareness that land subsidence has to be integrated into long-term flood management and mitigation strategies.

Integrated approach

Land subsidence is often literally a “hidden” issue. Not only does it take place out-of-sight, but its complex, cross-sectoral nature means that it is usually not fully recognized (or acknowledged), especially in the domain of governance and institutional mandates and responsibilities. As yet, insufficient account is taken of natural resource management, regional (urban) development, and strategic spatial planning, and in particular urban flood management, infra-structure design, and infrastructure maintenance. The detrimental effects of subsidence are ignored until they become a serious and costly issue, one causing significant economic losses and posing nuisance to millions of people. Moreover, acquiring, processing, and disseminating land subsidence information so that it reaches diverse stakeholders and decision-makers, is a complicated and multi-faceted task.

If proper attention is paid to developing the required technical, administrative, and institutional capabilities, the negative impacts of land subsidence can be mitigated and the process largely stopped. Therefore a **comprehensive and integrated approach** is needed consisting of the following elements:

- **Raise awareness** about land subsidence, to involve relevant stakeholders and to determine ownership and responsibilities.
- **Organize systematic monitoring** and ensure that data are reliable and easily accessible.
- **Develop in-depth knowledge** about the process of subsidence and develop models and tools to assess and forecast subsidence and to measure the effects of mitigative measures.
- **Assess vulnerabilities, risks and impacts** regarding flooding, buildings, infrastructure, roads and subsurface infrastructure, in the short and long term, including costs.
- **Develop responses and solutions** in a context of sustainable natural resources management, climate change scenarios, and socio-economic developments.
- **Address governance** by means of multi-sectoral policy development, coordination and participation of all relevant stakeholders, and develop innovative financing structures
- **Support decision makers** with models and tools for selecting the most appropriate adaptive measures (best practices), including their costs and benefits.
- **Exchange of knowledge and best practices** is important to avoid repetitive problems and duplication of (research) activities.



Deltares uses an in-house developed Integrated Assessment Framework that can be applied on any subsidence case. It is based on the DPSIR approach (Driving forces, Pressures, State, Impacts and Responses) and Spatial Layer model. The DPSIR aspects cover the cause-effect-response chain being elaborated for three spatial layers: the Occupation layer (land and water use), Network layer (infrastructure) and Base layer (natural resources subsurface).

Integrated Approach and Assessment Framework for Subsidence

Every city that wants to tackle its subsidence problem has to deal with questions such as: what are the main causes, how much is the current subsidence rate and what are future scenarios, what are the impacts and risks, how can adverse impacts be mitigated or compensated for, and who is involved and responsible to act? In order to answer these technical and governance questions, the integrated approach supports the (policy) development path that cities should follow, from problem identification to planning and implementation of solutions and their evaluation. Every subsiding city is somewhere along this development path (see table), ranging from being in an early analysis stage (for instance Dhaka, Bangladesh) to cities that more or less seem to have solved the problem at the other end of the spectrum (for instance Tokyo, Japan).

Steps	Questions	Technical aspects	Governance aspects	City example state of development
1. Problem analysis	• How much subsidence is there? • What are the causes? • Who is involved and responsible?	• Measurement data collection • Data analyses to disentangle subsidence causes • (Inverse) modelling to make predictions	• Awareness raising • Stakeholder analysis / identification of problem owners	• Dhaka • Manila • New Orleans • Jakarta
2. Planning	• How much future subsidence is predicted? • What are the current and future impacts (monetised)? • What are most vulnerable areas? • What are possible solutions?	• Scenario constructions • Modelling / forecasting • Damage assessments • Vulnerability and risk assessments • Decision support systems (6) • Cost-benefit analyses / multi-criteria analysis • Selection of structural measures in an integrated multi-sectoral perspective	• Capacity building / education • Multi-sectoral planning, participation, stakeholder engagement and commitment (4, 5) • Political action, development of policy, strategy and legal instruments • Planning and design of buildings and infrastructure, incl. building codes (8) • Decision-making on implementation (5)	• HCMC
3. Implementation	• What will be done, how and when and by whom?	• Installing monitoring systems (7) • Setting up pilot projects • Proposing innovative (alternative) solutions (3) • Implementation of structural mitigating and/or adapting measures (1, 2, 3) • Exchange of knowledge and best practices (10)	• Multi-sectoral cooperation / organisational structure • Implementation of non-structural measures (1) • Legal framework / operational procedures / guidelines • Enforcement of laws and regulations • Financing mechanisms / asset management (9)	• Bangkok
4. Evaluation	• Is the problem under control?	• Monitoring, remodelling • Compliance checking • Assessment and outlook	• Stakeholder evaluations • Public hearing	• Tokyo • Shanghai

The numbers between brackets refer to the key issues on the next pages.

Key issues to adress subsidence

In the framework of an integrated approach **10 key issues** and possible solutions are presented below:

1

Restriction of groundwater extraction

This measure is very important for counteracting human-induced subsidence.
In vulnerable areas extraction of groundwater should be reduced or completely phased out.
The following regulatory measures can be considered:

- Appropriate legislation and consistent implementation and enforcement of regulations
- Designation of groundwater regions and critical zones
- Restricted licensing and compliance checking for groundwater well drilling
- Universal groundwater use metering and charges for groundwater use

2

Natural and artificial recharge of aquifers

When addressed consistently and effectively, the reduction of groundwater mining can eliminate one of the primary causes of land subsidence. However, the prolonged effects of settlement, possibly taking up to 10 years, are not immediately solved. Natural and/or controlled groundwater recharge may be applied to speed up recovery, as well as controlled aquifer storage and recovery (ASR), a practice currently being developed and implemented in Shanghai and Bangkok.

3

Development of alternative water supply (instead of groundwater)

To meet the increasing (urban) water demand, an alternative water supply for industry and domestic users is required. The process of shifting to an alternative supply should include water demand assessments (water footprint) and cost/benefit analyses. To develop a sustainable alternative water supply, the reduction of surface water pollution is vital.

4

Integrated (urban) flood water management

Improved groundwater management and subsidence studies should be part of an integrated urban water (resources) management strategy that includes the water-subsurface interaction. Water resources management should be linked to flood mitigation. Ultimately, land subsidence is closely linked to integrated land and water management, including surface as well as subsurface resources and constraints.

5

Improving governance and decision-making

In many cases, governance is inadequate to address subsidence through an integrated multi-sectoral approach and to develop sustainable short- and long-term solutions. This involves (public) awareness, encouraging (public) participation, cooperation and coordination between stakeholders at different scales and levels, and enabling good decision-making supported by decision support models and tools.

6

Decision support models and tools

To support good decision-making, models and tools are needed. It is especially important to analyse the relationship between groundwater levels and subsidence, develop modeling and forecasting capabilities by implementing an integrated groundwater–subsidence monitoring and analytical model. Moreover, it is essential that local agencies have the expertise and tools to conduct studies, and that they are engaged in ongoing capacity building, training, and knowledge exchange.

7

Appropriate monitoring and database system

Ongoing studies show that the weak spot in efforts to reduce subsidence and related flood risks is acces to reliable ground truth data. To strengthen this area of weakness in order to build a good database with long time measurements of subsidence, it is necessary to develop and maintain geodetic monitoring networks throughout the metropolitan areas, with stable, precisely calibrated benchmarks and periodic leveling surveys.

8

Integration of geotechnical aspects in planning and design of buildings and infrastructure

In the planning and design of (heavy) buildings and road infrastructure, geotechnical research and modelling of the subsoil should be taken into account in order to avoid subsidence problems including differential settlements, in the short or long term. This approach will avoid considerable damage and high maintenance costs of infrastructure and buildings (foundations). During underground construction activities (those for deep parking lots or metro-stations or involving tunneling), the effects of de-watering should be minimized and, if necessary, monitored and/or mitigated.

9

Asset management, financing and public-private-partnerships (PPP)

To minimize damage caused by subsidence, the main financial risks associated with investments and maintenance of assets (buildings, infrastructure) should be assessed. This will lead to improved design options, programming and prioritization of investments, making use of Real Options Theory and Asset Management. This approach involves determining performance indicators, functional specifications, risk mitigation measures and bonus/ malus in (innovative) contracts. Moreover PPP and Private Financing approaches that build on sustainable business models should be explored.

10

Exchange of knowledge and best practices

Through international conferences, workshops, expert meetings, and courses, knowledge and best practices can be exchanged to extend the common knowledge base efficiently and effectively. This step can be further supported by development of collaborative research projects preferably in the framework of international (research) networks and initiatives such as the UNESCO, and the Delta Alliance.

References and further reading

Sea level rise

- Sea-Level Rise from the Late 19th to the Early 21st Century., John A. Church and Neil J. White, 2011
- Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, A.B.A. Slangen et al., Clim Dyn, 38 (5-6), 2012

Bangkok

- InSAR time series analysis of land subsidence in Bangkok, Thailand, Anuphao Aobpaet et al, International Journal of Remote Sensing, 2012
- The study of systematic land subsidence monitoring on critical groundwater used area project, Ministry of Natural Resources and Environment, Department of Groundwater Resources, 2012.

Dhaka

- GPS Velocities and Structures across the Burma Accretionary Prism and Shillong Anticline in Bangladesh M.S. Steckler et al, 2012

Ho Chi Minh City

- Ho Chi Minh City Flood and Inundation Management - Final Report, Volume 2: IFRM Strategy, Annex 3: Land Subsidence, Royal Haskoning-DHV and Deltares, 2013
- Monitoring Land Deformation Using Permanent Scatterer INSAR Techniques (case study: Ho Chi Minh City), Le Van Trung and Ho Tong Minh Dinh, 7th FIG Regional Conference , Vietnam, 2009

Jakarta

- Jakarta Coastal Defense Strategy (JCDS) atlas, 2011. Ministry of Public Works (PU), Deltares Research Institute and Urban Solutions, in association with Witteveen + Bos, Triple-A Team, MLD, Pusair, ITB.
- Influence of Groundwater Management on Land Subsidence in Deltas A Case Study of Jakarta (Indonesia), Bakr, M., Water Resources Management, DOI 10.1007/s11269-014-0893-7, 2015

Manila

- Investigating ground deformation and subsidence in northern Metro Manila, Philippines using Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), R.C. Eco et al, American Geophysical Union, Fall Meeting, 2011

Netherlands

- Shallow subsidence in the Dutch wetlands estimated by satellite radar interferometry, Miguel Caro Cuenca et al, Delft University of Technology, 2010
- Man-made lowlands, history of water management and land reclamation in the Netherlands, G.P. van der Ven, uitgeverij Matrijs, Utrecht, 1993

New Orleans

- The role of deep processes in late 20th century subsidence of New Orleans and coastal areas of southern Louisiana and Mississippi. Journal of Geophysical Research 116, R.K. Dokka, 2011
- Subsidence and flooding in New Orleans - A subsidence map of the city offers insight into the failure of the levees during Hurricane Katrina, Dixon, T. H. Amelung, F., Ferretti, A., Novali, F., Rocca, F., Dokka, R., Sella, G., Kim, S.-W., Nature, 441, 587-588, 2006.

Shanghai

- Regional land subsidence simulation in Su-Xi-Chang area and Shanghai City, China, Xiaoqing Shi et al, 2008

Tokyo

- Long-Term Urbanization and Land Subsidence in Asian Megacities: An Indicators System Approach, Shinji Kaneko and Tomoyo Toyota, In Groundwater and Subsurface Environments: Human Impacts in Asian Coastal Cities, 2011

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October, 2013 – first update January 2015

Deltares is a leading, independent, Netherlands based research institute and specialist consultancy for matters relating to water, soil and the subsurface. We apply our advanced expertise worldwide, to help people live safely and sustainably in delta areas, coastal zones and river basins. Our Taskforce Subsidence can give support on all issues related to subsidence.