DeltAlliance

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Sinking cities II – example cases

A step-by-step approach to address land subsidence in urbanising deltas

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 flood risk 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, as well as more guidance to support decision making.

In 2015, Deltares published the agenda-setting brochure 'Sinking Cities' to raise awareness on subsidence and the associated damage. Although awareness on subsidence is increased, it is far from finished, as exemplified by the frequent new discoveries of apparent new subsiding coastal cities. As there is a growing need in guidance this brochure presents a comprehensive and step-by-step approach to address land subsidence from the perspective of sustainable and resilient urban development, illustrated by real life case study examples. The lessons learned from these experiences provide valuable information and inspiration for decision makers and experts to address subsidence in urbanising deltas. It is expected that this guidance will further raise awareness and contribute to lowering the threshold to act while acknowledging the progress made over the last years.

A step-wise approach is elaborated along the stages of the policy cycle, with clear steps that need to be taken. For each of the 6 steps identified, there are questions that need to be addressed, technical and governance aspects that need to be considered to answer the questions, and products that form the outcome of the step to work towards a policy strategy (Table 1). This document offers guidance for the step-wise approach on land subsidence, by providing a real life example for each of these steps. The Sinking Cities 2 brochure contributes to the ongoing awareness raising on land subsidence, while acknowledging the progress made over the last years. It is expected that it will contribute to lowering the threshold to act and will start addressing land subsidence in more areas around the world. It offers a lead what to do next once a certain aspect is finalised.

Policy cycle	Questions to address	Step-wise approach		Products
		Technical aspects	Governance aspects	
Problem analysis	• How much subsidence is there? Are people aware of this? • What is impact of subsidence • What are the causes? • Who is involved and responsible?	1. Measuring • Measurement data collection • Impact assessment 2. Mechanisms • Data analyses to disentangle subsidence causes	• Awareness raising • Stakeholder analysis • identification of problem owners	• Subsidence map with current subsidence rates (+ sum) and impacts • Communication plan • Measuring plan and set-up • Subsidence database with publically available data • Subsidence map with causes of subsidence • Stakeholder mapping
Planning	• How much future subsidence is predicted? • What are most vulnerable areas? • What are possible measures? • What are the current and future impacts (quantified and monetised)?	3. Modelling • (Inverse) modelling to make predictions • Scenario constructions / analyses • Modelling / forecasting • Vulnerability assessment • Damage assessment 4. Measures - Cost-benefit analysis and decision support • Cost-benefit analyses / multi-criteria analysis of possible measures • Decision support system • Selection of (innovative) measures in an integrated multi-sectoral perspective	• Capacity building / education • Multi-sectoral planning, participation, stakeholder engagement and commitment • Political action, development of policy, strategy and legal instruments • Planning and design of buildings and infra-structure, incl. building codes • Decision-making on Implementation	• Subsidence map with future subsidence rates (+ sum) • Vulnerability map • Capacity building plan • Overview of possible measures • Subsidence impact map (current + future) • Decision support tools • Strategy and action plan (including selection of measures)
Implemen-tation	• What will be done, how and when and by whom?	5. Measures - implementation • Implementation of measures • Setup monitoring plan • Setting up pilot projects	• Multi-sectoral cooperation / organisational structure • Legal framework / operational procedures / guidelines • Enforcement of laws and regulations • Financing mechanisms / asset management	• Implementation plan (incl. organisation, operational procedures, legal aspects , financing, asset manage-ment) • Monitoring plan • Pilot sites
Evaluation	• Is the problem under control?	6. Monitoring and evaluation • Monitoring,remodelling • Setup evaluation plan • Compliance checking • Assessment and outlook • Exchange of knowledge and best practices	• Stakeholder evaluations • Public hearing	• Evaluation plan (technical and soc-economic) • Best practices • Knowledge exchange plan

Table 1. Integrated framework and stepwise approach addressing all aspects of subsidence, incorporating technical as well as governance aspects (Deltares, 2018)

Step 1. Measuring subsidence (example case Ganges–Brahmaputra–Meghna delta and Dhaka, Bangladesh)

1.1 Subsidence rates in Bangladesh and Dhaka

For the highly populated Ganges–Brahmaputra–Meghna delta, a large range of net subsidence rates are described in the literature (between -1.1 mm/yr (i.e. uplift) and 43,8 mm/yr), yet the reasons behind this wide range of values are poorly understood (Brown, S., R.J. Nicholls, 2015). The highest rates were recorded in Dhaka and Kolkata suggesting that anthropogenic influence is affecting the rate (figure 1).

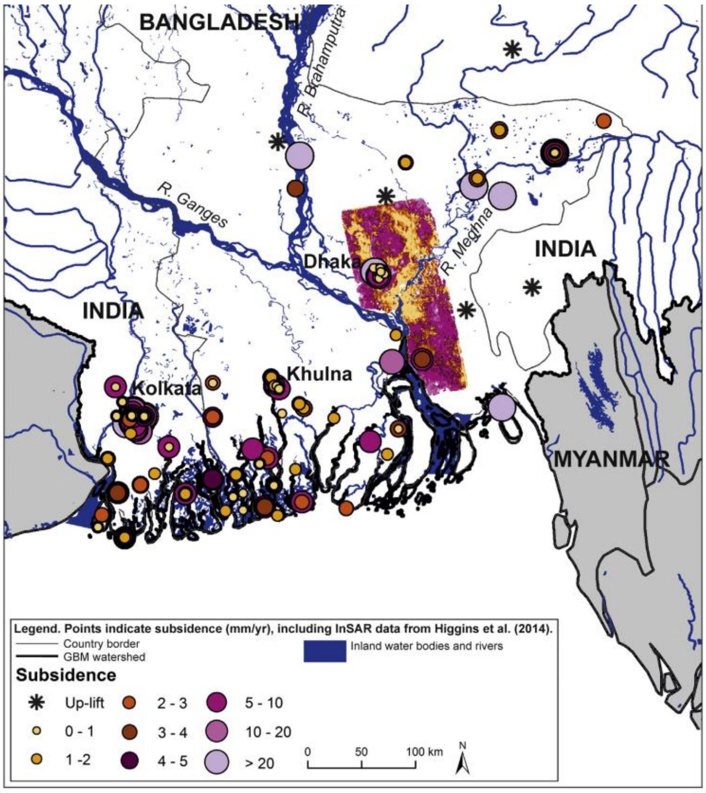


Figure 1.1 Rates of subsidence recorded from the literature for the GBM delta (Brown, S., R.J. Nicholls, 2015)

The long-term subsidence measured by the GPS in Dhaka is around 12.3 mm/yr (2003 – 2012, Steckler et al. [2013]). The periodic vertical oscillation is caused by elastic deformation and rebound of the entire delta under the weight of monsoon surface water and groundwater (Steckler et al., 2010). (figure 2 and 3).

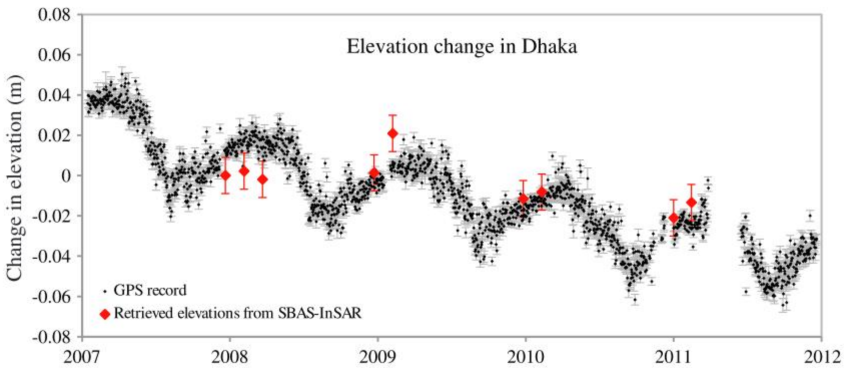


Figure 1.2 Elevation change from the Dhaka GPS record (black, with 1 σ uncertainty in grey) (Steckler et al., 2010) and SBAS-InSAR-derived elevation change with 2 σ uncertainty at the same location (red) (Higgins et al., 2014).

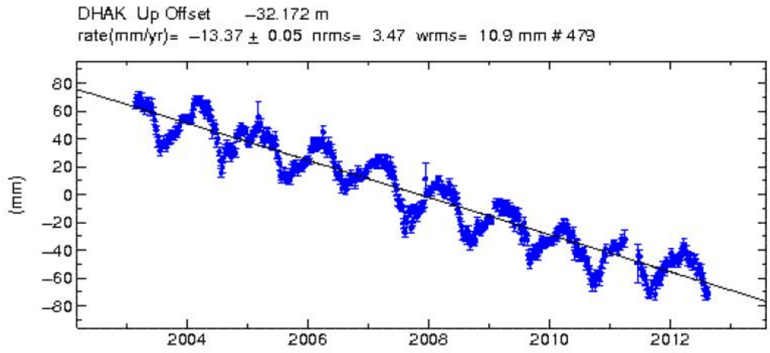


Figure 1.3 Elevation change in Dhaka centre based on one GPS station on Dhaka University (IWM, 2013)

Average subsidence rates in the city of Dhaka range from 0 to >10 mm/yr with variability likely related to local variations in shallow subsurface sediment properties. Outside of the city, rates vary from 0 to > 18 mm/yr, with the lowest rates appearing primarily in Pleistocene Madhupur Clay and the highest rates in Holocene organic-rich muds. Mapped marsh deposits to the east and northeast of Dhaka correspond to areas of high subsidence (Higgins et al., 2014).

1.2 Urban development in subsidence prone areas

In urban areas, subsidence remains a long-term challenge which is difficult to manage, especially given the rapid rate of urbanisation which is often unplanned. Urban population is projected to increase from 2010 to 2025 by 29%, 49% and 43% in Kolkata, Khulna and Dhaka, respectively (cf., UN-Habitat, 2013) so human pressure and potentially subsidence is likely to increase due to groundwater abstraction and/or drainage, depending on the geotechnical characteristics of the subsurface. Subsiding areas in East Dhaka may reveal already rapid groundwater abstraction and sediment compaction in an active industrial area (Higgins et al., 2014). The spatial correlation between InSAR-derived subsidence rates and NEHRP soil class also suggests that subsidence in Dhaka reflects differential compaction or consolidation of the subsurface (figure 4). Nevertheless there are major plans for urban development in East Dhaka, to host an extra 5 million inhabitants (J. Bird et al, 2018), hence taking into account subsurface stratigraphy seems to be vital for urban development planning.

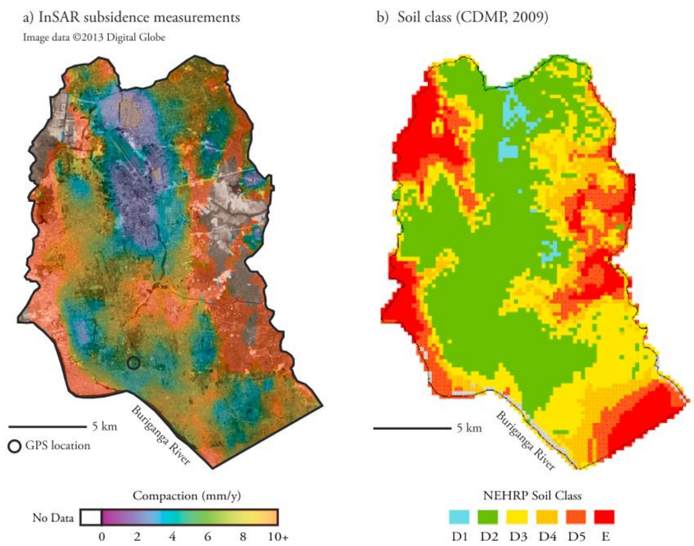


Figure 1.4 a) InSAR-derived average annual subsidence rates in the city of Dhaka, underlain by a satellite image of the city, b) NEHRP Vs30 soil classes in the city of Dhaka, from Comprehensive Disaster Management Programme [2009] (Higgins et al., 2014).NEHRP class indicates the average shear wave velocity from the ground surface to 30 m depth. Class D1 and D2 soils are most stiff and correspond to the stiffest Madhupur clay layers and to localized talus deposits; classes D3 and D4 are less stiff units corresponding to Holocene alluvial (floodplain) sands, silts, and clays. Class E (soft soil) primarily corresponds to Holocene marsh deposits, as well as modern (< 500 years) artificial fill [Comprehensive Disaster Management Programme, 2009].

1.3 Measurement data and methods

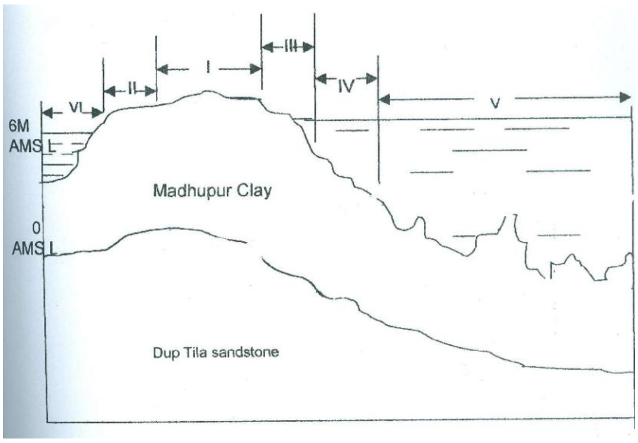
Data regarding subsidence are scarce, because funding and resources are limited In Bangladesh. Further research is certainly required to produce better data about subsidence. Due to multiple causes of subsidence and a general lack of monitoring, particularly in remote areas, understanding the causes and patterns of subsidence is challenging. Moreover limited knowledge of subsidence can hinder management responses (Brown, S., R.J. Nicholls, 2015). In the Bangladesh Deltaplan 2100 subsidence is identified as a substantial knowledge gap which should be addressed.

Many different measurement methods were used, especially carbon dating, groundwater levels, borings/well logs/auger and neotectonics. A disadvantage of many of these methods is that they only record subsidence at one location, and one point in time, rather than being integrated over various time periods and spatial areas. Given that the causes of subsidence can be highly localised and occur at varying depths, this can create a biased view, particularly where there may be an intention to measure high rates where visual changes can be seen (Brown, S., R.J. Nicholls, 2015). GPS and InSAR are two advantageous and emerging methods of measuring subsidence, which over a period of decades will potentially grow into a very useful resource, such as gaining a better understanding of seasonal changes, or possible reverses in land motion (e.g. at Raipur, as reported in Higgins et al., 2014).

Improved monitoring is required over a wider area, to determine long-term trends, particularly as short-term records are highly variable. Focus in regions where wide spread development is occurring or is expected would be advantageous (Brown, S., R.J. Nicholls, 2015). Monitoring stations in recording subsidence need to be installed in locations which are more prone to land subsidence and stations should be as close as possible to the point of abstraction of ground water.

1.4 Geotechnical characteristics of the subsurface in Dhaka

The Geological Survey of Bangladesh studied in early 1990s the geotechnical properties of the subsurface of Dhaka city. Depending on constituent elements of the soil, their physical properties, homogeneity and geotechnical engineering behaviours, in this study Dhaka city was categorized into seven engineering geologic units (figure 5). After this time the city has expanded much in all directions. Dhaka city is on the southern fringe of Madhupur Tract. This tract has good quality consolidated soil from geotechnical considerations, hence good construction of buildings. But the city continues to expand beyond this. Therefore, future research/study on subsidence should focus on this variation of geomorphic and soil properties, addressing also how much land subsidence is responsible for collapse of buildings (n.b. A study done in 2010 by the Bangladesh Ministry of Housing and Public Works mentioned that the number of risky buildings in Dhaka is not less than 80000).



Name of Engineering Geologic units	Label of the units
Madhupur Clay	I
Old natural levee	II
High floodplain and gullyfill	III
Active natural levee, flood plain and sand bar/point bar	IV
Depression and abandoned channel	V
Channels (other)	VI
Artificial fill*	F

Figure 1.5 Generalised west-east cross-section showing engineering geologic units of Dhaka City (source: Shams, 1999)

1.5 Change of groundwater levels in Dhaka

In Dhaka city water supply almost depends on groundwater abstraction. Most rapid and higher rates of decline occur over Dhaka city and adjacent areas where groundwater abstraction is the highest in the country. This abstraction has caused a sharp drop in water level throughout the city and turned into two cones of depression in the water level (figure 6). Groundwater level data of Upper Dupitila aquifer system of Dhaka city demonstrates a steady downward trend. Depletion started from or near before the 90's. At present this depletion rate of Upper Dupitila aquifer in the city is about 2.5m to 3.5m per year (figure 7).

Groundwater abstraction could be a main cause of subsidence. However so far there has not been any significant study done whether ground water withdrawal caused any subsidence. Therefore research/study is needed to collect data and to reveal the relation between ground water withdrawals and subsidence among others by installing subsidence monitoring stations near the abstraction wells.

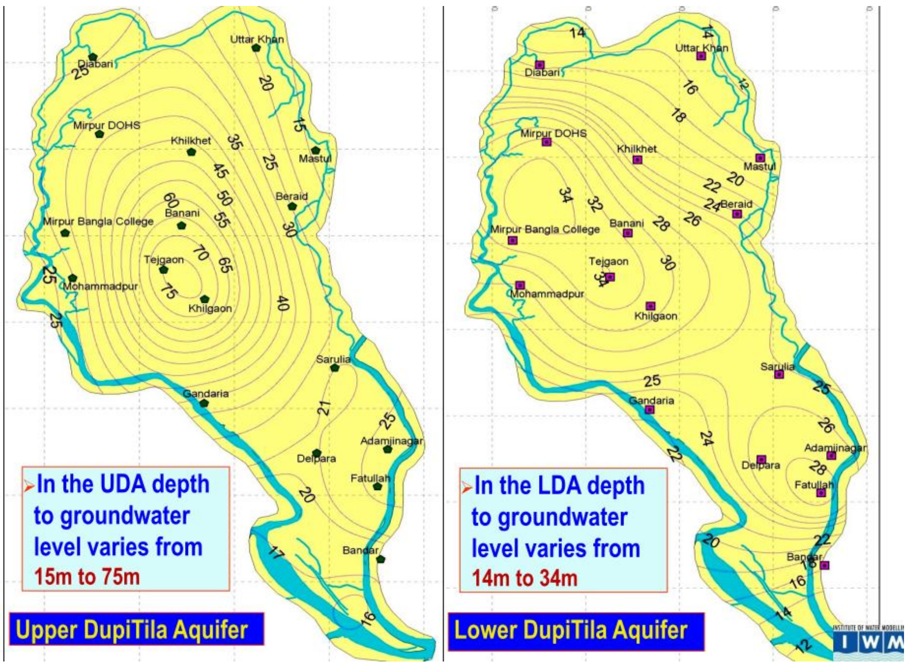


Figure 1.6 Contour map showing depth to groundwater table as on June 30 2009 in Dhaka Centre (IWM)

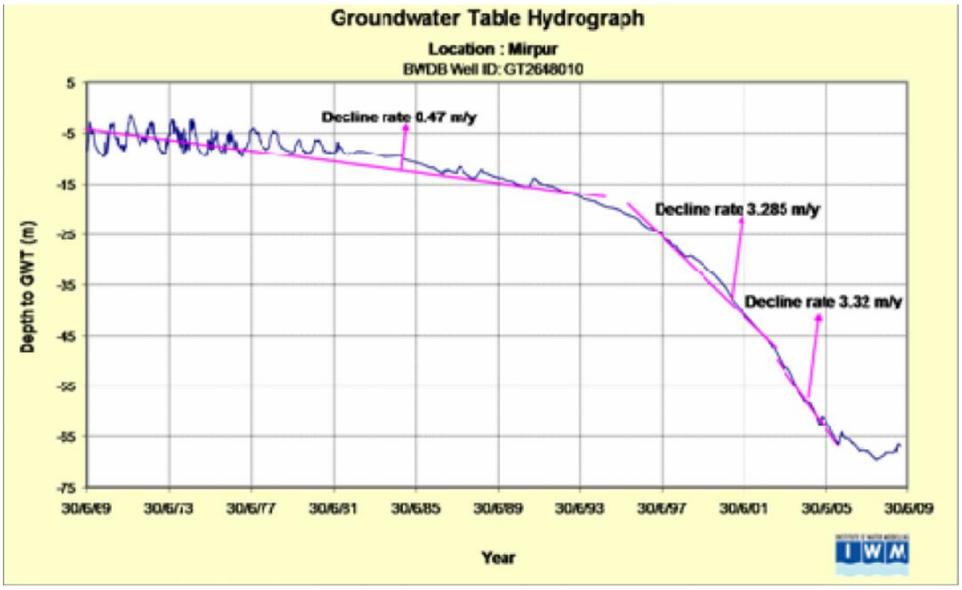


Figure 1.7 Continuous declining of groundwater table in Mirpur area of Dhaka City in period 1969 – 2009

1.6 Lessons learned and recommendations

- Urbanising deltas have a high risk of subsidence, which may result in huge costs and loss of lives if there is a lack of awareness and attention for this issue. The rate of subsidence will depend on the prevailing natural or human induced mechanisms, which can be rather slow or very fast (see separate chapter)

- In many cases subsidence is ignored because of lack of measurement data or other obvious reasons (political will, technical incapability, financial resources) until the detrimental impacts of subsidence becomes undeniable visible, such as water logging or flooding, and damaged buildings and infrastructure. However the longer you wait with assessing the situation, the higher the impacts of subsidence may be, hence the more difficult and/or expensive the counter measures will become.

- In order to prevent or reduce human induced subsidence at an early stage it is very important to assess whether subsidence is a problem and what the impacts are. Accurate and sufficient measurements in space and time are required to reveal the subsidence problem and to develop and validate subsidence forecasting and impact models.

- Measurements should encompass the subsidence rate itself, and indirectly the geotechnical characteristics of the subsurface (stratigraphy) and the change of groundwater levels, as these will determine the vulnerability for human induced subsidence which is vital for urban development planning (see also separate chapter on mechanisms)

- There are many measuring methods available, all with their advantages and disadvantages:

    - Subsidence rate itself: optical levelling, GPS, LIDAR, InSAR and field observations

    - Geotechnical characteristics of the subsurface: core drilling, …

    - Change of groundwater level: piezometers, …

- In order to build a reliable and accurate database with publically available data on subsidence, it is necessary to develop and maintain geodetic monitoring networks throughout the metropolitan areas, with stable, precisely calibrated benchmarks and periodic levelling surveys. Moreover the geotechnical characteristics of the subsurface and the change of groundwater levels should be mapped and monitored at sufficient spatial and temporal scale.

Step 2. Understanding subsidence Mechanisms (example case Jakarta, Indonesia)

Northern Jakarta is a case where severe subsidence (Figure 1) has led to both adaptation (flood defence) and planned mitigation (strong reduction of groundwater use) measures. In the decision process on mitigation, clarification of the mechanisms responsible for the subsidence was an important step. This step is elucidated in this sub-document.

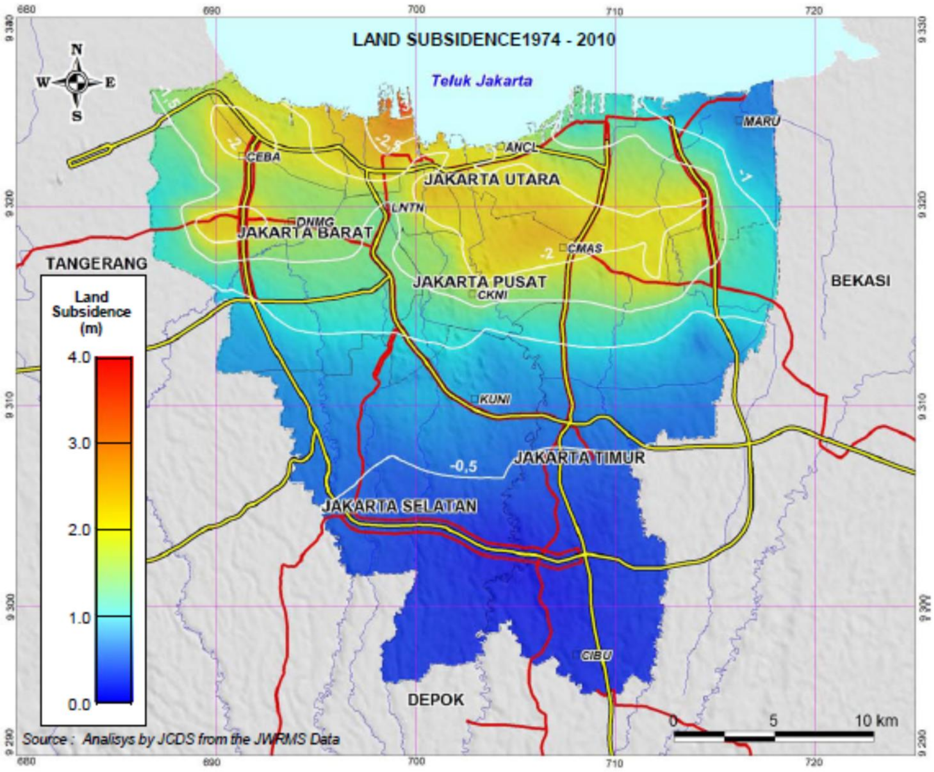


Figure 2.1 Reconstructed land subsidence in the period 1974-2010 in Jakarta (JCDC, 2011).

2.1 Subsidence measurement and subsidence awareness

Land subsidence was recognized already in 1926 in northern Jakarta from optical levelling, but first reports of subsidence-related impacts to infrastructure and flooding date from 1978 (Abidin et al., 2001). Dedicated land subsidence measurement/monitoring started in the late 1990's with the installation of GPS stations by the Technical University of Bandung and resulted in research publications that basically served the academic community. After Jakarta was hit by the most severe flooding in three centuries in 2007 where the seawall was overtopped during high tide and seawater flooded 40% of the city, awareness progressively grew among authorities that land subsidence posed a problem that required attention. Apart from immediate action to improve flood safety and initiatives to develop longer-term water management plans, the need to understand and predict the land subsidence was brought to the table during a 'Round Table Conference on Subsidence' in 2015.

2.2 Discourse on subsidence mechanisms

Various potential causes of land subsidence had been put forward in various groundwater management studies or the Jakarta area in the 1990's (Rismianto and Mak, 1993; Maathuis et al., 1996):

- Tectonics (faulting and crustal warping due to tectonic plate motion)
- Settlement due to surface loads (buildings, roads)
- Background consolidation/compaction/degradation of sediments and man-made materials (e.g., fills)
- Groundwater extraction induced aquifer/aquitard compaction

Although these and many other studies since, have argued groundwater use to be the dominant cause of land subsidence, parties advocating a prime role of some of the other causes got involved in the process in 2015. While disputes were not all resolved and different ‘schools of subsidence mechanisms’ remain in Indonesia, the following arguments and observations are considered to be of particular value in the discourse on subsidence mechanisms:

- Deep-pole GPS stations founded at 200-400 m below ground surface showing negligible subsidence while surrounding land levels subsidence at rates that are up to two order of magnitude higher. The stations basically serves as an extensometer.
- GPS stations in southern Java that do not show significant ground motion associated with the subduction of the Australian (tectonic) plate along southern Java.
- Observed subsidence rates of 5-15 cm/yr that are orders of magnitude higher than tectonic and natural compaction rates that are gleaned from the geological record in the Jakarta area.
- GPS data showing negligible land subsidence in a rural (fish-pond) area along Jakarta Bay.
- Models indicating subsidence due to the load of buildings is limited to the vicinity of those building (max. 50 m).
- The correlation between loci of observed subsidence and piezometric head decline.
- The correlation between subsidence loci and areas with industry that strongly rely on ‘deep’ groundwater.
- Levelling- and GPS-based subsidence reconstructions showing strong acceleration of subsidence in the period with massive growth of deep well extraction (late 70’s and 80’s).
- InSAR and GPS data documenting a strong reduction in subsidence rate following the closure of a large deep groundwater extraction in 2010 in northern Jakarta (Figure 2).
- Models showing the observed subsidence rates and magnitudes can be accounted for by observed hydraulic head drawdowns.
- Examples elsewhere in the world where subsidence can be clearly attributed to groundwater extraction and the case of Tokyo in particular, where subsidence was successfully stopped after complete cessation of groundwater use.

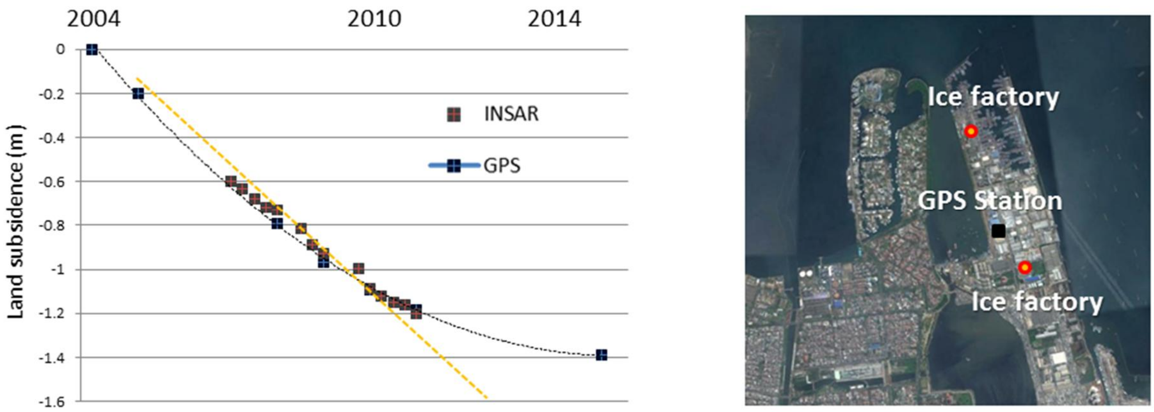


Figure 2.2 Subsidence measurements showing that subsidence of ~ 20 cm/yr at Muara Baru (N. Jakarta) progressively decreases after the ice factory, which extracted large amounts of groundwater, closed in 2010. Courtesy of H. Andreas (ITB, Bandung).

2.3 Mechanisms and subsidence mitigation

Coeval with studies and discussion on subsidence mechanisms, a roadmap was developed with involvement of all stakeholders to strongly reduce groundwater use. The roadmap includes both technical and non-technical measures such as improved law enforcement, legal framework revision, water conservation, and provision of piped water from surface water reservoirs. Given the lack of consensus that groundwater use is the main cause of the subsidence, three factors appear to have been of great importance for authorities to ultimately decide on the implementation of the roadmap: 1. Awareness that effective mitigation of other mechanisms than groundwater use (tectonics, natural compaction, existing tall buildings) is not possible, and that the decision to take action need not await consensus on the underlying mechanisms. 2. Information, supported by process modelling, that subsidence is expected to decrease slowly after the moment groundwater abstraction is strongly reduced, and that urgent action therefore is important to limit the accumulation of additional subsidence (Kooi and Yuherdha, 2018). 3. The successful mitigation of land subsidence elsewhere, for instance in Tokyo, Bangkok and Shanghai.

2.4 Lessons learned and recommendations

Some of the key lessons learned in the Jakarta case are:

- The importance of broad stakeholder involvement.
- The great value of high-quality, extended subsidence records in locations with different surface and subsurface conditions (preferably linked to potential mechanisms).
- The importance of subsurface data on geology, hydraulic head time series, geotechnical properties of key strata as well as extensometer monitoring data.
- The availability/unavailability of mitigation measures associated with the various potential subsidence mechanisms should be linked to the research and discussions about the underlying causes of subsidence.

Step 3. Modelling land subsidence (example case the Mekong Delta, Vietnam)

This section is largely based on the paper Minderhoud et al., 2017 (Minderhoud, P.S.J., Erkens, G., Pham, V.H., Bui, V.T., Erban, L., Kooi, H., Stouthamer, E. (2017). Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta, Vietnam. Environ. Res. Lett. 12, open access, https://doi.org/10.1088/1748-9326/aa7146.

3.1 Introduction: land subsidence in the Mekong Delta

The low-lying and densely populated Mekong delta (MKD), largely located in Vietnam, is fertile, intensively cultivated, and home to ~17 million people. The delta is facing global sea-level rise, natural decrease in fluvial sediment supply (Darby et al., 2016), salinization (Renaud et al., 2015) and coastal erosion (Anthony et al., 2015), and on top of all that, land subsidence (Erban et al., 2014; Minderhoud et al., 2017). Land subsidence contributes to increased flood risk in the MKD and may eventually lead to permanent inundation of parts of the delta.

Groundwater overexploitation has been proposed to be the main driver of subsidence in the MKD (Erban et al., 2013, 2014), corresponding to observations in other subsiding deltas and coastal areas around the world. Groundwater extracted in the MKD is used for domestic, industrial and agricultural purposes. Surface water is often polluted and/or saline, resulting in large parts of the delta depending on groundwater as the main source to meet the (increasing) freshwater demand (Wagner et al., 2012). In 1991, when groundwater monitoring in the MKD commenced, ground water levels in the aquifer system were at more or less natural levels in most parts of the delta. Over the past 25 years, as a result of groundwater exploitation, hydraulic heads (i.e. water pressure) declined throughout the entire delta. As a result, fine-grained sediment started to consolidate, causing aquifer-system compaction (e.g. Galloway and Burbey 2011, Gambolati and Teatini 2015), which is expressed as land subsidence of the delta surface.

Erban et al. (2014) used InSAR (Interferometric Synthetic Aperture Radar) to determine land subsidence rates of 16 mm/yr^{-1} from 2006–2010 at 15 monitoring stations in the Mekong Delta. Locally, specifically in Ho Chi Minh City (HCMC), local extreme rates of 46 mm/yr^{-1} were found (Erban et al., 2014).

3.2 The importance of modelling land subsidence

As useful as the InSAR measurements may seem, the data only cover part of the delta as result of lacking reflectors in the rural areas. Interpolation of the measurements to retrieve future scenarios of land subsidence is not producing accurate results, as the spatial heterogeneity of the delta subsurface and variability in the hydrogeological situation, remain unaccounted for. In addition, temporal variations in extraction amounts and more complex scenarios that include relocation of groundwater extractions throughout the delta can never be captured by simply extrapolating current rates. Finally, the relative contribution of groundwater extraction to the total observed subsidence rates was unknown, as other factors will contribute to the total subsidence as well.

Because of these limitations, groundwater extraction-induced subsidence over the last 25 years in the MKD was quantified using a model. The model existed of two parts: a hydrological (ground water) model (MODFLOW, USGS), and a one-way coupled geo mechanical land subsidence model SUB-CR (Kooi et al., 2018). The groundwater model simulates groundwater drawdowns based on measured time series of hydraulic heads and an estimate of the extraction history. A newly developed 2.5D model of the delta subsurface serves forms the modelling framework (Figure 1). The corresponding aquifer system consolidation is calculated using the SUB-CR subsidence module, enabling delta-wide groundwater extraction-induced subsidence modelling.

Until now, the modelling has been used to simulate the past situation (hind casting), which was an important step towards disentangling the measured total subsidence signal into the relative contribution of different natural and human-induced drivers to total subsidence for the MKD. In the future, the model set-up also allows for forecasting of land subsidence in the MKD under different ground water use scenarios. This will greatly benefit thorough and knowledge-based predictions of delta-wide subsidence for the coming decades, supporting urgently needed decision-making in subsiding deltas (Galloway et al., 2016).

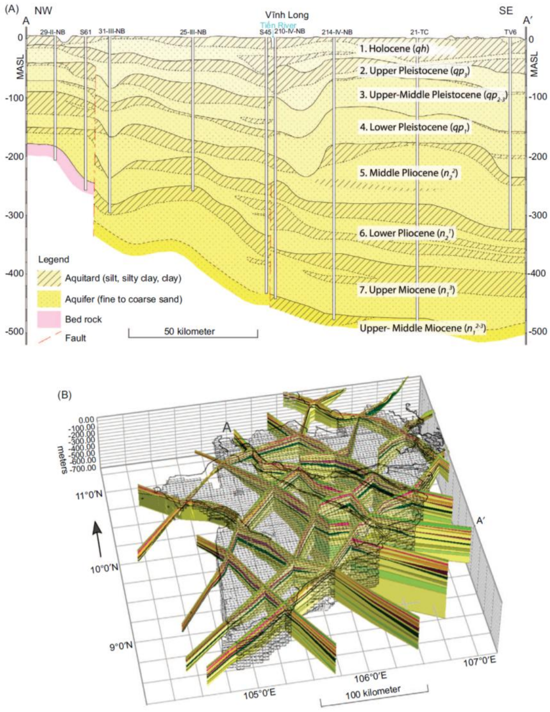


Figure 3.1 The 2.5D subsurface model based on existing data that has been constructed to serve as the geological framework for the coupled ground water subsidence model (from Minderhoud et al., 2017)

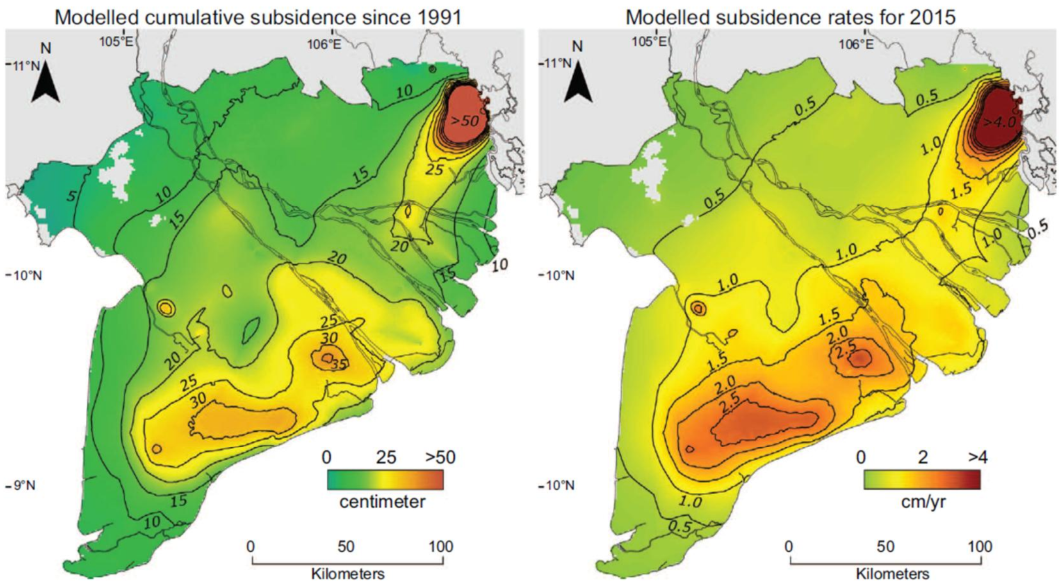


Figure 6. (*a*) Modelled cumulative subsidence due to groundwater extraction-induced during 25 years of groundwater exploitation from 1991 to 2016. (*b*) Modelled groundwater extraction-induced annual subsidence rates for 2015.

Figure 3.2 Modelled cumulative subsidence (left panel) over the last 25 years (1990-2015) and annual subsidence rates (for 2015, right panel) for the Mekong delta. The model results allow identifying subsidence hot spots, such as urban areas.

3.3 Benefits of the land subsidence model

In contrast to many subsidence studies that rely on point measurements and modelling results, a partial or full 3D model provides quantitative estimates for an entire delta plain, including all its cities and rural areas, and demonstrates spatial differences in subsidence due to groundwater extraction. This is important information, as for instance in the MKD, groundwater extraction-induced subsidence seems to be highest in urban and industrial areas, where high, concentrated groundwater usage creates local subsidence hotspots. In the rural parts of the delta subsidence rates are slightly lower, but because of the areal extent, rural area are still the largest contributor to groundwater extraction-induced subsidence at the delta scale. The subsidence model outcomes show that for the MKD, in ~75 % of the cases the InSAR-measured subsidence is at least matched by the best estimated modelled subsidence (Minderhoud et al., 2017). These numbers suggest that groundwater extraction is a major subsidence driver in the MKD. However, other drivers likely contribute substantially to the total subsidence experienced in the delta as well.

Monitoring subsidence by measurements (for instance by InSAR, LiDAR or GPS) is essential to facilitate management decisions in subsiding deltas and should be invested in. However, 3D numerical models, as has been developed for the Mekong Delta, have the potential to provide highly relevant predictions of delta-wide subsidence, supporting the urgently needed decision-making in subsiding deltas. They also have the capability to forecast subsidence under different management scenarios and decisions and to evaluate the effectiveness of certain measure. In that sense, subsidence models form an integral part of the subsidence policy cycle.

For the MKD, the hind casting results of the best estimate model suggests that a quarter century of pumping-induced subsidence caused the delta to sink on average by ~18 cm over the past 25 years, with areas over 30 cm. At present, the average groundwater extraction related subsidence rate in the MKD lies around 1.1 cm yr^{-1}, with local extremes over 2.5 cm yr^{-1}, exceeding local rates of absolute sea level rise (~3 mm yr^{-1}) by an order of magnitude.

3.4 Lessons learned and recommendations

Important aspects to consider when modelling subsidence in deltas, coastal plains or cities are:

- When sufficient hydrological and geological data is available, this modelling approach can be applied to other delta systems worldwide facing groundwater-extraction related subsidence, to estimate a range of subsidence rates even when no direct subsidence measurements, such as InSAR, are available.
- The modelling results will greatly benefit from available data, such as high resolution InSAR studies, measured soil mechanical parameters, and a dense network of extensometers and ground water observation wells.
- It is important to have some basic understanding of the subsidence rates caused by other processes in the study area, not to overestimate the contribution by ground water extraction.
- The modelling in this case study has been conducted by using the MODFLOW software developed by the USGS. This is a widely used software package for regional scale studies, which means that there multiple research groups and consultancy companies that offer support with this package. Although originally a hydrological model suite, it contains subsidence packages that can be used to model land subsidence.

Step 4. Measures - Cost-benefit analysis and decision support (example case Gouda, The Netherlands)

4.1 Introduction

The historic city centre of Gouda is subsiding approximately 3-5 mm/year. Many buildings and houses from the 16th till the 20th century were built on shallow foundations and thus subside with the soil. To accommodate this, the groundwater table has been artificially lowered over the last centuries. Further lowering of the groundwater table however – though desirable from the perspective of flood risk reduction - might cause significant damage to structures that are built on wooden foundations. Decision-makers in the city of Gouda have realised that the conventional measures addressing land subsidence no longer suffice and new strategies are needed. In 2014, the municipality forged a coalition with the aim to jointly develop future-proof strategies for central Gouda. The coalition consists of governmental agencies (municipality of Gouda and Water Authority Rijnland) and a range of research and knowledge institutes.

Figure 5.1 The Turfmarkt in Gouda, sept 2015 (Photo by C. Seijger)

Since 2014, the following steps have been taken with coalition participants to work towards a strategy for dealing with subsidence in the historic town:

- Problem analysis: A group model was developed to analyse the problem of land subsidence in the city centre of Gouda in a collaborative modelling session, identifying the systemic relations between socio-economic and physical elements of subsidence (figure).
- Strategies and adaptation pathways: Definition of future (policy) perspectives or strategies for the year 2060; distinctive in their allocation of responsibilities (public or private) and in strategic decisions to cope with land subsidence.
- Cost benefit analysis: The decision making process in Gouda was supported by a quick-scan cost-benefit analysis of the two 'extreme' future (policy) perspectives.

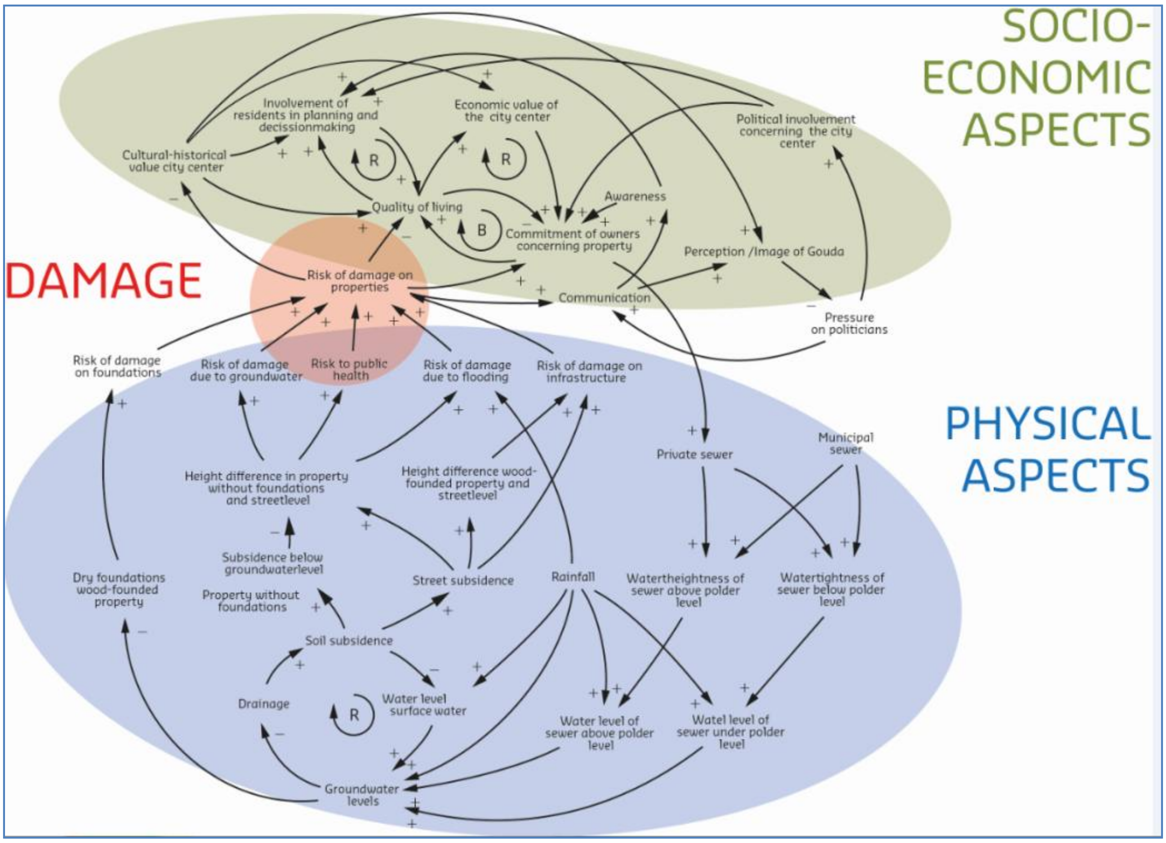


Figure 5.2 Causal loop diagram, showing systemic relations between socio-economic and physical elements of subsidence in Gouda, with risk of damage to houses as main interlinking element (from Seijger et al. 2018).

As illustrated by Figure 2 subsidence is a complex problem: multiple factors contribute to the rate and type of subsidence, there are various direct and indirect impacts, multiple affected stakeholders and no clearly outlined responsibilities.

4.2 Strategies and adaptation pathways

Due to the complexity of the problem, dealing with subsidence typically entails developing a strategy on various dimensions. Two extreme future perspectives or strategies were developed with key stakeholders, to increase insight in the possibilities and implications of dealing with subsidence:

- ‘Keep height’: prevent or reduce further subsidence of soil and all structures and infrastructure.
- ‘Follow subsidence’: focus on mitigating subsidence damage rather than prevent subsidence itself.

In each perspective, adaptation pathways and key ‘tipping points’ were identified at which point ‘business as usual’ is no longer an option – that is, subsidence damage is expected to reach a socially unacceptable level. This was done for different sectors, i.e. water management, housing, infrastructure and the sewage system. In a next step, roles and responsibilities for public and private parties were identified for both action perspectives.

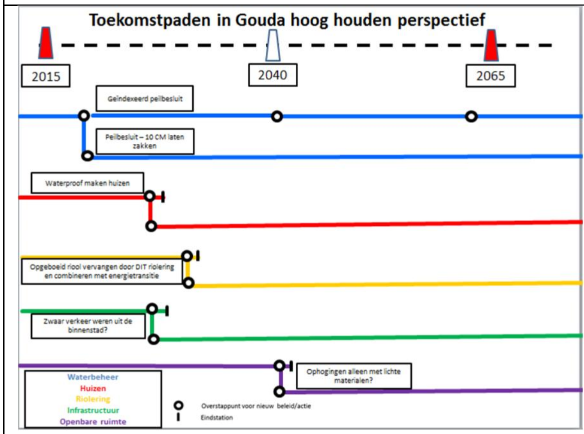
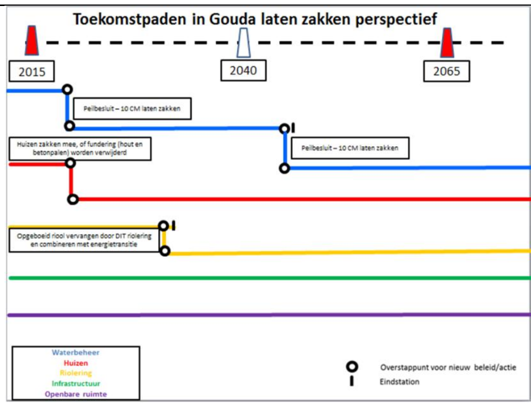
Perspective: 'Keep height'	Perspective: 'Follow subsidence'
	

Figure 5.3 Action perspectives and adaptation pathways for subsidence in Gouda (Hommes et al., 2018)

4.3 Cost-benefit analysis

After the initial definition of action perspectives, the decision making process in Gouda was supported by a quick-scan cost-benefit analysis. Cost-benefit analysis (CBA) is an approach that assesses the economic rationale for investment in adaptive or mitigating strategies/ solutions, from a general welfare perspective – it is not concerned with the feasibility, stakeholders or financing and legal aspects. By monetising all effects of subsidence, for example based on restoration costs, revealed or stated preference or by comparing lifecycle costs, the shared metric allows a comparison between policy alternatives and the reference alternatives– i.e. business as usual. Typically, a CBA includes the following steps: problem analysis, definition of a reference alternative, definition of policy alternatives, determination of effects, determination of project costs, sensitivity analysis and reporting.

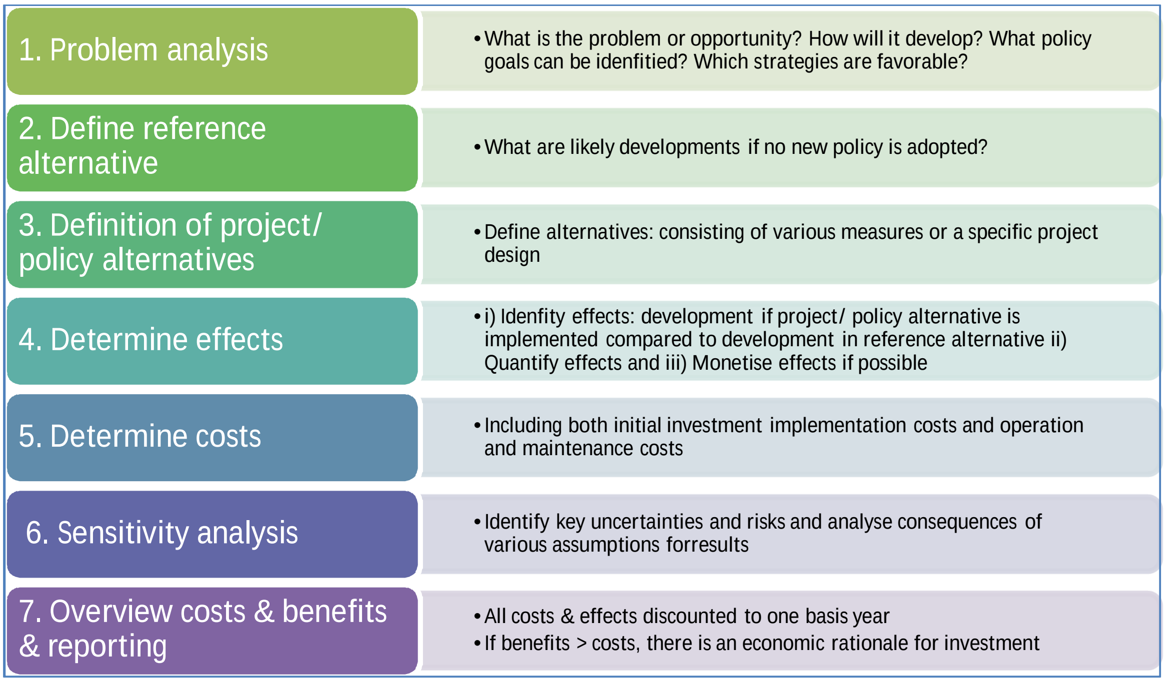


Figure 5.4 Overview of cost-benefit analysis methodology

Gouda: Quick-scan CBA
In 2017 a quick-scan CBA of action perspectives 'Keep Height' and 'Follow subsidence (Kok, 2017). In the reference alternative - no new policy – it is expected that the water levels will be lowered again in the future, as in the previous centuries, resulting in a continuing subsidence of 3-5mm/year. Among other things, in time this might lead to significant damage to approximately 400 housing foundations which will need to be replaced – costing between €50.000-70.000 per house. Furthermore, construction and operation and maintenance costs of infrastructure (including roads, sewage, public space, cables & pipes, embankments and public space) will remain high as subsidence accelerates their degradation.

In the action perspective 'Keep height', the following concrete measures are considered: replacing shallow building foundations in the inner city (~1500) to stop their subsidence; periodically elevating gardens and public space (including street) to keep level with buildings; and where possible, ground infrastructure on foundations.

The action perspective 'Follow subsidence' includes the following measures: strengthening structures to cope with potential damage; measures to prevent damage to wooden pole foundations; waterproofing buildings to cope with high (ground)water levels; using flexible cables and pipes to prevent breakage.

The analysis concludes that expected damage from subsidence in central Gouda is between €26 – 40 million before 2100 in the reference alternative. The 'Keep height' action perspective prevents approximately € 4 – 11 million of this damage, but costs a disproportionate € 130 million, especially due to the expensive reconstruction of foundations. The 'Follow Subsidence' action perspective does have an economic rationale: preventing approximately €13-20 million of damage, whilst costing €7-16 million in measures.

Current status in Gouda
In the initial phase (2014-2017) subsidence in Gouda was studied to increase understanding of the problem, and first steps were taken towards identifying possible future policy directions. Presently, the most promising strategies are further specified and analysed in more detail, working towards an official soil subsidence strategy for the city centre (in Dutch: Kaderbesluit Bodemdaling Gouda), which in turn will inform the water policy decision scheduled in 2019, as well as the municipal sewage plan.

4.4 Key lessons learned

Seijger et al. (2018) analysed the process of the past years in which the coalition is working towards developing policy on the subsidence problem. Some key lessons that are identified include:

- During the problem analysis phase (e.g. in stakeholder engagement and communication), it is good to realise that inhabitants do not necessarily care about land subsidence directly, but rather about its negative impacts such as damage to individual properties and reduced liveability in their city, including e.g. increased pluvial floods, broken door entrances, and the smell of sewage spillovers.

- Developing future perspectives and strategies is a useful way to explore different options to address land subsidence. By specifying actions and responsibilities for public and private parties the strategies become more realistic. Discussions about the strategies yielded lessons on how and when to implement them.

- The cost benefit analysis brought valuable new insights to the decision making process: beyond a general idea of the feasibility of an action perspective (costs) it also gives insight in the economic rationale from a welfare perspective to take action. The municipality of Gouda views the Quick-scan CBA as a real game changer, and a valuable instrument to further develop strategies and offer analytical support to the decision making process (Bodemplus, 2018).

Step 5 Implementation of measures (example case Bangkok)

Since the emergence of various problems associated with groundwater in the 1960s and 1970s the government has implemented numerous measures to mitigate these problems. In summary the following measures are implemented in Bangkok:

- Policy and regulatory measures
- Groundwater monitoring and database system
- Decision support tools for management and planning

5.1 Policy and regulatory measures

In Bangkok extreme land subsidence by groundwater extraction was successfully reduced by law, regulations and restrictions for groundwater extraction (fig. 1), as monitoring data showed a clear correlation between total land subsidence and the piezometric level decline. Since 1983 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. The controlling of groundwater use and collecting of groundwater fees and groundwater conservation tax in the critical areas resulted in increasing water levels (fig. 2) and decreasing rates of land subsidence (fig. 3-5). Although water extraction is now regulated, land subsidence is still taking place at the rate of 20-30 mm/year in most affected areas in the southeast and southwest suburbs of Bangkok.

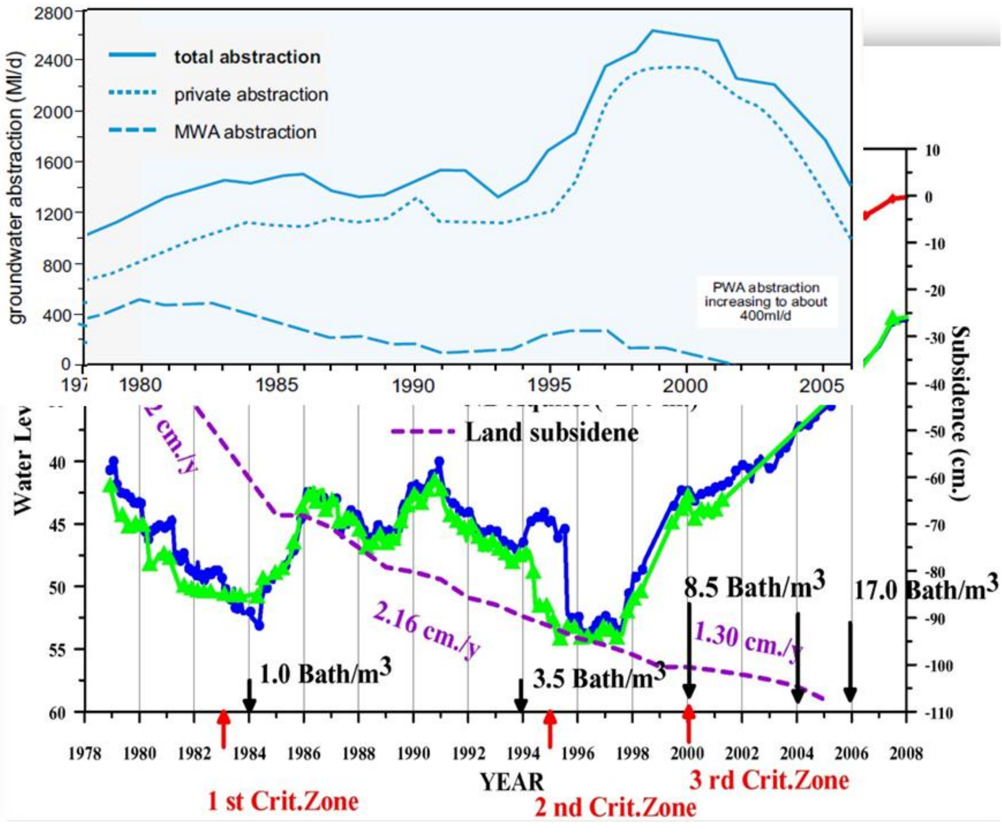


Figure 5.1 Reduction of subsidence in Bangkok by restrictions for groundwater extraction (groundwater tariff and other regulations)

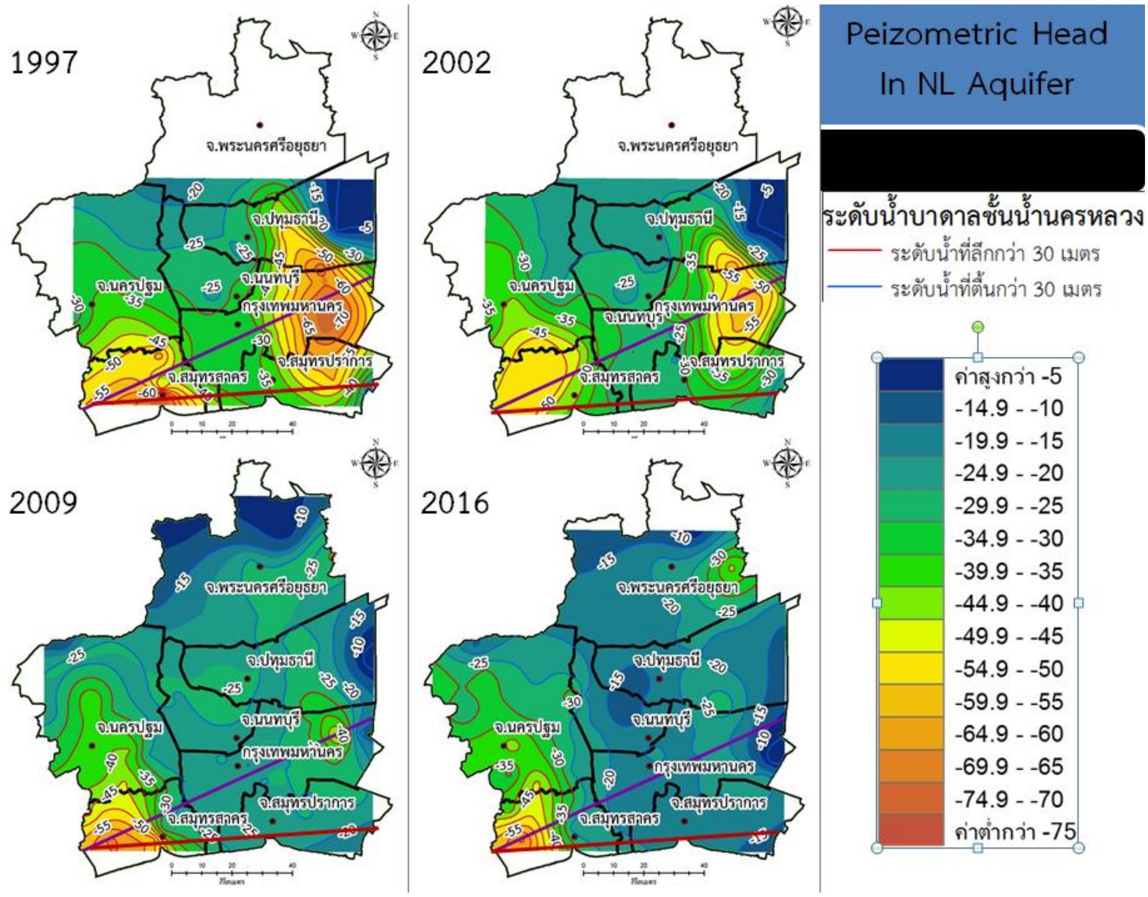


Figure 5.2 Increasing groundwater levels (piezometric head) in the NL aquifer in Bangkok

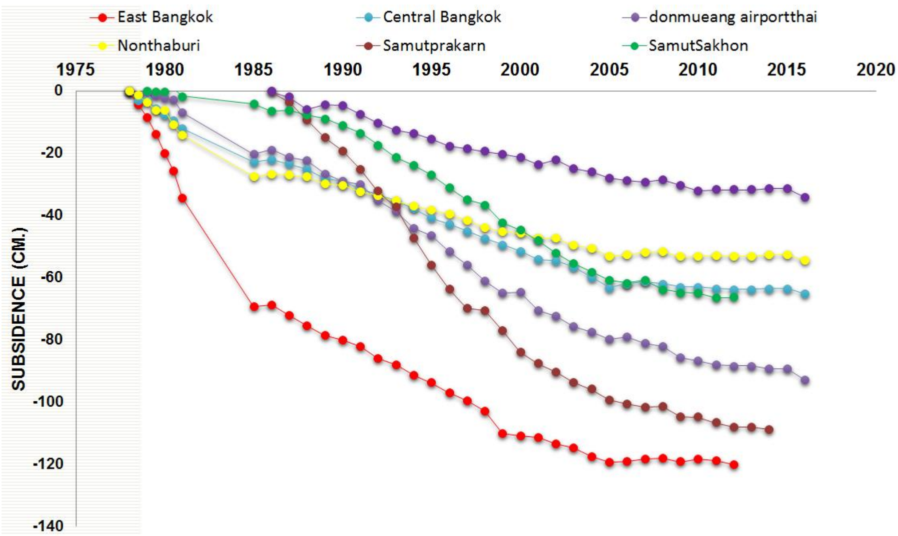


Figure 5.3 Subsidence in several areas of Bangkok in period 1978 – 2016 (Chusanathas and Lorphensri, 2017)

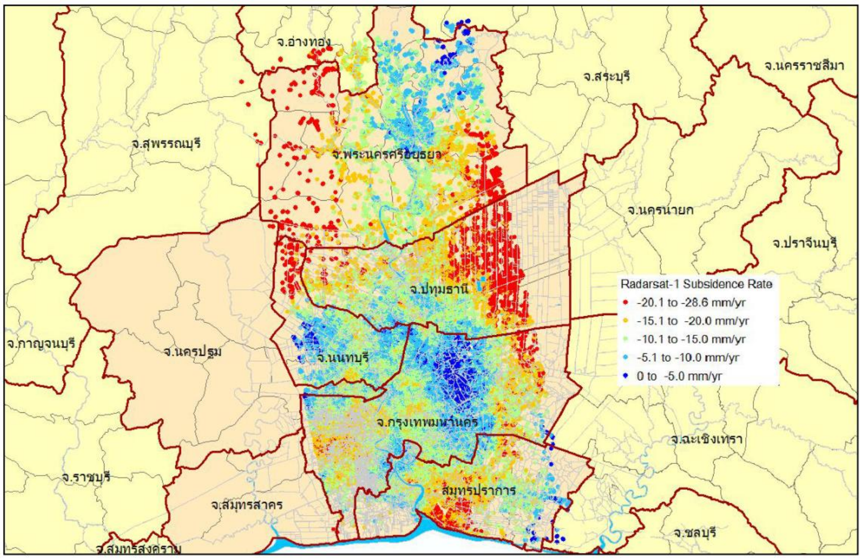


Figure 5.4 Land subsidence rate (mm/year) of Radarsat-1 Images from October 2005 to March 2010 (DGR, 2011)

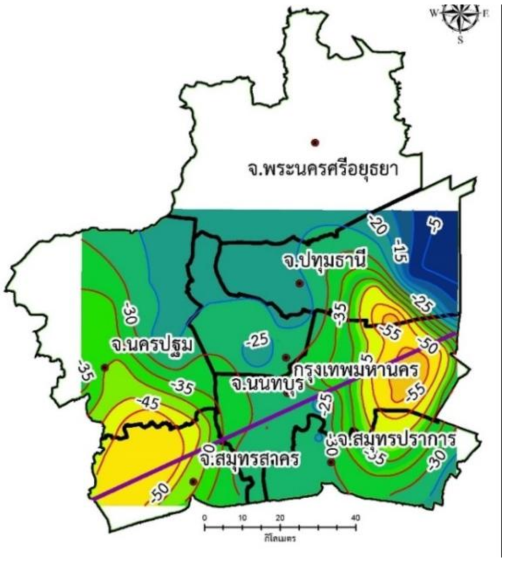


Figure 5.5a Subsidence in Bangkok in mm/yr in period 1996 - 2000

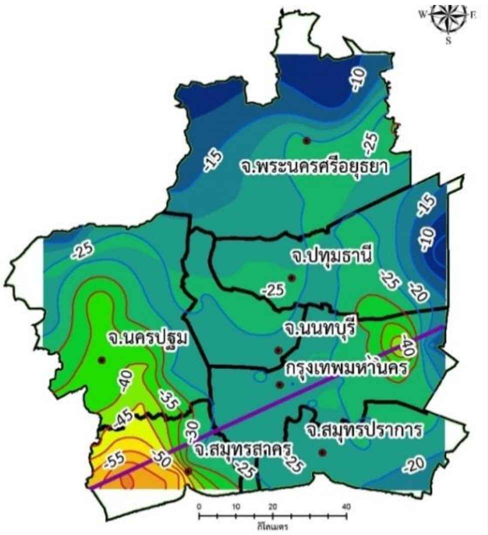


Figure 5.5b Subsidence in Bangkok in mm/yr in period 2005 -2011

Comprehensive law for groundwater and enforcement

A specific law concerning groundwater in Thailand came into effect in 1978, and it has been amended twice: in 1992, and in 2003. It contains provisions for controlling the exploration and drilling for groundwater, the use of groundwater, the recharging of aquifers through wells, and the protection and conservation of groundwater resources in the country. Failure to comply with this law may result in fines or imprisonment. Law enforcement is being done through meter inspections, well decommission inspections and capture of illegal and hidden wells.

Designation of groundwater regions and critical zones

To control groundwater use and mitigate environmental problems associated with it, areas most severely affected by groundwater-related problems such as land subsidence and groundwater depletion were designated as Critical Zones where more control over private and public groundwater activities was instituted. This involved also relocation of large groundwater users, such as industries, outside critical zones.

Licensing and charges for well-drilling and groundwater use
Under the Groundwater Act, the government initiated licensing for the installation of wells and private groundwater use. Licenses were required to extract groundwater, and pumpage limits were instituted through these permits. This involved implementation of Groundwater Use Charges (currently 8.5 baht/m3), Conservation Charges (currently 4.5 baht/m3), levying surcharges and penalizing violators of regulations.

Groundwater use metering
The installation of well meters was enforced in 1985 in support of the use charges that the government started to levy from private users at that time.

Establishment of groundwater quality standards
To promote groundwater and environmental quality conservation, standards for groundwater for drinking purposes were established through the Groundwater Act and, in 2000, groundwater quality standards for the conservation of environmental quality were issued (PCD, 2004).

5.2 Monitoring and database system

A levelling network to monitor land subsidence was established in 1978 by Royal Thai Survey Department (RTSD). Another levelling network was established in 1979 by the Bangkok Metropolitan Authority (BMA) as reference benchmark for constructions and civil works. An extensive groundwater monitoring network and database system is in place (fig.6). There is also a License database and related billing system.

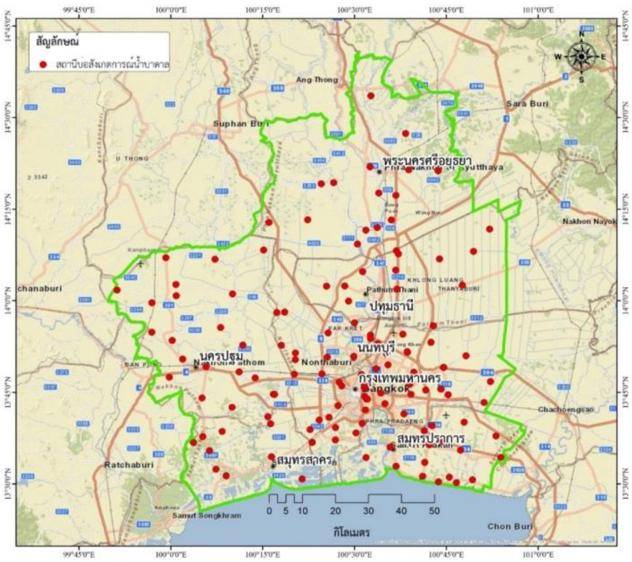


Figure 5.6 Groundwater monitoring network in Bangkok

5.3 Decision support tools

A numerical groundwater model coupled with a geographical information system is an important tool for decision support such as permitting groundwater use and improvement to the framework of groundwater conservation taxation. Moreover, INSAR technology is used to map the area and rate of land subsidence area. This new technology will enhance the efficiency of land subsidence detection in addition to the conventional ground survey (CCOP, 2010). A Geographic Information System was developed to support integration and collective interpretation of available knowledge and scientific findings, through groundwater modelling results and maps, and making them accessible to all the stakeholders.

5.4 Lessons learned and recommendations

For the implementation of measures the following aspects are most relevant:

- Evidence-based, scientifically sounds information, building on (regular) monitoring and modelling systems
- Political will and sense of urgency; this involves good communication/awareness raising, capacity building and stakeholder involvement. The sense of urgency is often increased by incidents such as flooding, collapse of buildings or failing infrastructure.
- Good examples by pilots and demonstration projects will strengthen political and societal support
- Multi-sectoral cooperation is needed to implement an integrated approach and related set of measures reinforcing each other and also clearly beneficial for citizens. This involves among others conjunctive use of groundwater and surface water, but also developing alternative water supply or reducing water demand.
- A legal framework for measures is essential, consisting of appropriate laws, regulations, (economic) instruments and related enforcement. This involves also a an 'accountable' charging system and penalizing violators of regulations.
- Tools for management, planning and decision support are very helpful for experts and decision makers, such as web-applications, GIS, visualisations and serious games.
- A comprehensive implementation and action plan is needed with division of tasks and responsibilities, building on an effective governance and organisational structure.
- Sufficient long-term funding is needed for continuous monitoring and knowledge development through research programs

Step 6. Monitoring and evaluation of land subsidence (example case Shanghai, PRC)

6.1 Land subsidence in Shanghai

Shanghai is one of the largest urban areas in southeast Asia and home to 24 million people. The city has experienced severe land subsidence as a result of excessive ground water extraction for domestic and industrial use. The first deep well in Shanghai was installed in 1860. Land subsidence in Shanghai is reported as early as 1921. Average subsidence rates since then were approximately 26 mm per year. After the Second World War, under conditions of economic growth, the extraction of groundwater accelerated and in 1965 the maximum recorded cumulative subsidence by one of the bench marks, was as high as 2.63 meter. Between 1957 and 1961 the highest rates of 10 cm per year were attained.

As a result of the subsidence, parts of Shanghai now form a bowl-shaped depression locked between less subsided higher grounds. Two distinct areas with subsidence are the Eastern and Western Shanghai industrial districts, where more than 80 percent of the total amount of groundwater was extracted.

6.2 Counter measures

In 1966, a series of countermeasures were taken aiming at bringing the land subsidence in the urban area of Shanghai back under control. These measures were:

- In 1963 a resolution was passed by the Shanghai Municipal Government restricting groundwater use. The industry was encouraged to use surface water instead, and in necessary to install refrigeration installations to be able to use the water for cooling purposes. After these measures had been implemented in 1965, the hydraulic heads started to recover and land subsidence in the urban area decreased from year to year.
- Since 1966, groundwater has been artificially recharged. Artificial groundwater recharge happens seasonally, where in winter water is recharged for use in the summer and vice versa. As a result of the artificial recharge, hydraulic heads were further elevated, zonally even above regional hydraulic heads. The recharged water also provided a new source of warm and cold water for the industry. Along with the periodic fluctuations of groundwater levels during winter recharge and summer exploitation, alternating expansion and compression has taken place. In 2011 artificial recharge exceeded groundwater withdrawal
- Before the 1960s, ground water was mainly extracted from relatively shallow aquifers. As remediation measure, groundwater withdrawal was partly transferred to deeper aquifers. This resulted in decreased rates of land subsidence in the Shanghai urban area.

As a result of the hydraulic head (groundwater pressure) recovery, land subsidence rates decreased to 2011 to an average rate of 5.5 mm/year. Average cumulative land subsidence between 2001-2011 reaches 0.055 m.

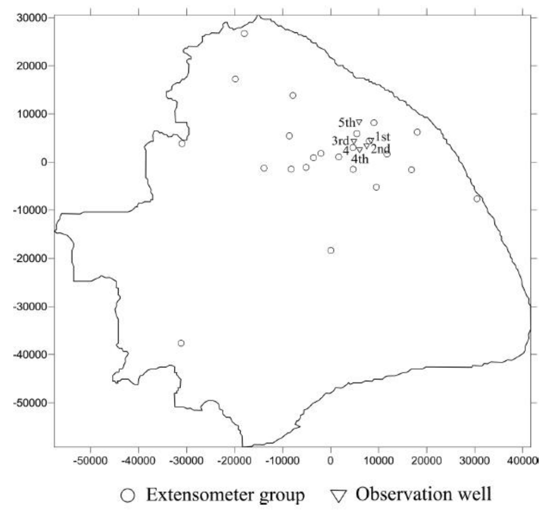


Figure 6.1 Locations of extensometer groups and observation wells in Shanghai (from Zhang et al., 2015)

6.3 Monitoring land subsidence

At present, Shanghai in the Yangtze Delta is the only area in China where subsidence is well controlled. The local governments of the provinces make great efforts to monitor and control land subsidence. An essential element of this strategy is the monitoring network (Fig. 1. Land subsidence in Shanghai is traditionally monitored by means of extensometers, benchmarks and ground water observation wells (Fig. 2). There are 25 extensometer groups which are anchored in the underlying bedrock. The oldest have been installed in the 1960s to capture the accelerating subsidence rates and have been operational ever since. Another group was installed in the late 1990s and have been measuring compaction since 1998.

Figure 6.2 A benchmark site in Shanghai. The transparent floor tiles are the locations of the benchmarks and observation wells, each with different foundation depths and well screens (photo G. Erkens).

6.4 Evaluation of land subsidence over time

After the local governments recognized the financial, social and environmental consequences of land subsidence, technical and policy/governance measures were implemented to manage groundwater extraction. Specifically, when realisation came that land subsidence actually hinders sustainable social and economic development of the Yangtze Delta fuelled effective control of land subsidence by administrative means. Numerical land subsidence models supported the detailed mitigation measures implemented in Shanghai. Measuring results are coevally used to monitor and evaluate progress and success of the land subsidence mitigation strategy.

A remarkable example of the strict monitoring and subsequent prompt action with measures is the period 1990-2000. During this timeframe, rapid economic growth and development in China increased the water demand and thus the extraction from the deeper aquifers as a result of the previously implemented policy to assign these deeper aquifers as the preferred ground water resources. As a result of the increased extraction, land subsidence accelerated once again. To curtail this, new strict rules for use of deeper groundwater were promptly implemented in 2004.

Currently, the maximum allowed land subsidence in Shanghai is 6 mm per year. If this exceeded, extra measures, such as stricter controls on ground water extraction, are implemented. Possible consequences of the (lower) land subsidence rates are accepted and may be mitigated if required. In this way, Shanghai actively controls land subsidence. Other areas in China, notably the cities of Cangzhou and Tianjin in the North China Plain, issued – inspired by the successful control of land subsidence in Shanghai - similar decrees of Administrative measures on land subsidence in 2007 and 2014, respectively.

6.5 Lessons learned and recommendations

- The first question to ask is: when is the land subsidence problem considered under control? The required level of control depends on the accepted level of residual damage that may still occur at the desired rate of land subsidence. The appointment of the acceptable residual rates of subsidence and associated damage is foremost a policy issue, and heavily relies on accurate damage estimates which are often rare. But, the establishment of a 'safe' level of land subsidence is a crucial step in mitigating and controlling land subsidence. This level will most likely not be zero: either a small amount land subsidence (geologically caused for instance) has to be accepted, or mitigation actions cause land subsidence to reverse into uplift.
- An important element in the monitoring is a dedicated measurement network which is structurally and consequently operated. This is required to closely follow the occurring land subsidence. This monitoring system may consist of in-situ measurements of hydraulic heads and land subsidence with observation wells, benchmarks and extensometers, in combination with mapping technique such as radar satellite measurement techniques.
- Along with the establishing of a monitoring network, a data system with basic data services was established by the Shanghai Geological Survey. This facilitates awareness raising on the subject and provides information on how subsidence is monitored and controlled.
- Seamless cooperation between the land subsidence monitoring units, the modelling units and policy making departments is required to swiftly act when 'safe' levels of land subsidence are crossed. This requires operational units in which these different groups regularly meet and discuss the required actions.

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Colophon

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