Advances and Practices on the Research, Prevention and Control of Land Subsidence in Coastal Cities

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Abstract: Land subsidence severely threatens most of the coastal plains around the world where high productive industrial and agricultural activities and urban centers are concentrated. Coastal subsidence damages infrastructures and exacerbates the effect of the sea-level rise at regional scale. Although it is a well-known process, there is still much more to be improved on the monitoring, mapping and modeling of ground movements, as well as the understanding of controlling mechanisms. The International Geoscience Programme recently approved an international project (IGCP 663) aiming to bring together worldwide researchers to share expertise on subsidence processes typically occurring in coastal areas and cities, including basic research, monitoring and observation, modelling and management. In this paper, we provide the research communities and potential stakeholders with the basic information to join the participating teams in developing this project. Specifically, major advances on coastal subsidence studies and information on well-known and new case studies of land subsidence in China, Italy, The Netherlands, Indonesia, Vietnam and Thailand are highlighted and summarized. Meanwhile, the networking, dissemination, annual meeting and field trip are briefly introduced.

Key words: land subsidence, coastal cities, case studies, International Geoscience Programme

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1 Introduction

Land subsidence, the lowering of ground surface due to natural and human-induced processes occurring in the shallow and deep subsurface, is a worldwide geohazard. Land subsidence causes damages and has widespread impacts on a variety of infrastructures, e.g., sewer systems, roads, buildings, subway tunnels and in coastal low-lying areas. In the cities in proximity to shorelines, such as Shanghai, Jakarta and Venice, it is particularly alarming as it reduces the ground elevation with respect to the sea level.

Nowadays the majority of coastal areas affected by land subsidence are characterized by a limited surface elevation

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relative to the sea level (e.g., deltas, estuaries, lagoons). The low surface elevation, together with the high population density, directly threatens the sustainable development of such regions (Slangen et al., 2012). Coastal cities are economically and socio-politically important, and there are no indications that neither subsidence nor the resulting damage will be reduced in the near future, unless targeted mitigation measures are being taken (Erkens, 2015).

One of the important causes of land subsidence is certainly the overexploitation of groundwater (Chaussard et al., 2013). Dropping hydraulic heads and lowering of phreatic groundwater level induce the compaction of subsurface strata and consequently the sinking of the ground surface. Despite cases where groundwater exploitation is strictly regulated by governments, there are many coastal areas where it is the only source for water supply and extractions are uncontrolled. Considering the continuous population growth and the economic development in coastal cities, the water requirements for living and production are expected to increase along with land subsidence.

Another important cause of land subsidence directly related to the rapid development and population increasing in coastal cities, is the large-scale urbanization. The load of new built-up areas and engineering works induce shallow subsurface consolidation, which act also over long periods. Although land subsidence caused by new urbanization significantly threats the safety of population, stability of infrastructures (Tosi et al., 2012; Minderhoud et al., 2018; Wang et al., 2018) and (local) economies, the current state of scientific knowledge is insufficient to cope this critical issue.

Land subsidence also exacerbates the effect of global sea-level rise, being the Relative Sea-Level Rise (RSLR), the combination of sea-level changes and ground movements. To note that land subsidence exceeds absolute sea-level rise (SLR) in many coastlands. Projections until 2100 based on IPCC scenarios expect a global mean absolute sea-level rise in a range of 3–10 mm $year^{-1}$ (Slangen et al., 2014). However, current observed subsidence rates in coastal megacities are in the range of 6 –100 mm $year^{-1}$ and projections till 2025 expect similar subsidence rates. Without actions, parts of Jakarta, Ho Chi Minh City, Bangkok and numerous other coastal cities will sink below sea-level (Bucx et al., 2015).

Coastal subsidence causes damages of billions of dollars per year (Wang et al., 2014) and, because of its impact on society and economy, it is one of the most challenging research fields till today. Over the last decades, significant progress on land subsidence knowledge and control have been achieved in more developed countries or regions in Europe, USA, Japan and Shanghai in China. However, in many developing or less developed countries such as Indonesia, Egypt, Vietnam and Iran, the study, monitoring and impact analysis of land subsidence, as well as investigation on its development, prevention and management are still poorly considered or neglected, which severely increase the hydrogeological hazard and lead to numerous environmental problems that severely restrict sustainable development of many economic activities in these regions.

Within this context, in 2018, the International Geoscience Programme (IGCP) approved the project No. 663 “Impact, Mechanism, Monitoring of Land Subsidence in Coastal cities” (IM2LSC).

The aim of this paper is to present the IGCP 663 project and to provide the research communities and potential stakeholders with major advances on coastal subsidence studies. This was achieved by a short description of the project with information on how to join the participating teams, followed by an overview of well-known and new case studies on land subsidence in China, Italy, The Netherlands, Indonesia, Vietnam and Thailand . The paper ends highlighted the key points emerged from the analysis of coastal land subsidence.

2 The IGCP 663 Project (IM2LSC)

The project IGCP 663 is a scientific cooperative program between institutions and researchers to develop better understanding of land subsidence at international level, especially focusing on the less developed countries in Asia, Africa and Latin America. IGCP 663 plans to research the impacts of human activities and sea-level rise, hydro-mechanism and monitoring methods of land subsidence in coastlands with special focus on coastal cities.

The project results are expected to be transferred to sites in other developing countries, and recommendations will be released to play an effective role in the planning, construction, management and security assurance for different coastal cities.

Specifically, the project IGCP 663 aims to: (1) Develop theoretical and technological knowledge and solutions required for the prevention and control of land subsidence in coastal cities; (2) Improve understanding of the interaction between land subsidence, human activities and sea-level rise in coastal cities; (3) Improve design and construction standards of land subsidence monitoring networks, and promote optimal land subsidence survey and monitoring techniques; (4) Construct an international researcher network to promote the connection and research capacity among scientists of different disciplines from different countries; (5) Promote the project results to serve the planning, construction, management and security assurance in worldwide coastal cities that are under the influence of land subsidence, and gain social benefits; (6) Provide supports for the safeguard and maintenance of UNESCO’s World Heritage in coastal cities.

IGCP 663 is implemented along two parallel directions. The first is to focus on basic research regarding scientific development concerning monitoring, mechanisms and control of land subsidence in coastal cities. The second is to disseminate the scientific achievement of the project in the international network of scientists.

The IGCP 663 website is updated continuously (http://www.kllsmp.com/IGCP663) in order to provide the scientific community and stakeholders with information on the ongoing research activities, outcomes of studies, workshop organization and other events and links to additional initiatives and projects focusing on land subsidence, such as the UNESCO Land Subsidence International Initiative (formerly Working Group, http://landsubsidence-unesco.org) and IGCP project 641 (http://www.igcp641.org). At present, nearly 100 scientists in the field of land subsidence from China, Italy, the Netherlands, Indonesia, Mexico, America, Thailand, Vietnam and Pakistan have joined the project.

Scientists, stakeholders, practitioners, and students worldwide are invited to register and participate in the project activities as well as to attend the annual meetings. The first annual meeting was held in 2018 in Shanghai. Over two days, more than 50 participants shared the latest research results and advanced governance experiences on land subsidence were discussed, providing international vision and thinking for further studies. They provided different perspectives on analysis and monitoring land subsidence causes (Yan et al., 2019), such as groundwater withdrawal for drinking water(e.g., Jakarta), land reclamation and groundwater lowering for construction (e.g., Shanghai), phreatic groundwater level lowering (drainage) (e.g., Netherlands), extraction of hydrocarbons (e.g., northern Netherlands).

Advance governance experiences, including coastal subsidence prevention and control actions, have been discussed in the round table with the presence of national and regional water authorities, bringing as examples the cases of land subsidence in North China Plain, Tianjin, Pearl River Delta, Shanghai, Italian coast, the Dutch delta, the Mekong delta, Jakarta and Bangkok. Shanghai has been set as an example of how could be dealt with subsidence by, for example, taking measures of constructing a comprehensive monitoring network, implementing artificial recharge, restricting groundwater pumping, developing policies and regulations.

The project team conducted a series of field trips during the project meetings in Shanghai and Jiangsu province, China (Fig. 1), and a field survey of the Mendota, California, the USA, where about 9 m cumulative subsidence occurred over a period of 50 years due to over-extraction of groundwater.

The feasibility of global coastal subsidence mapping has been discussed and the following steps of work have been planned. (1) Set-up of a GIS of coastal cities classified on the basis of the magnitude of the subsidence with metadata including ranges of sinking velocities, areal extent (km^2), causes, and bibliography; (2) Inclusion of maps available from published works in the GIS; (3) Set-up of a new global coastal subsidence map obtained by the homogenization and redrawing of maps previously developed by different authors.

The workshops of IGCP 663 organized annually provide a friendly platform for participants to communicate their own research results and to bring together global experts, and research facilities to solve the global-scale problems.

3 Main Advances on Land Subsidence Knowledge

This section highlights the major advances on coastal subsidence studies and summarizes information on well-known and new case studies of land subsidence, methodologies used for monitoring, data analysis and mapping in order to provide a “state of knowledge” in different study areas.

3.1 Coastal reclaimed areas in Shanghai, China

Reclaimed soils are widely developed in coastal areas of Shanghai. The problem of continuous uneven land subsidence has occurred in the area for a long time because of the variable thickness, properties and compressibility of the reclaimed coastal soils.

In order to accurately predict land subsidence and reduce its impact, the investigation of land subsidence in the reclaimed area was carried out along the coast of Shanghai. The spatial distribution characteristics, physical and mechanical properties of the reclaimed soil and its underlying natural sedimentary deposits on the eastern coast of Hengsha Island, Pudong and Nanhui of Shanghai were investigated (Fig. 2).

By means of scanning electron microscope (SEM), X-ray diffraction (XRD), polarized light microscopy (PLM) and mercury intrusion pore measurement (MIP), the structural differences of the reclaimed soils and its underlying natural sedimentary sequence were studied on the micro scale.

The reclaimed soils of Hengsha Island were characterized by plant debris, artificial geotechnical debris and shell debris, with a disordered spatial distribution of particle morphology. The surface of soil particles was often adhered with more fine flake particles. Conversely the natural sediments forming the Hengsha Island were characterized by a generally uniform texiture distribution. Obviously, silty and clay soils were characterized by an anisotropic distribution of particles (Fig. 3, 4). The bioclasts were also contained, and the long axis of clastic particles was usually distributed along the soil bedding (or intersected at a small angle). The sand grains were uniformly distributed, generally clean without plant debris.

The reclaimed soils along the eastern coast of Pudong often contained plant debris, and the spatial distribution of particle morphology is disordered. The surface of soil particles was often adhered with more fine flake particles. The grain size distribution of the eastern Pudong natural sedimentary soil was generally uniform, and the anisotropic distribution of particles was detectable in the vertical bedding profile of clay soil (Fig. 3, 4).

The particle morphology spatial distribution of reclaimed soil was disordered under polarized light microscopy. To note that the mineral particles of sedimentary soil presented anisotropy controlled by sedimentation. The quantitative analysis of spatial anisotropic distribution on mineral particle morphology was used to distinguish between reclaimed and sedimentary soils. The special microscopic structure of the reclaimed soil was an important internal cause of land subsidence developed in the reclamation areas. Therefore, the stratigraphic structure can be determined by distinguishing between reclaimed and sedimentary soils, so as to accurately predict and take measures to reduce future potential land subsidence in the coastal reclamation areas.

Fig. 1. Field trips during the project meetings in Shanghai and Jiangsu province, China.
(a) Visit to the Key Laboratory of Land Subsidence Monitoring and Prevention, Ministry of Land and Resources of China; (b) Field investigation on remains of land subsidence in Shanghai.

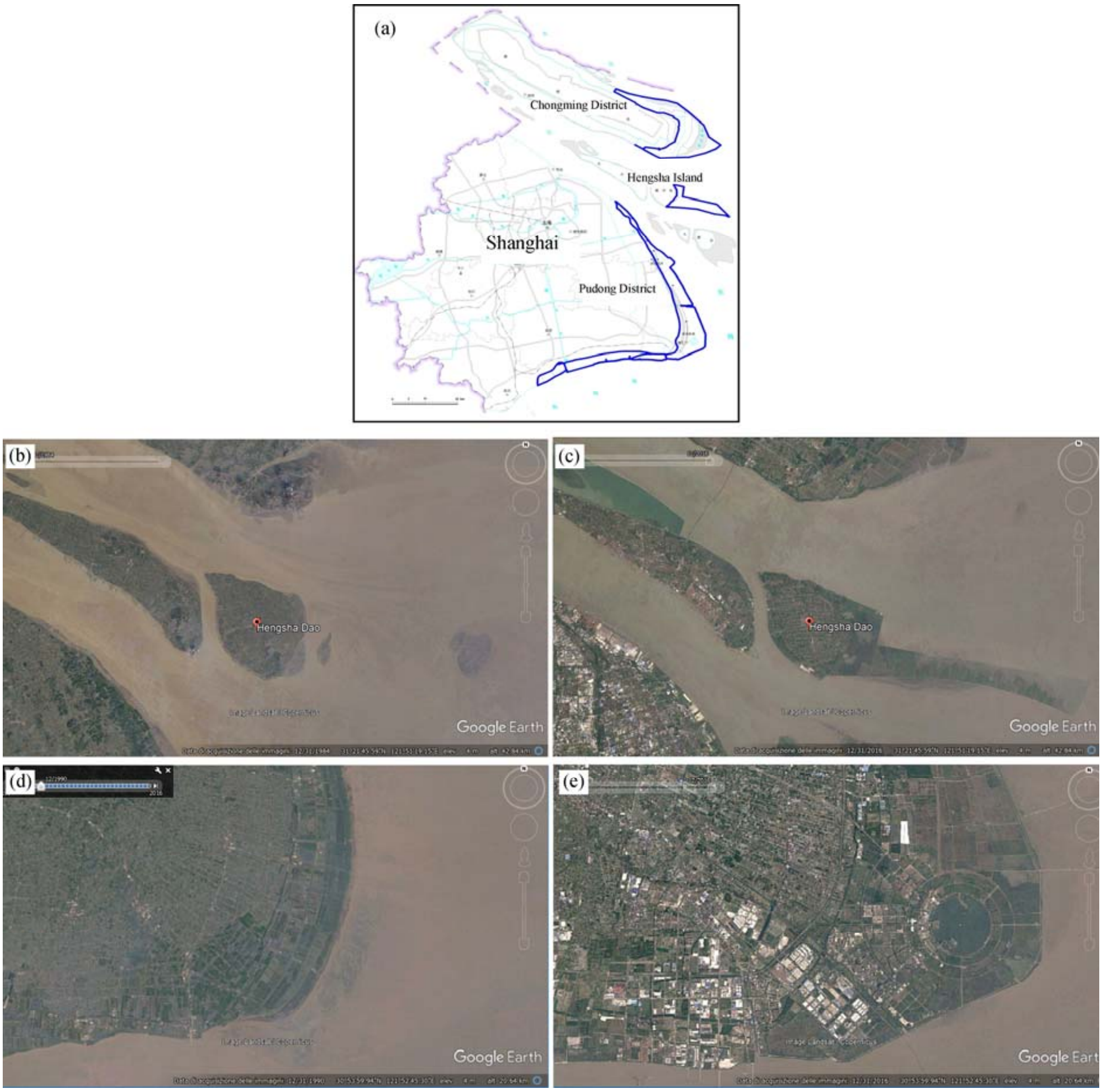

Fig. 2. Map of reclamation areas in Shanghai (a); Hengsha Island in 1984 (b) and 2016 (c); Nanhui in 1990 (d) and 2016 (e).

3.2 Historical and natural heritages (Italy)

The Italian study area cover the Northern coast of the Adriaticsea, which is one of the major low-laying coastal plain facing the Mediterranean Sea. Major cities as Venice and Ravenna, the Po river delta and a number of estuaries and lagoons are endangered by land subsidence and sea level rise due to global changes. Admittedly, the Venice area holds a great natural, historical and cultural heritage that is jeopardized by the continuous loss in elevation with respect to the mean sea level. For this reason, it has been always considered a pilot area for developing scientific researches and monitoring methodologies aimed at better understanding of the process of land subsidence and sea-level rise. The city of Venice and its surrounding lagoon is presently one of the sites worldwide most sensitive to land subsidence. Even a few mm loss of ground elevations seriously compromises the heritage and safety of the city and induces significant changes in the transitional coastal environments in relation of their small elevation above the sea.

In the last decade, satellite SAR-based interferometry has been extensively used to detect ground movements. Most of the satellites have been tested and used (ERS, ENVISAT, ALOS, COSMO-SkyMed, TerraSAR-X and SENTINEL) and a great effort has been dedicated to improve the quantification of land subsidence at a very high spatial resolution. The vertical accuracy has been guarantee by high precision leveling surveys carried out on a very extensive monitoring network. The increased spatial coverage of the measured points (Fig. 5) revealed areas severely affected by subsidence formerly unknown and allowed to update many conceptual model of the driving mechanisms (Tosi et al., 2009; Da Lio and Tosi, 2018). Furthermore, taking into account the recent improvements of A-DInSAR sensors such as the COSMO-SkyMed satellites and the current ESA Sentinel missions, which act at higher temporal and spatial resolution, a novel methodology was developed to exploit the potential contained in the A-DInSAR displacement time series (Bonì et al. 2016). The methodology was applied in the coastal area of Ravenna for the identification of ground motion areas in the period from 1992-2016 (Fiaschi et al., 2016).

The main results of recent researches focused on land subsidence in the Italian coastal test sites are: (1) The implementation of appropriate analyses combining data sets obtained by SAR-based interferometry using different SAR sensors (C-, L-, X- band) allowed to overcome the limitation of each single satellite capability and offered the possibility to improve the spatial coverage of land movement data in heterogonous coastal environments (Tosi et al., 2016). (2) The use of artificial corner reflector to provide ground displacements in areas with lack of reflectors as well as the synergy of SAR based interferometric data with those provided by other satellites and airborne sensors has been positively evaluated (Strozzi et al., 2013). (3) High resolution and long-term analysis data obtained by SAR-based interferometry depicted a new image of the land subsidence pattern at the Venice coastland and revealed a very high heterogeneity of the ground dynamics both at the local and at the regional scales (Tosi et al., 2010). (4) Short-term man-induced displacements affect the historical centre of Venice. About 25% of the city experienced movements due to anthropogenic causes in 2008 (Tosi et al., 2013). (5) Natural and man-made salt marshes are characterized by a quite wide range of subsidence rates. The displacements range from small uplifts to subsidence rates of more than 20 mm/year and land subsidence is much larger on man-made than natural salt marshes, with a significant negative correlation with the marsh age (Da Lio et al., 2018). (6) Significant settlements of a few centimetres per year have been detected at the three inlets where new structures and restoration works were carried out (Tosi et al., 2012, Tosi et al., 2018). (7) Newly built-up areas induced local land subsidence with sinking rates up to three times higher than those characterizing the older urban areas (Da Lio and Tosi, 2018; Tosi et al., 2018).

3.3 Compaction and oxidation of Holocene coastal-plain deposits (The Netherlands)

The Netherlands is located in NW-Europe bounding the North Sea (Fig. 6). Our case study area covers the coastal-deltaic plain in the western part of The Netherlands. This area is characterised by a cover of onlapping Holocene coastal-deltaic deposits, up to a thickness of 20 m in the west. Current surface elevation ranges from 1 m in the east to almost -7 m in excavated former peat areas (AHN, http://www.ahn.nl/common-nlm/viewer.html). Approximately 50% of the coastal-deltaic plain is currently situated below sea-level. The western part of the coastal plain is the most densely populated part of The Netherlands and hosts the major and economically important cities of Rotterdam and Amsterdam.

The Netherlands has a long history of subsidence due to large-scale drainage of the extensive peatlands in the coastal plain area. Human-induced drainage started already in the Roman Period ca. 2000 years ago (Pierik et al., 2018), but was intensified and consistently expanded approximately 1000 years ago under conditions of rapid population growth. Land was reclaimed for agriculture and peat was excavated for fuel (Borger, 1992; Van Dam, 2001; Erkens et al., 2016). Due to continued drainage of this area inducing compression of peat and clay layers and oxidation of organic material above phreatic groundwater level, land subsidence is still going on with typical regional rates of 1-12 mm/yr (Koster, 2017). During the extreme drought of the summer of 2018, rates up to 7 cm/6 months were measured (Hanssen, pers. comm.), although it remains to be seen how much of this is irreversible.

In the Netherlands, subsidence causes considerable damage to agricultural production, infrastructure and other public and private assets, possibly adding up to 22 billion Euros by 2050 (Van den Born et al., 2016). Moreover it gives rise to serious safety issues due to increased flood risks and land subsidence caused by peat oxidation is associated with considerable greenhouse gas emissions which will further contribute to climate warming. In some areas tipping points have already been reached, where current land-use can no longer be maintained without considerable costs.

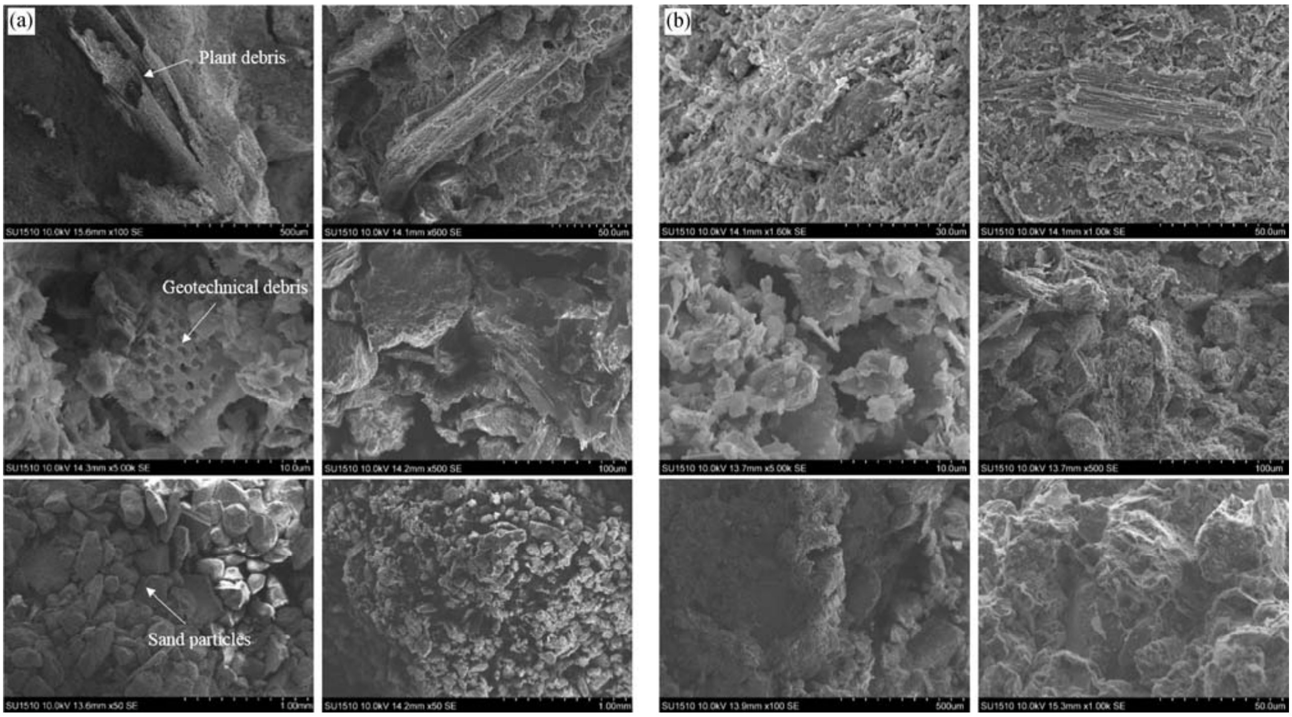

Fig. 3. SEM results of the reclaimed soils on eastern coast of (a) Hengsha Island; (b) Pudong area.

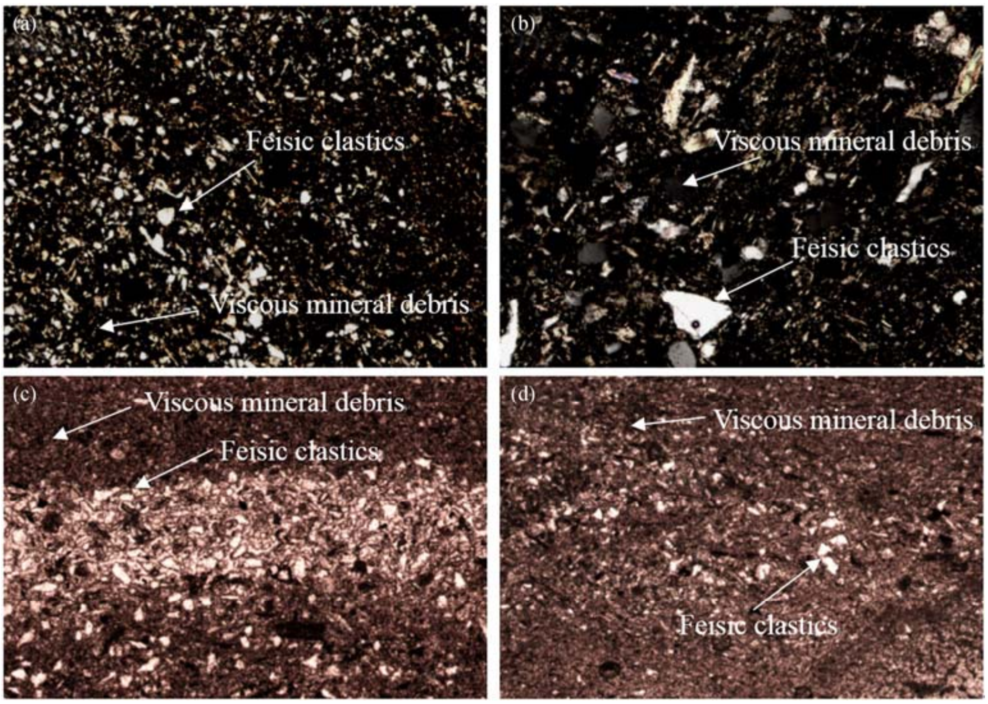

Fig. 4. PLM results of the reclaimed soils and natural sedimentary soils.
(a) Reclaimed soils in Pudong area; (b) reclaimed soils on Hengsha Island; (c) natural sedimentary soils in Pudong area; (d) natural sedimentary soils on Hengsha Island.

Recent research has been focused on the reconstruction of human-induced land subsidence in the coastal plain enabling the quantification of long term subsidence rates, the development of methods and algorithms to quantify and predict land subsidence by peat compression and oxidation (Erkens et al., 2017; Koster et al., 2018a, 2018b, 2018c; Van Asselen et al., 2018), characterization of void ratio and compressibility of peat and 3D distribution of organic matter to implement in the 3D geological (GeoTOP; TNO-GSN) voxel model of the Netherlands (Koster et al., 2018a), monitoring of surface motion (Hanssen et al., 2018), existing governance lock-ins and

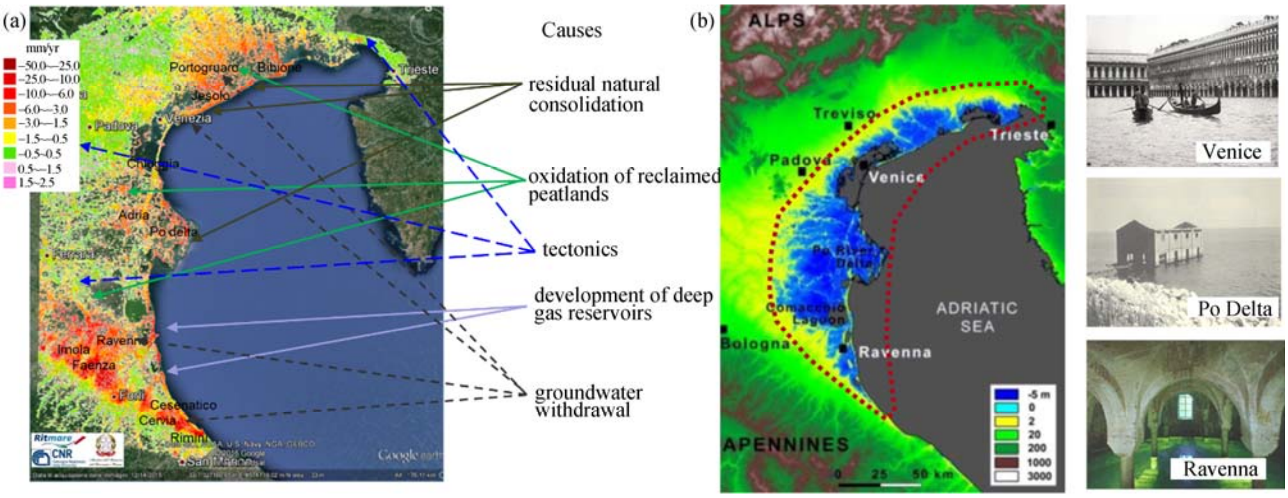

Fig. 5. Northern coastland of the Adriatic sea.
(a) Map of the ground movements obtained by SAR-based interferometry showing the high heterogeneity of the displacement rates and the main driving mechanisms; (b) digital Elevation Model and images of typical consequences of land subsidence.

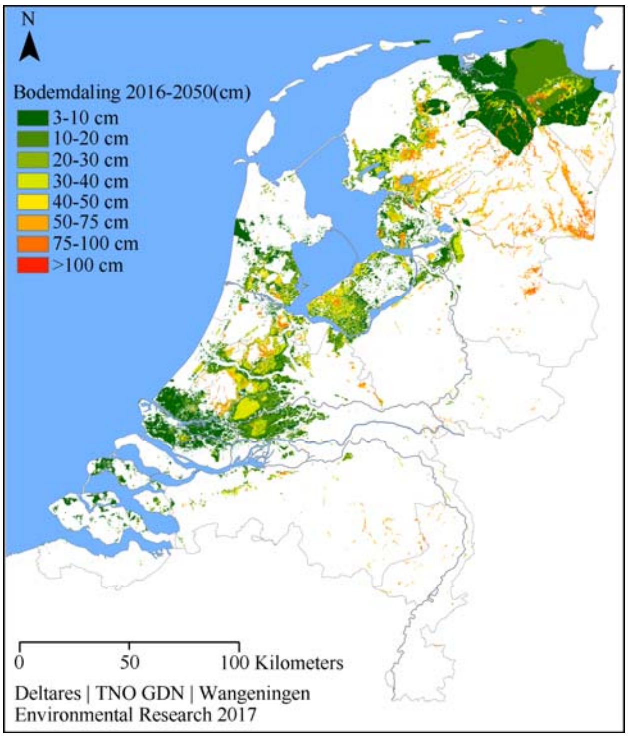

Fig. 6. The new predictive map of subsidence in the Netherlands due to peat oxidation and compaction of clay and peat layers under business-as-usual conditions for the period 2016-2050 (Erkens et al., 2017; bodemdaling = subsidence).

path dependency in subsidence (Seijger et al., 2018).

Main results of recent research advances on subsidence of the Dutch coastal plain are as follows.

(1) Post-depositional land subsidence due to peat compression and oxidation has been quantified by using 1) a reference-level regression method (following and locally applied by Van Asselen, 2005) in which reconstructed Holocene reference groundwater levels were used to assess subsidence due to peat compression for the entire coastal plain by calculating the difference between reference groundwater level and the current depth of ^{14}C-dated peat beds intercalated within the Holocene sequence (Koster et al., 2018c); 2) dry bulk density measurements of compacted and uncompacted peat samples to calculate the original thickness of compacted peat layers and respirometer measurements of peat samples to determine the oxidation potential of peat (Van Asselen et al., 2018); and 3) cone penetration test (CPT) data to quantify thickness reduction of compressed peat layers and to determine the potential for future subsidence. This method makes use of the relationship between net cone resistance and the reduction in peat thickness due to compression. This promising application of CPT-data, of which usually numerous amounts are available in urbanized coastal areas, allows to identify the subsurface layers that are responsible for land subsidence due to compression and enables correlation with measured subsidence rates (Koster et al., 2016).

(2) For the 3D geological voxel model also a method has been developed to attribute the for subsidence relevant parameters organic matter/clastic content and void space to the peat voxels (Koster et al., 2018a). These methods are generic and can also be applied to 3D geological voxel models of other deltaic-coastal regions. Subsidence of peat due to the lowering of phreatic groundwater levels leading to peat compression and oxidation was quantitatively evaluated by using a 3D geological subsurface voxel-model, modelled phreatic groundwater levels (calculated lowering: 0.25 and 0.5 m during a period of 15 and 30 years), and functions for peat compression and oxidation (Koster et al., 2018b). Results of this study show that for these scenarios the agricultural areas surrounding the cities of Rotterdam and Amsterdam may subside 0.3 to 0.8 m. The cities will subside < 0.4 m due to the presence of a meters thick anthropogenic layer on top of the peat that was originally situated at shallow depth. This layer compressed the peat below it to a depth below groundwater level and protects the peat against further oxidation. In the surrounding agricultural areas however,

peat is often still occurring at shallow depth or at the surface, making it very vulnerable for compression and oxidation. Averaged subsidence rates, 7-13 mm/year, for the calculated scenarios correspond with the current subsidence rates in the parts of the coastal plain with a subsurface consisting of predominantly peat (Koster et al., 2018b).

(3) In 2017, new predictive maps of subsidence in the Netherlands were published (Fig. 6; Erkens et al., 2017) as part of an initiative to supply data for policy decisions on climate adaptation. As input for the calculations, geological models (from TNO-GSN), hydrological data (phreatic groundwater levels) and standard nation-wide geo mechanical parameters were used. For the period 2016 -2050, subsidence as a result of peat oxidation and compaction of clay and peat layers was calculated under business-as-usual conditions. This implies that subsidence is compensated by lowering of the groundwater levels to maintain the freeboard. As a result, subsidence accelerates, which forces lowering of the groundwater level, making subsidence a self-perpetuating process (cf. Erkens et al., 2016). Calculations were based on two existing models: peat oxidation based on empirical relations between average lowest groundwater levels and oxidation in The Netherlands and compaction based on Koppejan (Terzaghi -based). In post-processing, existing gas-extraction and salt-extraction subsidence prognoses were added to the map. The map shows that large part of the Dutch coastal plain, which already experienced most human-induced subsidence over the last 1000 years, will continue to subside the coming decades as the underlying processes still apply.

(4) A nationwide spatial-temporal map STM of surface motion was developed for the Netherlands, and released to the general public (https://bodemdalingskaart.nl). The dataset is purely geodetic and combines 7 absolute gravity stations, more than 200 permanent GNSS stations, and more than 30 million radar time series from the Sentinel-1 mission. Due to this combination, absolute instead of relative surface motion is estimated. Estimating the entire distribution of displacements within 2 km grid cells allows for a significant improvement in the precision of the displacements, as well as the robust detection of different driving mechanisms. In effect, this allows for the disentanglement of Holocene and sub-Holocene drivers (Fig. 7; Hanssen et al., 2018).

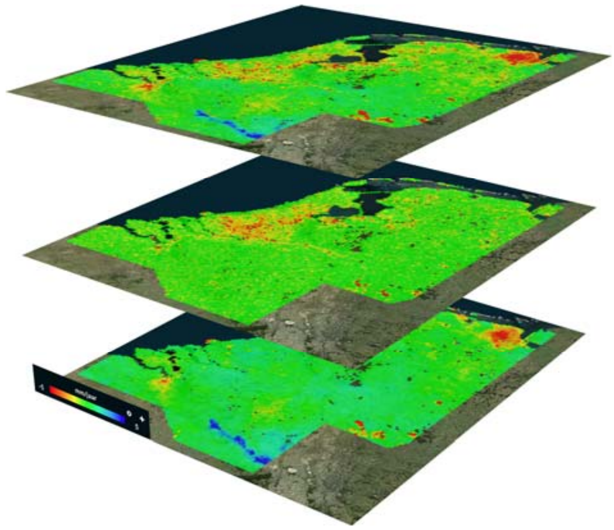

Fig. 7. Three subsidence maps of The Netherlands showing total subsidence (upper map), deep subsidence (middle map) and shallow subsidence (lower map) (Hanssen et al., 2018, 'Actuele Bodemdalingskaart Nederland', www. bodemdalingskaart.nl, Netherlands Center for Geodesy and Geo-Informatics).

3.4 Overexploitation of groundwater (Jakarta, Indonesia)

Jakarta is the capital city of Indonesia, in where land subsidence is quite a well-known phenomenon. The occurrence of land subsidence was recognized at least in the early the development of the city.

Land subsidence was quantified by repeated levelling surveys, GPS surveys, InSAR measurements, and extensometers. Over the recent years, the yearly value of Jakarta subsidence generally ranged from 1-10 cm/year and reached 20-26 cm/year in certain places, especially in the northern part of the city (Abidin et al., 2001, 2004, 2008, 2011; Ng et al., 2012; Chaussard et al., 2013).

The main cause of land subsidence in Jakarta is overexploitation of the multi-aquifer system (Fig. 8). Sixty percent of the people in the city still relay on groundwater. The impact of land subsidence today could be seen in several ways, such as tidal inundation ("Rob" in Javanese word), infrastructure damages, drainage problems, and a wider expansion of flooded areas (Fig. 9). Ongoing actions in adaptation and mitigation to land subsidence in the city are involving sea dyke establishment and an attempt of water management.

A comprehensive design for the water management in the city is estimated to be acccomplished in next ten years. The conversion of groundwater use to others alternatives remains challenging. The surface water resources continuously decrease because the 13 rivers crossing the city are now very poluted. Storage water in retention area faces challenge of land acquisition while rain harvesting is still beyond the agenda. Concerning programs of water recycling, any specific policies are available until today. Presently, Jakarta relays only on the 'sea dyke' to temporary prevent the city flooding although the dyke is also sinking 10 cm/year. The dyke was risen 1 m around 2008 after the big coastal flooding occurred in 2007, but in the recent days the sea water overtops the sea wall protections again.

3.5 Unraveling delta subsidence (The Mekong Delta, Vietnam)

The Mekong delta has one of the largest, but also lowest elevated delta plains on Earth. Its vast, flat delta surface hosts a highly-productive agricultural economy and urban and industrial areas are expanding rapidly. While in Ho Chi Minh city, located in the adjacent and interconnected Saigon river delta, land subsidence was recognized already over a decade ago, for the Mekong delta awareness on land subsidence emerged only in 2014. An InSAR analysis by Erban et al. (2014) revealed for the first time negative surface elevation changes in many parts of the delta. In recent years, land subsidence research in the Mekong made steps towards linking the observed subsidence signal to various natural and human-induced mechanisms and assessing the relative contribution of the main drivers. It became apparent that subsidence in the Mekong delta stemmed from an array of driving factors and processes and the relative contribution of each factor can spatially be highly variable. Two mechanisms were found to be dominantly responsible for subsidence of the Mekong delta at the scale of the entire delta: (1) compaction of shallow Holocene sediments by natural sediment loading, enhanced by anthropogenic loading and drainage, and predominantly causing high subsidence rates near the coast (Zoccarato et al., 2018; Minderhoud, 2019); and (2) extraction-induced subsidence following groundwater overexploitation from the deeper subsurface (Minderhoud et al., 2017; Minderhoud, 2019). Urbanized areas and cities experience the highest subsidence rates in the Mekong delta (Minderhoud et al., 2018) and next to groundwater extraction and natural compaction also other human-induced mechanisms, such as loading by infrastucture or buildings and increased surface water drainage, contribute to additional subsidence (Fig. 10). Urbanized areas are therefore among the most complex areas to determine the exact contribution of individual driving mechanisms as they can spatially be highly variable on a small scale. As the phenomenon of accelerated, human-induced subsidence is rather new in the Mekong delta, there is still much to be gained by implementing mitigation measures to reduce subsidence. Future efforts will require the combination of high-resolution subsidence measurements combined with detailed subsurface mapping and numerical modeling to unravel the land subsidence signal for these hotspot areas.

Main results of recent research advances on subsidence of the Mekong delta are the following: (1) A data-mining method was developed to determine the relationship between land-use histories, derived from a new optical remote sensing-based, 20-year time series of land use, and InSAR-derived land subsidence rates. This method enables the prediction of subsidence rates as a result of land-use history and provides a promising approach for upscaling and producing subsidence estimates for adjacent, larger regions lacking direct subsidence measurements (Minderhoud et al., 2018). (2) With a novel

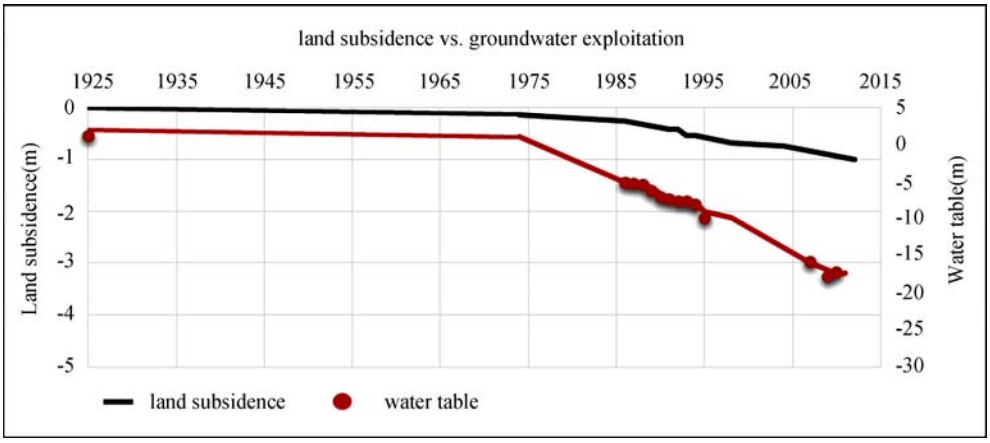

Fig. 8. Land subsidence versus groundwater exploitation in Jakarta city Indonesia.

Fig. 9. The impact of land subsidence in Jakarta, e.g., tidal inundation “rob”, crack on infrastructure, the “sinking” bridge, problem in drainage, and problem of low level on the house to the road.

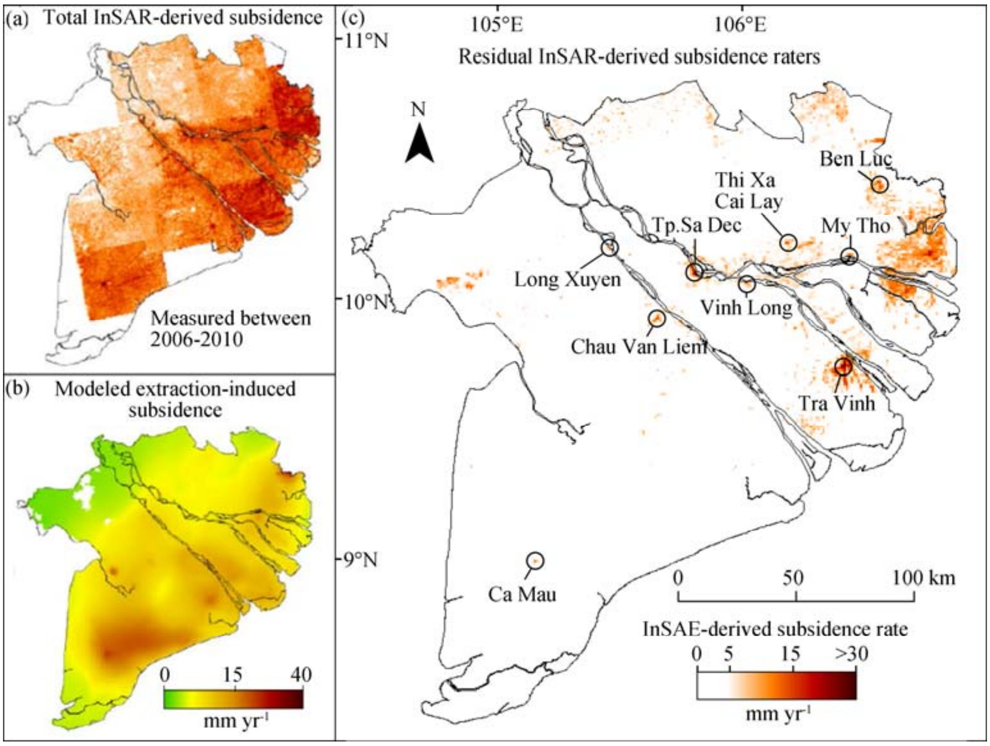

Fig. 10. Residual InSAR-derived subsidence rates in the Mekong delta (c) unrelated to groundwater extraction highlighting cities as subsidence hotspots.
(a) Total InSAR-derived subsidence rates from 2006-2010 by Erban et al. (2014); (b) modeled, best-estimate groundwater extraction-induced subsidence for 2006-2010 (by Minderhoud et al., 2017; Minderhoud, 2019).

numerical model, capable of simulating sediment accretion and natural consolidation, the formation and evolution of the Mekong delta over the past 4000 years was simulated. This showed that present-day rates of natural compaction of the shallow Holocene deposits can reach annual rates up to several centimetres (35 mm yr^{-1}) at the present-day coastline as result of past delta evolution (Zoccarato et al., 2018). (3) A newly developed hydrogeological numerical model of the Mekong delta was used to calculate both groundwater flow and groundwater extraction-induced land subsidence including the contribution of creep in the aquifer-system. This study revealed that groundwater overexploitation and extraction-induced subsidence only commenced recently. In the last two decades increased extraction led to widespread drawdowns of hydraulic head in the multi-aquifer system and accelerating rates of aquifer-system compaction (Minderhoud et al., 2017).

3.6 Controlling of groundwater (Bangkok, Thailand)

Bangkok is located in the Central plain of Thailand, known as the Lower Chao Phraya Basin. There are 8 confined aquifers in the basin, consisting of sand and gravel intercalated by clay layers. Most of the groundwater extraction in Bangkok is from a depth range between 100 and 250 m deep, where 3 principal aquifers are located: Phra Pradang (PD), Nakhon Luang (NL) and Nonthaburi (NB) aquifers (100, 150 and 200 meters below ground surface, respectively) (Fig. 11). Groundwater development for public supply in Bangkok began in 1954. After 1967, high withdrawal of groundwater was observed in Eastern Bangkok, with the lowest water level of 30 m below land surface measured in the NL aquifer in Central Bangkok and the eastern suburbs.

The Thailand Groundwater Act was established in 1977 to control and regulate the use of groundwater, protect natural resources and environment, protect public health and prevent land subsidence. This law stated that groundwater is a public asset, and everyone who wants to drill and use groundwater must apply for the permits from the Director of the Department of Groundwater Resources. In 1983, critical zones were established and Groundwater Tariff was first implemented in 1985 in the six provinces of Bangkok and vicinity.

Over the periods between 1978 and 1988 and from 1978 to 2005 the cumulative subsidence in Bangkok and adjacent vicinities amounted to 10-70 cm and 10-105 cm, respectively. The first cadastral survey of surface elevation in Bangkok was conducted in 1978 by the Royal Thai Survey Department (RTSD). Subsequent cadastral surveys discovered varying amounts of land subsidence in the area. Many observation wells were installed by the Department of Mineral Resources (DMR) in order to measure the water level in each principal aquifer. The correlation between water level decline and the rate of subsidence from 1978 to 1982 was clearly pointed out. The water level in PD aquifer (100 m zone) declined about 3 m with a subsidence rate of about 40 cm (subsidence rate of 9.7 cm/year in 4 years). In 1984, after introducing the tariff of 1 baht/m^3, the water level substantially

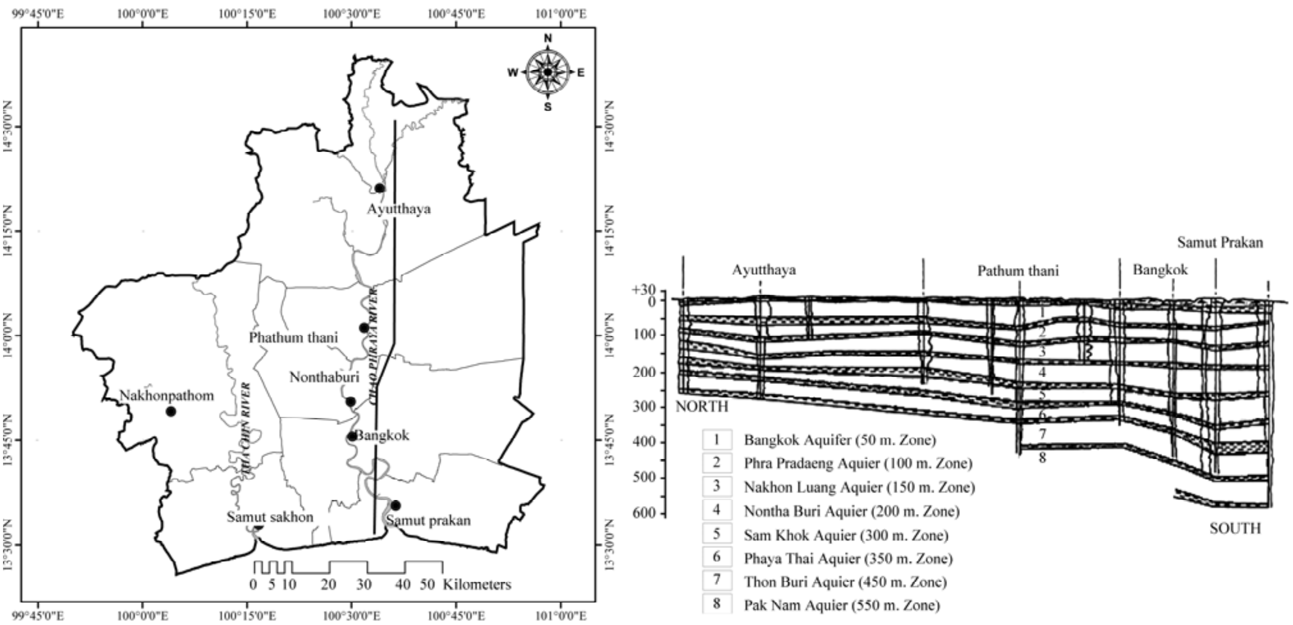

Fig. 11. Hydrogeologic cross-section A–A ‘of the eight aquifer systems (Ayutthaya to Samut Prakan), Bangkok, Thailand (modified from Ramnarong and Buapeng, 1992)

recovered by about 5 m in PD aquifer, 8 m in NL aquifer, and 10 m in NB aquifer. As a result, the rate of subsidence decreased from 9.7 cm/year to 2.2 cm/year. However, from 1991 to 1995, groundwater demand increased during a period of economic and industrial growth, and the water level continued to decline, in spite of the introduction of a 3.5 baht/m^3 tariff increase introduced in 1994. In 2000, after rising the tariff to 8.5 Baht/m^3, the water level of the aquifer substantially recovered and the subsidence rate was decreased to 1.3 cm/year. At present, the subsidence rate was stabilized and a certain uplift was recorded in some areas. The overall area subsidence rate was 1 cm/ year (Lorphensri et al., 2011) (Fig. 12).

The Groundwater Conservation Strategy by implementation of groundwater tariff and groundwater conservation tax has proven to be the most successful way in controlling groundwater usage and promoting public awareness on the importance of groundwater and the environment

4 Conclusive Remarks

Over the last two decades, the awareness on the importance that land subsidence plays on coastal processes at the regional scale is increased. Specifically, it clearly appears that land subsidence can contribute primarily to the relative sea level rise affecting coastal zones with a characteristic length ranging from hundreds of meters (e.g., the scale of a newly reclamation area) to a few hundreds of kilometers (e.g., the scale of a delta plain).

Unfortunately, investigations on land subsidence are still not well coordinated in many countries and different research groups separately conduct studies often dispersing precious strengths. The IGCP 663 provides an important opportunity to worldwide researchers to share expertise in land subsidence including basic research, monitoring, modelling and management.

The first step of the IGCP 663 has allowed to provide a comprehensive outline on land subsidence due to groundwater withdrawal for drinking water (e.g., in Jakarta and Bangkok) and crop production (e.g., in the Mekong delta), lowering of the water table for urbanization development (e.g., in Shanghai), compaction due to new buildings, oxidation of peat and compaction of soft soils (e.g., in The Netherlands and north-eastern Italy), extraction of hydrocarbons (e.g., in The Northern Netherlands). Shanghai, Venice, and the Dutch coastland represent significant examples of how land subsidence can be monitored, predicted and managed. Integrated monitoring networks, artificial recharge, restriction of groundwater pumping, and other specific regulations represent the key steps to reach the purpose.

The importance of advanced monitoring methodologies for improving knowledge on land subsidence has been pointed out. Monitoring land subsidence with a proper accuracy in heterogeneous coastal environments including urban areas, wetlands and lagoons, is generally problematic. Distinguishing between natural and anthropogenic components in the cumulative values provided by measurements has always been a challenge. Over the last twenty years, the quantification of land subsidence benefited from advanced SAR-based interferometry methods. The increased spatial coverage of the radar targets, properly calibrated by leveling and GPS ground data reveals areas severely affected by land subsidence formerly unknown. The integration of interferometric products obtained by different SAR sensors allows overcoming some of the intrinsic limits of each single satellite and takes advantage of their capabilities in observing different characteristics of the

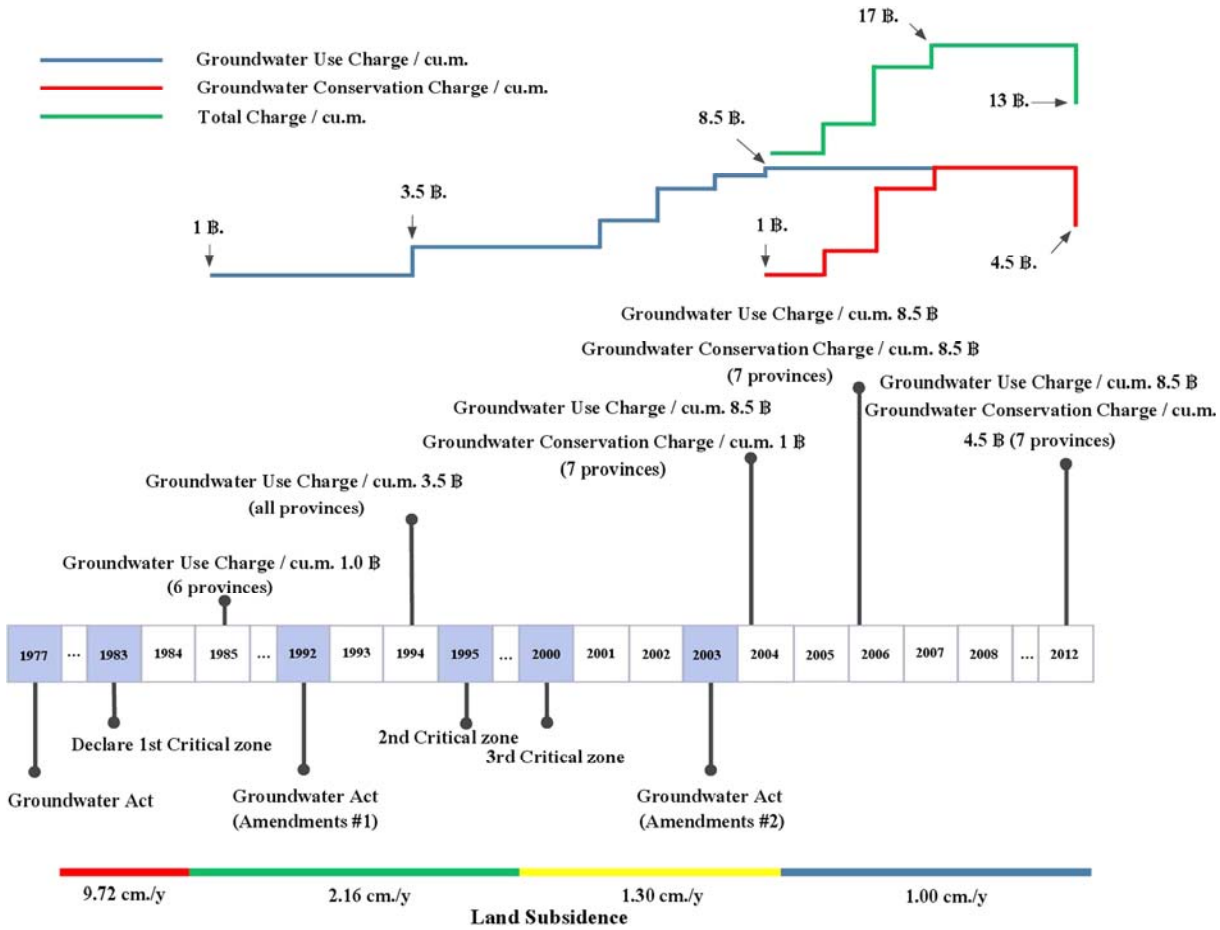

Fig. 12. Timeline of response to land subsidence in Bangkok.

ground movements.

A future project goal is the set-up of a global coastal subsidence map. This outcome will be particular valuable for the stakeholders in charge of the management of coastal cities and low-lying areas, especially in view of the expected sea level rise.

Through the cooperation and exchanges developed within IGCP 663, the research communities and stakeholders are invited to contribute in enhancing the public awareness on land subsidence and support the project in the compilation of widely-used guidelines for investigating driving mechanisms, monitoring, as well as developing prevention and control technology in coastal cities around the world. These guidelines will help the governments and decision makers in providing optimal solutions to manage coastal cities affected by land subsidence.

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