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Sustainable development of coastal cities through control of land subsidence: activities of IGCP Project 663 in Jakarta

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The awareness on the importance that land subsidence plays on coastal processes at the regional scale is increased over the last two decades, and it clearly appears that land subsidence can contribute primarily to the relative sea level rise affecting coastal zones. Jakarta is one of the cities mostly affected by the combination of sea-level rise and land subsidence. In this paper, the activities carried out in Jakarta under the umbrella of the IGCP Project 663 were presented, and the possible measures and best practices mitigating land subsidence for the research associates and potential stakeholders were provided, with which can serve as inspiration for authorities and communities facing land subsidence. Meanwhile, major achievements of IGCP 663 in Jakarta were summarized and introduced, including dissemination session, scientific session and field trips. Specifically, major advances on coastal subsidence studies regarding the effect of relative sea level rise, subsidence mapping, monitoring and simulation, as well as the support of policy making are highlighted and summarized.

Introduction

The IGCP Project 663 (Impact, Mechanism, Monitoring of Land Subsidence in Coastal cities – IM2LSC) is a scientific cooperative program between institutions and researchers to develop better understanding of land subsidence at international level (Yan et al., 2020), and its second international workshop was held from September 17 to 21, 2019 in Jakarta, Indonesia, which included dissemination and scientific activities. Nearly 100 members of the IGCP 663 project teams and representatives of UNESCO Land Subsidence International Initiative (LaSII) from China, Italy, the Netherlands, Indonesia, Thailand,

Vietnam and Pakistan attended the workshop, among which over 90% were from developing countries.

This workshop arranged a roundtable meeting, annual work report, keynote lectures, oral and poster presentations by young professionals, technical teaching and training, field trips, etc. The Indonesian government held an official ceremony for the release of the “Road map for prevention and control of land subsidence in the coastal lowland of Indonesia”. The vice-president of the UNESCO LaSII, Pietro Teatini, addressed the conference and gave a keynote lecture.

After the meeting, a field trip was organized in Jakarta, and four sites seriously affected by land subsidence were investigated.

Dissemination Session

Low-lying coastlands generally encompass a variety of environments, such as farmlands, estuaries, deltas, lagoons and urbanized areas including valuable ecosystems, historical heritages and economic activities, which are severely jeopardized by land subsidence combined with sea-level rise. Within IGCP 663 we developed an analysis of the vulnerability of these environments to relative sea level rise (RSLR) considering an uneven land subsidence distribution that improved the assessment of vulnerability to RSLR at the regional scale. The outcomes of the analysis are available to the authorities responsible for water resources and coastal protection (Wang et al., 2012; Erkens and Stouthamer, 2020; Yang et al., 2020).

Jakarta is one of the cities mostly affected by the combination of sea-level rise and land subsidence. It has been calculated that if necessary measures are not taken, around 27% of Jakarta may be below the sea level in 2025 (Andreas et al., 2018). The project team promoted the development and launch of a “Road map for prevention and control of land subsidence in the coastal lowland of Indonesia” (Fig. 1), and co-hosted an official ceremony with the Indonesian government

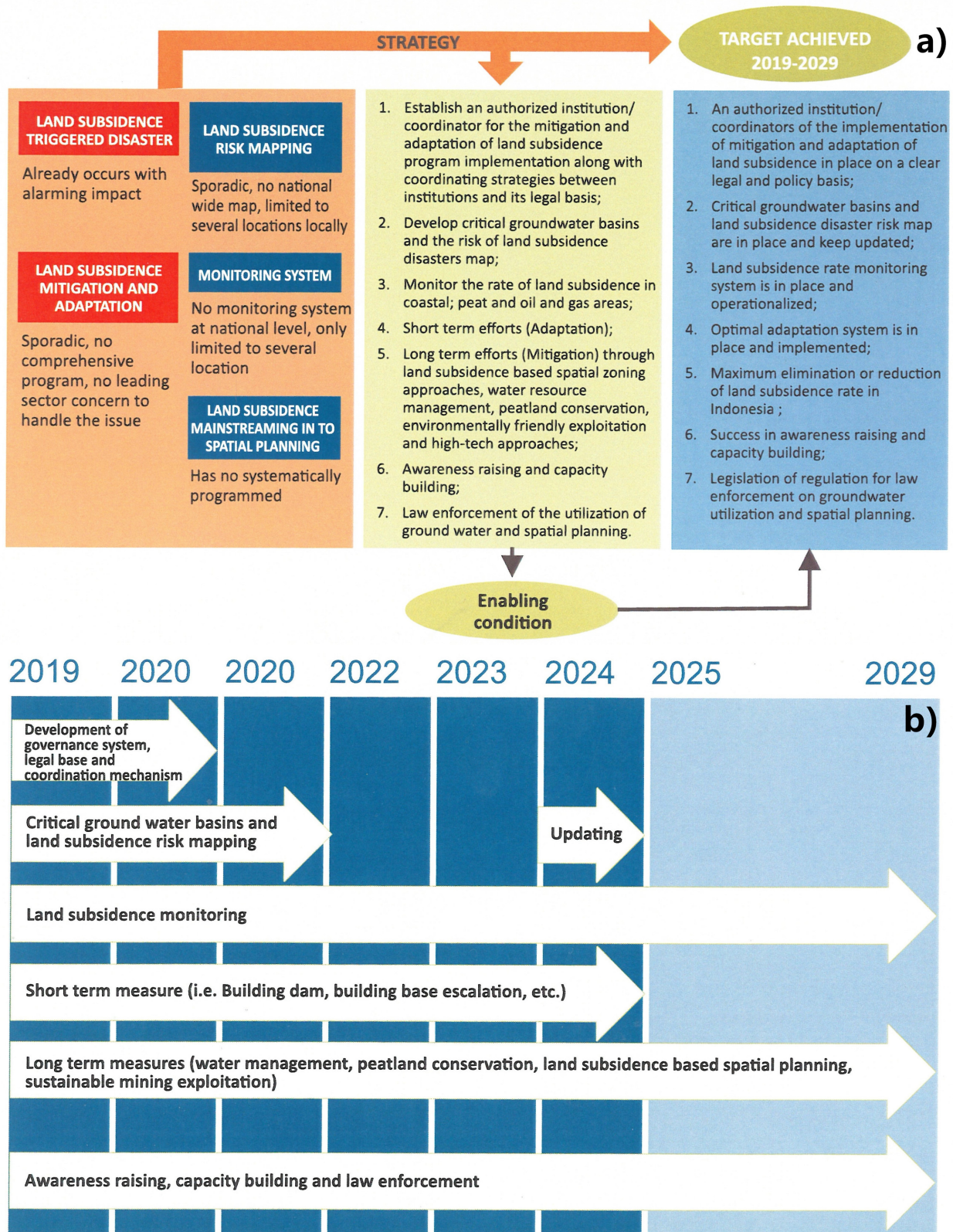


Figure 1. Road map for prevention and control of land subsidence in the coastal lowland of Indonesia: (a) general framework; (b) time frame (<http://bit.ly/roadmaplandsubsidence>).

for releasing the “Road map” during the 2019 project annual meeting. The Road map for mitigation and adaptation against land subsidence has been created in Indonesia and is an important first step towards the

implementation of mitigation and adaptation measures. Therefore, IGCP 663 would provide support in defining the next steps and developing the workflow, as well as providing expertise and an overview of best

practices, tracking the implementation of the road map and asking for progress to be presented during meetings.

In addition, five fascinating scientific courses have been developed for young scientists and stakeholders during the 2019 Annual Meeting of IGCP 663 in Indonesia. The course contents included several topics such as data interpretation, monitoring, simulation and prediction of land subsidence. Meanwhile, presentation opportunities were provided for young scientific and technological talents from China, Italy, Vietnam, Thailand and Pakistan to exchange and improve their research, results and ideas.

Scientific Session

The Effect of Relative Sea Level Rise

According to the historical data, most of the coastal plains in the world have faced a loss in surface elevation, despite in some of them it significantly reduced over the last decades, e.g., Shanghai-China (e.g., Wang and Jiao, 2015), Nagoya-Japan (e.g., Tosi et al., 2010), Venice-Italy (e.g., Tosi et al., 2020). While elevation loss due to land subsidence is mostly irrecoverable, global sea-level rise is increasing. Therefore, RSLR poses one of the greatest threats to transitional coastal systems around the world. Although expected sea-level rise due to climate change is the most widespread concern, locally the effect of land subsidence can be much greater. Analyses of coastal vulnerability to RSLR generally neglect or over-simplify land subsidence patterns affecting large areas. This can lead to inaccurate assessments of vulnerability that do not take account of the spatial variability of ground movements.

The case studies of the Po river delta (Italy) and the Mekong Delta (Vietnam) have been deeply discussed in the scientific session.

A reliable assessment of the vulnerability to RSLR at the Po delta (Italy) scale was developed (Da Lio and Tosi, 2019). An index-based method for assessing the vulnerability of the Po delta to RSLR under present and future SLR scenarios, which considers the spatial variability of land subsidence, was set up. The key results of this study are: 1) The overall assessment reveals that almost half of the Po delta is in a condition of critical or extreme vulnerability to RSLR in the ongoing long-series scenario, i.e. the linear trend computed on the 1875–2017 data recorded by the Trieste tide gauge is about 1.3 mm/yr, reaching more than 80% by 2025 in the future scenario, i.e., the linear trend of 3.8 mm/yr results from the short time series 1992–2017. 2) At the entire-delta scale, the high heterogeneity of the vulnerability to RSLR reflects the combined result of the selected indices (i.e., ground displacements and hydro-morphology of the delta area). 3) Combined with a posteriori analysis of the classified thematic layers, the vulnerability assessment helps to understand the intrinsic role of the various indices, highlighting the crucial role of the uneven subsidence rates and conversely that assuming these to be uniform across the delta area is not helpful. 4) Land subsidence plays a key role in vulnerability to RSLR, subsidence rates generally being greater than the ongoing SLR trend, whether SLR is inferred from the long or the short data series, whereas subsidence and SLR rates contribute equally to RSLR in 2050. 5) More than 70% of the Po delta is characterised by moderate to extreme vulnerability to RSLR, with agricultural areas most affected.

For the Mekong Delta, Vietnam, a comparative study has been car-

ried out to investigate the effect of using surface elevation data from different sources and accuracy on sea-level rise assessments (Minderhoud et al., 2019). A new surface elevation model of the Mekong Delta was created based on local surface elevation data derived from a detailed topographical map referenced to Vietnamese geodetic datum (TopoDEM). The TopoDEM was used to create new RSLR impact assessments which were compared to previous RSLR assessments made using globally available, spaceborne elevation data (SRTM). This revealed that the delta's elevation was previously overestimated by more than a meter in earlier RSLR assessments and that in reality the Mekong delta is much more exposed to RSLR than earlier assessments indicated. This demonstrated the potential implications of using global spaceborne DEMs and neglect of vertical datum conversion to a local tidal datum on RSLR impact assessments and highlights the importance of accurate, ground-truthed elevation data.

Subsidence Mapping

According to the statistical results of historical articles and documents, nearly 90 countries with land subsidence records worldwide were identified, and a country map of land subsidence distribution was drawn (Fig. 2).

In addition to the global land subsidence mapping, a more detailed map at regional and local scales has been planned to develop. One of these, i.e. the land subsidence contour cloud map of the Yangtze river delta is already completed and uploaded to the IGCP 663 project website (<http://igcp.sigs.cn>).

The collaborating for the global subsidence mapping with the UNESCO Land Subsidence International Initiative (LaSII) and IGCP 641 was developed, and the results showed that nineteen percent of the global population may face a high probability of subsidence (Herrera et al., 2021). More information can be found on the website of LaSII (<https://www.landsubsidence-unesco.org/maps/>).

Monitoring and Simulation

Some efforts have been made to enrich the monitoring and simulation methods of coastal land subsidence.

A new Multi-Anchor System for monitoring deformations of different soil layers in boreholes was developed, and its experimental application was successfully tested at Changxing Island, Shanghai. We are also carrying out research and field experiments on the use of distributed fiber sensors for recording land displacements, and further joint results are expected.

Multi-anchor-based (extensometer) monitoring is also being deployed in different parts of The Netherlands to document land surface subsidence caused due to peat oxidation and slow compaction (creep) of underlying Holocene soft-soils (van Asselen et al., 2020). Multiple sites are monitored in small areas to study the efficacy of alternative drainage-infiltration practices to reduce land subsidence. Furthermore, various geodetic techniques (spirit levelling, airborne LIDAR, InSAR) are tested at these sites in order to develop effective approaches to monitor land subsidence over extensive peat meadow areas in The Netherlands.

The data of these monitoring sites will be used to calibrate and validate land subsidence and peat-oxidation derived CO₂-emission

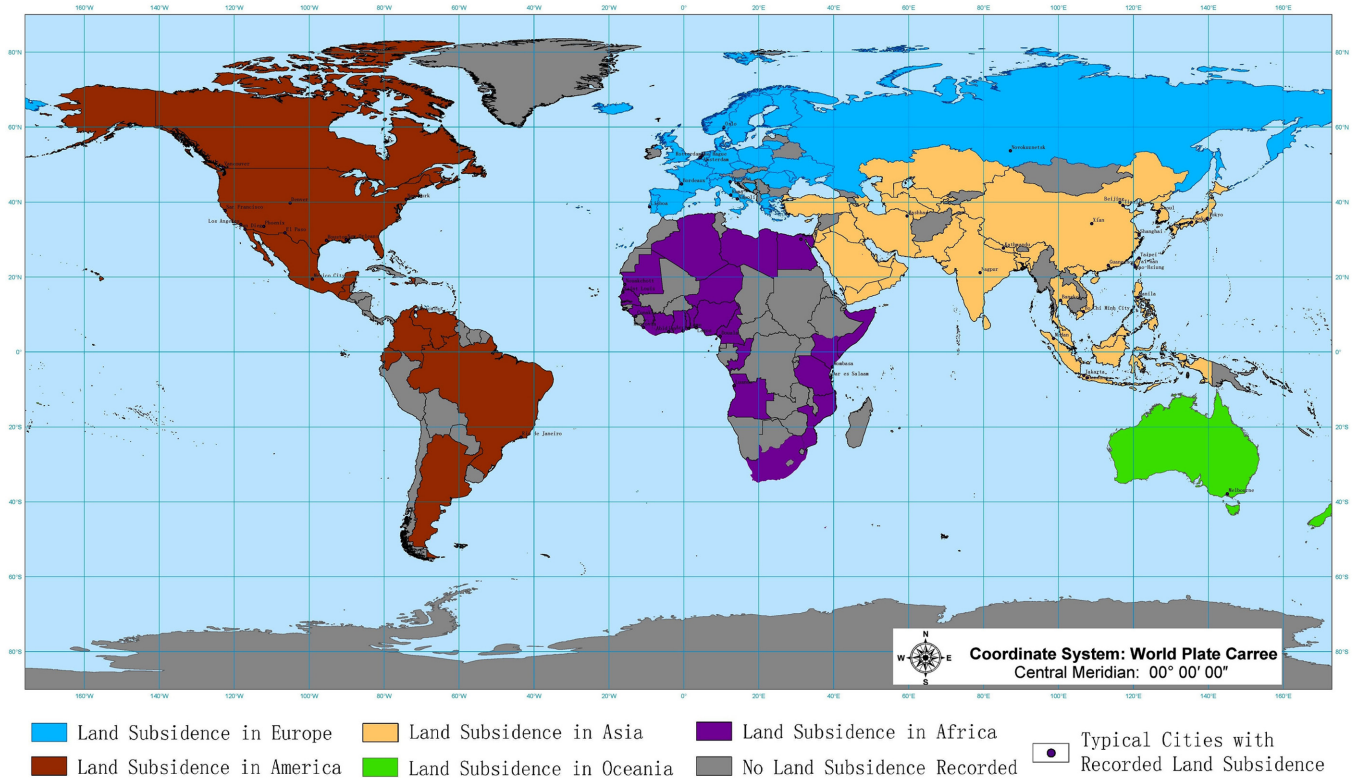


Figure 2. Map of global land subsidence distribution.

models of The Netherlands that are linked to a 3D geological model of the subsurface on a 100 m resolution spatial grid (Bootsma et al., 2020). To enrich simulation capabilities, isotache-based soft-soil creep formulations have been implemented in a new aquifer system compaction package SUB-CR for MODFLOW (Kooi et al., 2018) and in a 1-dimensional finite element simulator that allows study of the subsidence response to changes in dynamic water table conditions (Kooi and Erkens, 2020a). SUB-CR has, amongst others, been used to make subsidence projections for northern Jakarta (Kooi et al., 2020b) and in the Mekong delta (Minderhoud et al., 2017; 2020). The code is available for collaborative research projects. The finite-element code has been used for the city of Gouda to investigate and intercompare the effectiveness of measures that (a) prevent anomalous water table drop during a drought, (b) suppress the seasonal variability of the water table, and (c) involve a permanent rise of the mean water table.

Support of Policy Making

At present, Shanghai is in the period of slight land subsidence, but the characteristics of uneven subsidence are significant. Therefore, the main factors affecting land subsidence have changed from the unreasonable exploitation of groundwater in history to the superposition of groundwater exploitation and dewatering in deep foundation pit. In support of policy making, besides the release of the “Road map for prevention and control of land subsidence in the coastal lowland of Indonesia”, the overall-process coordinated control system of groundwater exploitation and recharge and deep foundation pit dewatering

(dual factors) were summarized and proposed. According to the requirements of dual factors management system, the work flow was proposed, including dynamic regulation of groundwater exploitation and dewatering, demonstration of foundation pit dewatering and water resources, information sharing of land subsidence, data collection and exchange of project completion, law enforcement of monitoring facility damage et al. The dual factor management system is gradually put into use by the local government in Shanghai.

For the Vietnamese Mekong Delta future subsidence and the implications for flood exposure for different groundwater extraction scenarios were quantified by using a delta-wide 3D hydrogeological model (iMOD-SUB-CR, Minderhoud et al., 2017). Scenarios range from immediately stopping groundwater extraction to doubling of the present extraction rate. Its effects on subsidence and flood risk were visually presented for the years 2030, 2050, 2080 and 2100 (Minderhoud et al., 2020). These process-based scenarios quantifications using numerical models enable policymakers to make well-informed decisions regarding groundwater extraction and land subsidence.

Field Trips

There are at least 132 districts in 21 provinces in Indonesia with currently indicated land subsidence. We investigated 4 typical sites severely affected by historical land subsidence. One of these is Muara Baru, where 1.4 m of ground elevation was lost from 2004 to 2015 (Fig. 3).

Stop 1: Muara Baru, 6°6'10"S 106°48'3"E (WGS1984)

The Deep Pile Bench Mark (DPBM) was destroyed by land subsidence (Fig. 4a), and a residential block was abandoned due to permanent coastal flooding (Fig. 4b).

The concrete plinth of a DPBM, which was used to measure the displacement of deep rock strata, was damaged and separated due to differential subsidence between shallow soft soil and bedrock (Fig. 4a). The DPBM was installed in 2009 anchored at a depth of 300 meter. In 10 years' time, ~80 cm of differential subsidence occurred between 0 and 300 meters. On top of that the benchmark itself also subsided ~40 cm (GPS measurement), which represents the subsidence that happened deeper than 300 meters. In total the location of benchmark experienced ~120 cm subsidence since 2009. In addition, due to the impact of land subsidence, this seaside residential block was inundated with seawater from time to time, and people in the houses had/have to go in and out by boat (Fig. 4b).

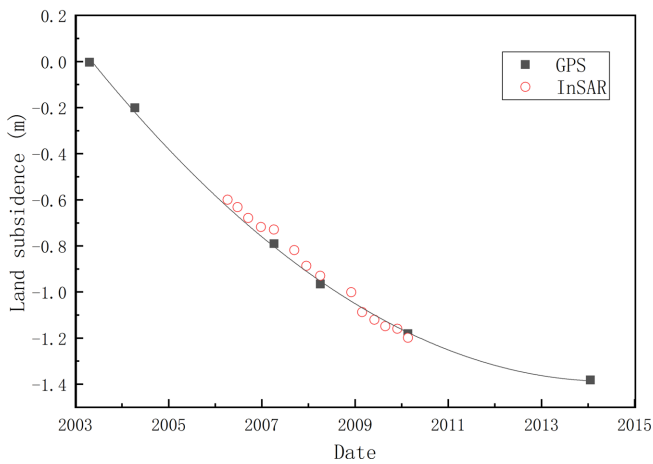


Figure 3. Average local land subsidence monitored by InSAR and GPS in Jakarta.

Stop 2: Pluit Pumping Station, 6°6'32"S 106°47'51"E (WGS1984)

The Old Sea Dyke and the Newest Sea Dyke was used to protect land from coastal flooding due to the land subsidence (Fig. 5a). We can see that when the flood season comes, the high tide is already higher than the levees that have been built, and the houses of coastal residents are often flooded (Fig. 5b). Because of the rapid increase of RSLR, the design of the seawall has been revised, before its construction is completed, to build a higher one. The use of a pumping station is also necessary to keep the water level in the mainland lower than the sea level, especially when experiencing sea level events higher than usual.

Stop 3: Kamal Pumping Station, 6°6'25"S 106°43'33"E (WGS1984)

It can be seen clearly that sea level is 2 m higher compared to river water level. At this location we also see a drowning road due to land subsidence and coastal flooding.

In addition, the local surface water pollution is also very serious. There are not enough alternative water sources, so that groundwater is still an important resource for local people.

Stop 4: Green Bay Area, 6°6'29"S 106°46'49"E (WGS1984)

Indonesian coastal cities such as Jakarta, Semarang, Demak, Pekalongan and Surabaya experience serious land subsidence.

The Green Bay Mall area is still sinking 80~100 mm/year at the moment (Fig. 7). The coastal peatland region also experiences land subsidence, where the average land subsidence can reach 10-200 mm/year, and at the same time there is a sea level rise with an average of 4~10 mm per year. As a result, coastal cities suffer tidal flooding.



Figure 4. Some local remains of land subsidence: (a) damaged deep pile benchmark installed in 2009; (b) flooded apartment complex.



Figure 5. Sea Dyke in Jakarta: (a) the newest sea dyke; (b) the flood overflowed the dam.

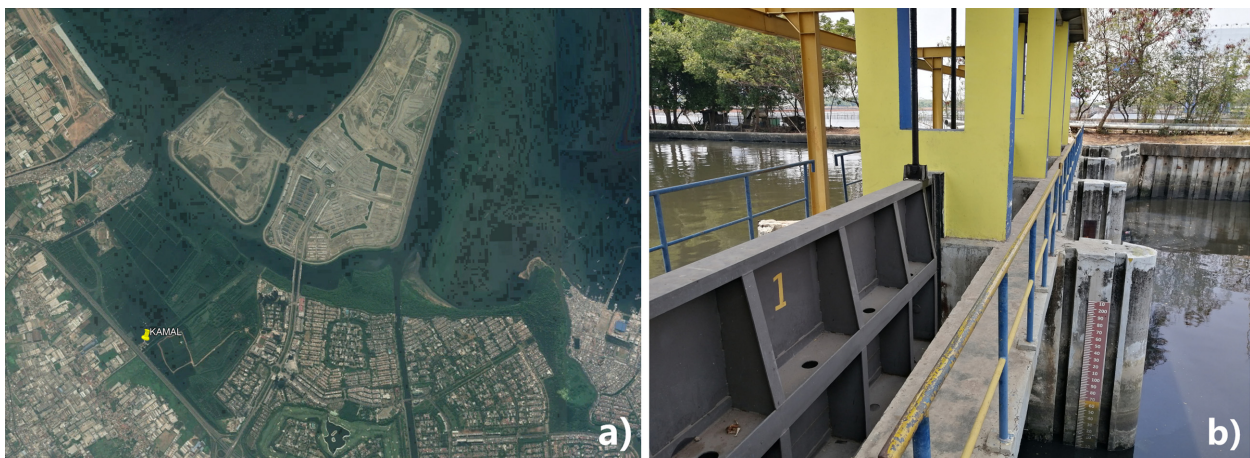


Figure 6. KAMAL pumping station: (a) satellite image of the Jakarta coastal lowland area; (b) difference between sea level (left) and water level of the inland river (right).



Figure 7. Green Bay Mall area in Jakarta.

Summary and Resolutions

During the second international workshop held in 2019 in Jakarta, Indonesia, the activities carried out under the umbrella of the IGCP Project 663 were presented. They focused on the discussion of the main scientific results, a series of technical teaching and training, dissemination, and a field trip. In addition, delegates of the UNESCO LaSII participated and the Indonesian government held an official release ceremony of the “Road map for prevention and control of land subsidence in the coastal lowland of Indonesia”.

The promotion of the scientific and technological cooperation on land subsidence worldwide, specifically in underdeveloped areas, is the key objective of the IGCP Project 663. This includes to provide more opportunities to young scientific and technological talents for improving their coastal subsidence knowledge in order to form a new generation of scientists and practitioners with expertise in impact assessment, monitoring and prevention technologies. In particular, the IGCP Project 663 funded eight young professionals, from China, Vietnam, Italy, Thailand and Pakistan to participate the 2019 IM2LSC annual workshop in Jakarta, and provided them the chances to give presentations and communicate with senior experts during the special sections.

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