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Trouble underground – Land Subsidence in the Mekong Delta

Implemented by

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Trouble Under Ground –
Land Subsidence in the Mekong Delta

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ACRONYMS

BBK	German Federal Office of Civil Protection and Disaster Assistance
BGR	German Federal Institute for Geosciences and Natural Resources
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESRI	Environmental Systems Research Institute
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GNSS	Global Navigation Satellite System
GS	Ground subsidence
InSAR	Interferometric Synthetic Aperture Radar
MARD	Ministry of Agriculture and Rural Development
MONRE	Ministry of Natural Resources and Environment
PS	Persistent Scatterer (point)

01 Summary

This report aims to contribute to a better understanding of land subsidence in the Mekong Delta. There are different drivers affecting the sinking land surface in the region. To what extent is the land sinking? In which locations? Is it occurring quickly or slowly? These are simple questions. Based on existing data it is not difficult to answer these questions. In contrast, questions concerning why subsidence is happening and what can be done to reduce its impacts, are much more challenging. It is clear that natural and anthropogenic factors are contributing. However, to what extent different drivers are responsible in different locations is still not well understood.

The main contribution of this report is the introduction of new data describing the sinking of land using satellite-based methods. Radar satellites collected a large amount of data with high precision covering the total area of the Mekong Delta. The new data describe vertical movements at 750,000 points in the Mekong Delta, and for each point 180 different time series data are available. This totals more than 135 million values and represents a big step forward compared to previously available data. The large amount of data allows a more detailed spatial and temporal analysis of land subsidence. Some infrastructure, such as buildings, bridges, and power pylons can be identified and a high temporal resolution (time series from the end of 2014 to early 2019) shows a linear development over the period of 4+ years; for example, urbanized areas sink by 2-4 cm/year and agricultural areas by 0.5 – 1 cm/year. By and large this confirms findings from previous research, though in much more detail and with more conclusive results.

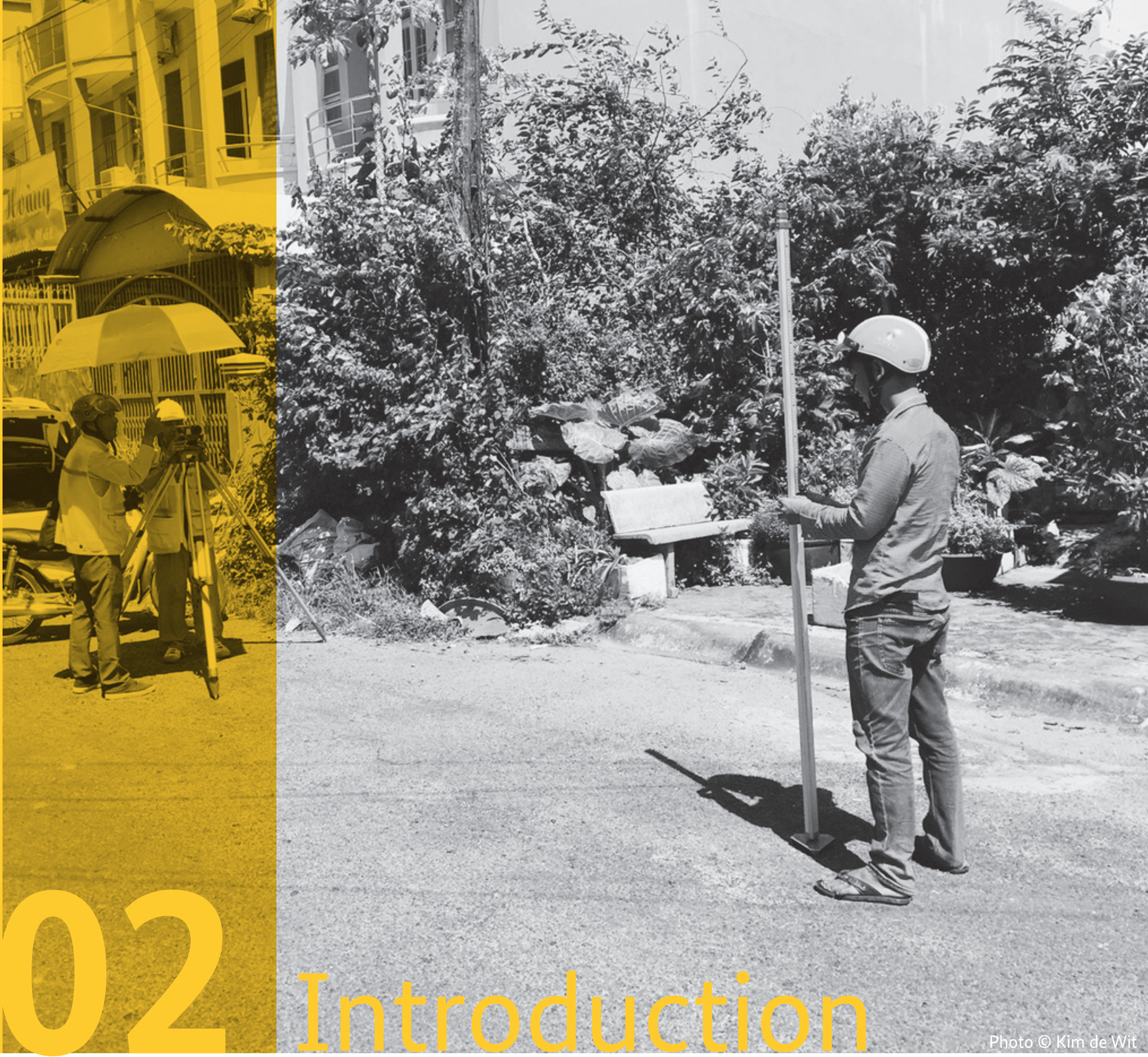
The impact of land subsidence on various aspects of human life is quite evident and visible all over the Delta. Almost every road bridge reminds vehicle drivers of roads sinking faster than bridges, leading to significant differences in height that forces drivers to slow down dramatically when driving onto and off of bridges. However, this is only one of many effects of land subsidence. Other effects include an increase in river-induced floods; erosion; salt water intrusion from the sea; instability of buildings (tilting, cracks); and the damaging and breaking of drinking water, sewerage, and drainage pipes. In the long run, low-lying areas will be submerged permanently. None of these effects are desirable. Identifying ways to reduce land subsidence and activities to mitigate these adverse effects are currently under consideration; however, there has been little action thus far.

An important technical and financial factor is groundwater extraction. Compared to other drivers it is relatively simple to reduce the influence of this driver by reducing or stopping the pumping water from the ground. However, in practical terms the enforcement of regulations on groundwater extraction is a significant problem.

The legal and policy framework is convoluted and state management roles and responsibilities at national and provincial levels are unclear.

In summary, the following land subsidence management activities are recommended:

1. Measure (ground motion data collection)
2. Understand the causes (research on the drivers)
3. Understand the (negative) consequences
4. Mitigate (reduce the speed)
5. Adapt (live with it)



02 Introduction

Photo © Kim de Wit

Vietnam's Mekong Delta is one of the largest deltas in the world. Like other deltas, its land is just above sea level and threatened by rising sea levels. This fact is well known and for decades Vietnam has been regarded as one of the most vulnerable countries to climate change. In the future, if solutions are not implemented, the low-lying Mekong Delta will be flooded by rising seas. There is another phenomenon that will aggravate the dire situation quicker than rising sea levels; the land is sinking faster than the sea water is rising. In some places the rate of sinking land is five or even ten times that of rising sea levels.

Firstly, there is a need to understand to what extent ground or land subsidence (the terms have the same meaning in this report) is happening where, how fast it is happening, and whether it is accelerating or slowing. Secondly, the causes of land subsidence need to be clarified. A third step is to study the consequences of land subsidence for human life in the Delta. Of course, continuing unmitigated subsidence will ultimately lead to the submergence of low-lying areas. Many effects are already visible today and understanding them is necessary for the planning and implementation of counter measures and the development of a long-term strategy.

The Mekong Delta is relatively young in terms of geological age. It emerged about 6,000 years ago[1] after the last ice age when the Mekong River began carrying sediments from the Himalayas down to present day Cambodia. The sediments settled in the sea and the sea bed rose until it became land. Gradually the coastline was pushed further and further out to its present location. The new alluvial plains were covered with floods for a good part of the year. Sediments were deposited and the sediments from the years before slowly compacted in a natural process. The surface of the land did not rise significantly as the shrinking of old sediments and replenishment by new sediments remained in balance.

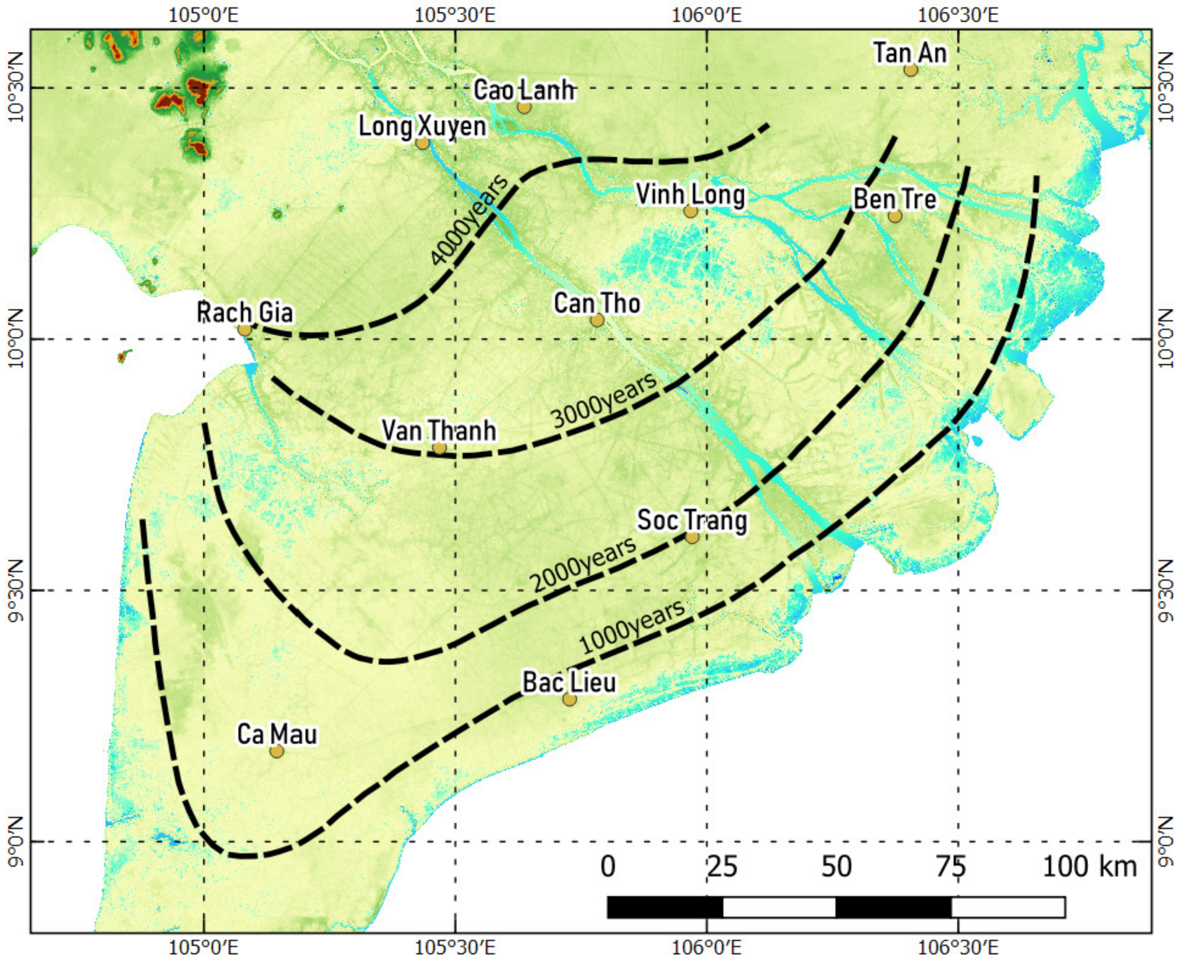


Figure 1: Shoreline migration in the Mekong Delta[2]

The dashed lines indicate the approximate shoreline at certain times. For geographic orientation, present day places and topographic heights are displayed.

This natural process happened over thousands of years, but significantly changed when humans built canals to drain the swampy wetlands for cultivation of rice and other crops. In many parts of the Delta, flooding was reduced considerably and limited to smaller areas or to flooding every few years when there was excessive discharge from the Mekong River. As a result, sediments in the river settled largely in the canals or continued into the sea. At this point, sediment was no longer spread over large parts of the Delta. However, compacting of the existing land continued resulting in net subsidence of the land surface. This process was subject to other anthropogenic influences. Loading the ground with infrastructure and buildings as well as pumping groundwater increases the sinking of land. The composition of different natural and man-made drivers of land compaction varies from place to place. This process is not yet completely understood and further research is expected to clarify local contributions to land subsidence.

03 Legal and institutional framework

In the context of legal regulations, terms are usually clearly defined in the first paragraphs of a law or decree. It appears that the term "ground" or "land subsidence" is not clearly defined in any law, although the term is mentioned in a number of such documents. There is no law listing the term in the respective definitions section. This report uses the term with the meaning presented in Wikipedia[3]: "Land or ground subsidence is the sudden sinking or gradual downward settling of the ground's surface with little or no horizontal motion. The definition of subsidence is not restricted by the rate, magnitude, or area involved in the downward movement. It may be caused by natural processes or by human activities."

From the context of the term "ground subsidence" used in laws in Vietnam (Vietnamese: sụt lún đất) it appears that it has different meanings. The Law on Water Resources uses the term in the way it is internationally understood[4]. It prohibits groundwater abstraction if it causes land subsidence. Another law refers to land subsidence due to floods and water currents[5], which appears to mean river bank erosion (Vietnamese: sạt lở bờ sông). The English term "landslide" is frequently used in English language documents in Vietnam, but it often appears to mean something different than the international meaning of "landslide" (Vietnamese: sạt lở đất). "Landslide" in Vietnamese documents may also refer to land subsidence.

This highlights the need for a legally binding definition of the term land subsidence (Vietnamese: sụt lún đất) in order to clarify what the laws or decrees actually regulate.

Keeping the internationally used definition of land subsidence in mind (solely negative, vertical ground movement, no horizontal movement) a number of Vietnamese legal regulations do not actually refer to such downward movements but to other phenomena. Laws and subsequent legislation in this category include:

- **Law on land[6]:** The law allows the state to acquire/expropriate land used by citizens for a wide range of reasons including land which is exposed to erosion or sinking or otherwise affected by other natural disasters. In the Decree on the Land Law it says[7]: The order and procedures for recovery of land in polluted areas at risk of threatening human life; land at risk of landslide or land subsidence or being affected by other natural disasters threatening human life are prescribed as follows: ... Both "sinking" and "land subsidence" seem to refer to natural disasters and not to land subsidence as a contributing factor.

- **Law on Natural Disaster Prevention and Control[8]:** This law states "Natural disasters include typhoons, tropical low pressure, whirlwinds, lightning, heavy rain, floods, flash floods, inundation, landslides and ***land subsidence due to floods or water currents***, water rise, seawater intrusion, extreme hot weather, drought, damaging cold, hail, hoarfrost, earthquakes, tsunamis and other types of natural disaster."[9] Land subsidence is not caused by floods or water currents and the law may actually refer to river bank erosion or landslides on mountain slopes. It might be advisable to include land subsidence as a contributing factor to disasters as slow subsidence does not constitute a disaster by itself.

- **Circular No. 41/2016/TT-BTNMT** dated December 21, 2016 on technical processes for the forecasting and warning of dangerous natural disasters: ..., ***ground subsidence induced by rain-induced floods or river flows***... As land subsidence is not caused by rain or rivers, the term "ground subsidence" appears to be referring to other natural hazards like river bank erosion or landslides on mountain slopes.

- **Circular No. 60/2015/TT-BTNMT** dated December 15, 2016[10] stipulates techniques for land survey and assessment. The General Department of Land Management under MONRE is responsible for observing and monitoring land resources, including land subsidence in mountainous areas, and river bank and coastal erosion. Land subsidence typically does not happen in mountainous areas but in alluvial plains. Therefore, it is likely that the term "land subsidence" refers to landslides, which often occur in the mountains.

In view of the major influence land subsidence already has or will have on many parts of Vietnam, it appears that legal regulations are currently insufficient to appropriately deal with the threat of inundation, erosion and salt water intrusion. The two ministries responsible for dealing with the phenomenon (MARD and MONRE) do not yet cover all aspects of land subsidence as far as binding legislation is concerned.

Steps in land subsidence management	Responsible institution	Legal basis
Measure	Not yet specified	None yet
Understand the causes	Not yet specified	None yet
Understand the impact	MONRE (only water related impact)	Law 17/2012/QH Circular 42/2015/TT-BTNMT
Mitigate	MONRE VNDMA	Law 17/2012/QH Circular 42/2015/TT-BTNMT Decision No. 48/2017/QD-TTg
Adapt	VNDMA is responsible for natural disaster prevention and control. This could be interpreted as to include adaptation. Many other institutions are supposed to integrate land subsidence adaptation measures but this is not provided for in legally binding documents	Decision No. 48/2017/QD-TTg

The main deficiencies are:

Measuring land subsidence

There are no detailed regulations on land subsidence observation. It is not mandatory to measure land subsidence for any agency. Frequency of data collection, scale (point density) and dynamics (in- or decrease of velocity), identification of high velocity areas, as well as standard products (maps, tables, frequency of updating) are not prescribed in legally binding documents. The Department of Surveying and Mapping under MONRE could be tasked to do this. Some data on subsidence have been collected but have yet to be published.

Law on Survey and Mapping[11]

Though this law provides for surveying and mapping as well as forecasting, warning, prevention and control of natural disasters, the observation of land subsidence is not mentioned. The regular observation of the height of the land surface to detect and measure land subsidence is the very basis for any other steps and explicitly mentioning it in the law would strengthen efforts to cope with the phenomenon.

Understanding the causes of land subsidence

No institutions are currently officially mandated to investigate the reasons for land subsidence on a permanent basis. Some research is done on a voluntary basis or in the context of stand-alone activities. MONRE and its related departments are currently preparing a larger project to determine the drivers of land subsidence. It would be a good option to integrate research on land subsidence in the Law on

Natural Disaster Prevention and Control as this law already provides for disaster related research, but land subsidence is not listed as one of the hazards or phenomena to be investigated[12]. By including the term "land subsidence" in the hazards covered by the law, MONRE would assume responsibility for such research. Decision No. 48/2017/QD-TTG of the Prime Minister[13] assigns the General Department of Geology and Minerals of Vietnam under MONRE to undertake such research. The national Government needs to make clear the roles and responsibilities for each ministry and department at national and provincial level.

Understanding the impact of land subsidence

The Law on Natural Disaster Prevention and Control mentions research regarding the impact of natural disasters as part of the national natural disaster prevention and control plan[14]**.** The plan has to include assessments of natural disaster risks and impacts that constitute a part of the risk. If "land subsidence" is included in the hazards covered by the law, it should be clear that research on impacts of land subsidence will be part of the national natural disaster prevention and control plan. The Ministry of Agriculture and Rural Development (MARD) is responsible for the elaboration of this plan[15].

The Law on Water Resources (51/2001/QH10) specifies that the reasons for the harmful effects of water (in other words the negative impact) have to be assessed and included in a master plan[16].

Mitigating land subsidence

This aspect is already integrated into the Law on Water Resources (no groundwater abstraction if it causes land subsidence), but other reasons, such as the lack of sediment disposal on fields, are not yet integrated. This is a task for MARD.

The main regulations and institutions concerning the mitigation of land subsidence are:

Decision on the Functions, Duties, Powers and Organizational Structure of the Vietnam Disaster Management Authority in connection with the Law on Natural Disaster Prevention and Control says the Vietnam Disaster Management Authority (VNDMA) shall "...conduct scientific researches, and technology transfer on natural-disaster prevention and control"[17]. Though the law does not specifically include land subsidence as a contributing factor to natural disasters, it seems to be clear that VNDMA has to look at different factors aggravating natural disasters, including land subsidence.

- **Law on Water Resources[18]:** To the best of our knowledge[i] this is the only law in Vietnam that refers to land subsidence directly and integrates the phenomenon into its provisions adequately. Land subsidence is mentioned 12 times in 5 of its 79 articles. Implementation of the law demands that water resources are used without causing or increasing land subsidence (e.g. Article 62).

  MONRE is the main institution responsible for implementation of the law, which includes land subsidence prevention and/or mitigation. This has been incorporated and specified through several regulatory documents for groundwater management and licensing (in reverse chronological order):

  - Decree No. 167/2018/NĐ-CP regulating the restrictions on groundwater abstraction: land subsidence is a factor for the delineation of restricted areas[19].
  - Circular No.75/2017/TT-BTNMT regulating the protection of groundwater in drilling, exploration and exploitation of groundwater: activity to be stopped if well drilling, aquifer testing or other non-exploitative use results in land subsidence.
  - Circular No.72/2017/TT-BTNMT regulating the backfilling and sealing of unused wells: production wells causing land subsidence and affecting groundwater quantity or quality, or affecting construction works or local communities negatively, should be filled in.

i The explanations concerning the Law on Water Resources are based on observations of BGR.

- Circular No.42/2015/TT-BTNMT regulating techniques for water resources planning: land subsidence to be considered as one of the consequences of groundwater abstraction; suitable mitigation measures are defined, including delineating restriction areas for groundwater exploitation; determining groundwater exploitation thresholds and plans for reducing groundwater exploitation; determining alternative water sources; proposing managed aquifer recharge.
- Circular 08/2015/TT-BTNMT regulating pumping test techniques in groundwater investigation and assessment: any risk of land subsidence from aquifer testing for porous and karstic aquifers must be avoided.
- Circular No.27/2014/TT-BTNMT concerning the registration of groundwater abstraction wells, licensing and extension, adjustment of licenses for groundwater pumping: land subsidence is a criteria for the delineation of registration areas.
- Circular No.40/2014/TT-BTNMT regulating groundwater drilling practices: any drilling activity causing land subsidence and affecting construction works or communities must be stopped; and consequences should be handled and compensated for by the owner of the drilling license.
- Decision No.15/2008/QĐ-BTNMT regulating groundwater protection: Prohibition of any new groundwater abstraction works to be built in land subsidence areas[20]

MONRE has anticipated and actively addressed challenges of land subsidence by setting and progressively developing the legal framework for mitigation measures, especially in the groundwater sector. However, the operationalization of these provisions is still lagging behind for a number of technical and institutional reasons. What is missing, for example, is a clear definition of the threshold(s) and criteria applied for an area to be considered as affected by land subsidence and hence subject to the aforementioned provisions. Also, it remains unclear whether proof of a causal relationship between observed land subsidence and groundwater extraction has to be established for an area and/or specific groundwater source to be subject to these restrictions. This is a highly complex issue especially in the Mekong Delta, as groundwater is abstracted from up to seven different overlying aquifers (groundwater bearing layers), and it remains highly uncertain to what extent depth and source of abstraction impacts on land subsidence observed at the surface.

Adapting to land subsidence

Land subsidence cannot be controlled very easily and the main coping strategy will most likely be adaptation. A key in developing counter strategies would be forecasts of flooding, erosion, and salt water intrusion. These forecasts should be done by considering other factors such as sea level rise by hydrologists at the Ministry of Agriculture and Rural Development (or an assigned office under the ministry). The product would be a legally binding forecast of land subsidence to be used by other institutions. This will include land-use planning, irrigation, and the construction of infrastructure, businesses, and private dwellings. The consideration of official land subsidence data should be integrated into the respective laws (meteorology and hydrology, land, irrigation, natural disaster prevention and control, and construction).

Decision on the Functions, Duties, Powers and Organizational Structure of the Vietnam Disaster Management Authority in connection with the **Law on Natural Disaster Prevention and Control** says the Vietnam Disaster Management Authority (VNDMA) shall "...conduct scientific research, and technology transfer on natural-disaster prevention and control"[21]. Although the law does not specifically include land subsidence as a contributing factor to natural disasters, it seems to be clear that VNDMA has to look at different factors aggravating natural disasters, including land subsidence.

There are several laws <u>not</u> mentioning land subsidence, but it may be worthwhile to consider integrating land subsidence in design adaptation measures.

- **Law on Irrigation[22]:** This law does not mention land subsidence, but irrigation planning shall "Forecast developmental tendencies and scenarios, water sources in the situation where they are impacted by climate change, natural disasters and river basin developments;..."[23]. Here, land subsidence as a factor contributing to changes in irrigation regimes should be mentioned.

- **Law on Meteorology and Hydrology** and a decree detailing provisions[24]. There are several references to rising sea levels and climate change in general in the law and the decree. Obviously, sea level rise and sinking land have very similar effects on the hydrology of water bodies covered by this law. GIZ perceives that climate change related phenomena seen in isolation from land subsidence represents a gap in the law.

- **Law on Construction[25]:** It is well documented how land subsidence affects buildings and other structures. Subsidence can cause severe damage threatening the functionality of buildings, but it appears that land subsidence does not have to be considered when designing and constructing infrastructure or buildings. GIZ recommends making it mandatory to consider adaptation to subsidence for the design of infrastructure and buildings.

- Decree 80 on Drainage and Treatment of Waste Water[29]: This regulation does not include any reference to natural hazards but it stipulates that ground altitudes are part of planning drainage systems (Article 6). This would be a suitable place for including forecasts of ground altitudes as drainage systems are supposed to last and be functional for many decades. The ground altitude may change due to land subsidence.

- **Law on Urban Planning[27]:** This law mentions that urban infrastructure planning shall integrate measures to prevent and mitigate damage caused by natural disasters[28], but there is no provision suggesting the consideration of land subsidence in this context. GIZ recommends to specifically include this aspect into an updated version of the law.

- **Law amending 37 laws[29]:** As with the Urban Planning Law, Law No. 35 does not specifically stipulate the use of data on land subsidence, but all plans are related to land use and strategic environmental assessments. These require land data, including data on land subsidence. GIZ recommends to specifically include this aspect into an updated version of the law.

04 Five steps of land subsidence management

This report divides different aspects of land subsidence management into five distinct steps.

1. Measure
   - Ground motion data collection
2. Understand the causes
   - Research on the drivers
3. Understand the consequences
   - Research on (negative) impact
4. Mitigate
   - Reduce the speed
5. Adapt
   - Live with it

The land area of the Mekong Delta is sinking at different rates across the region. In urbanized areas, land sinking is faster than in agricultural crop areas. The temporal and spatial resolution of collected data has to be sufficiently detailed to understand these trends.

Why is land sinking? Why is it sinking faster in cities? Why is it not slowing down in most places? Research identified some aspects causing land subsidence, but government, development partners, and researchers do not yet understand the contribution of different drivers and the patterns across the Delta.

Land subsidence is only one factor influencing development in the Mekong Delta. Climate change related sea level rise, reduced sediment load of the river caused by up-stream dam construction and sand mining, the proliferation of dikes reducing floods and urbanization, are other significant factors. Together, these developments will have grave consequences for the people living in the Delta.

As most of the consequences of land subsidence are perceived as undesirable, reducing its speed or even stopping it is crucial for the development of the Delta. Identifying and implementing such mitigation measures is difficult; practical and affordable options are limited.

If land subsidence cannot be stopped, it has to be adapted to. Simply abandoning the Delta is not an option for its millions of inhabitants. Depending on the urgency created by sinking land and rising seas, adaptation options will be varied.

4.1. Measuring land subsidence

Upward and downward movements of the earth naturally occur at less than one millimetre per year in stable regions of the earth. In more volatile places like the Mekong Delta, changes may be in the range of many mm to cm per year. The movements are very slow and observing them requires a lot of patience or very sensitive technology. It is actually not very difficult to spot signs of land subsidence in the Mekong Delta with the naked eye. Many bridges have deep foundations but adjacent roads do not. As a result, the roads often sink faster than the bridges and car drivers need to slow down for the significant differences in height caused by these uneven movements. This phenomenon is quite obvious but measuring the vertical movement over time is actually challenging. The main reason for this is the lack of stable reference points.

Ideally, there is a point nearby which is known to show no significant vertical movement. The surrounding area is measured from time to time against the stable reference, and vertical movement rates of the surrounding area is easily determined. Unfortunately, such stable points are very rare in the Mekong Delta. There are some rocky mountains in Kien Giang and An Giang provinces, which are regarded to be rather stable as their foundations are tightly connected to deeper rock layers in the earth's crust. However, these mountains are more than 150 km away from some places in the Delta and data errors may be bigger further away from these mountains. Except for these mountains, the land area of the Mekong Delta is a mix of mud, sand, clay and organic matter. These materials are compressible under pressure or when water is extracted and organic matter rots. These processes result in sinking of the earth's surface, and because of this there are no stable reference points in almost all areas in the Delta. This means that measuring is difficult but not impossible, and as a rule the data for places far from stable points are prone to more measurement errors than data near stable references.

There are many different technologies available to detect small amounts of vertical ground movement. Each has advantages and disadvantages. The best approach is combining different methods. If results from different methods arrive at the same land subsidence rates, one can be confident that these data can be trusted. In reality, data from different methods often shows slightly different results. Researchers discuss how such discrepancies occur and how to arrive at values reflecting the closest scenario based on all the available evidence.

The oldest method used to measure ground movements in the Mekong Delta is levelling with theodolites. The Vietnam Department of Survey and Mapping conducts such surveys. Typically, the points are located along roads. In the Mekong Delta, 150 to 250 points are measured every few years. The data are not publicly available. The data from the Department of Survey and Mapping used by GIZ for this report have not been verified.

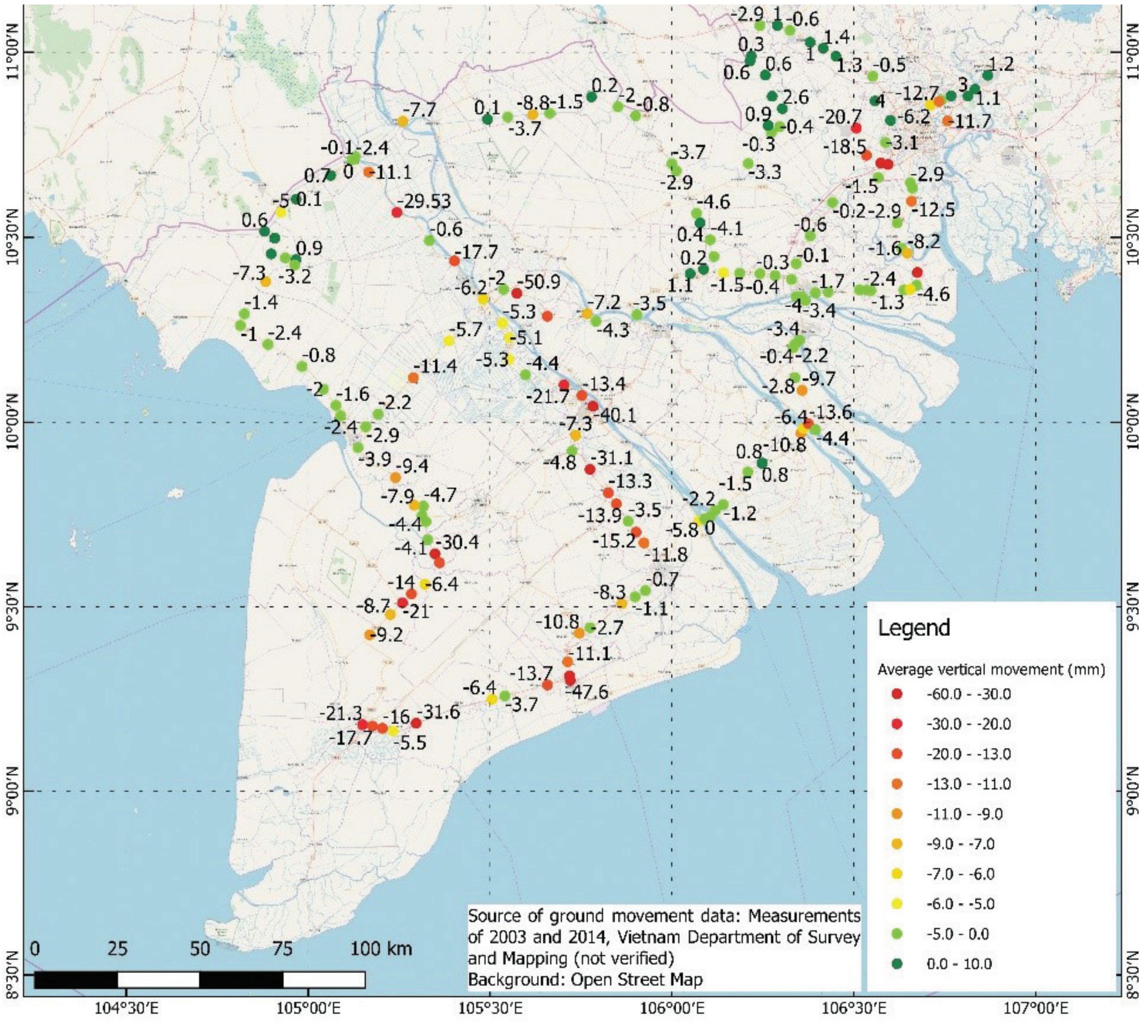


Figure 2: Average annual vertical movement in the Mekong Delta determined with levelling (source: Dep. of Surveying and Mapping, not verified)

Working with theodolites is time consuming and labour intensive; therefore, this work is carried out only every few years. Furthermore, the number of collected points is quite limited. Large areas of the Delta are not covered. For the documented points, subsidence rates of some millimetres up to some centimetres per year have been observed.

Figure 3: Levelling with a theodolite in Long Xuyen in the Mekong Delta by GIZ for measuring land subsidence at buildings (photo credit: Kim de Wit)

A very different approach is to drill deep holes into the earth and measure the deformation of the borehole bottom versus the surface of the earth. This was done in three locations in Ca Mau Province with support from the Norwegian Geoscience Institute in cooperation with other institutions[30]. The holes were about 100 m deep[31]. Solid bedrock is much deeper in Ca Mau (~300 m[32]), hence the installations can only measure compaction in the upper third of softer sediment layers. Annual subsidence rates detected in the upper 100 m of sediments are in the range of 2-4 cm/year[33].

A number of universities have measured shallow land subsidence using a similar approach. They press long sticks into the ground until they hit relatively dense sand layers that the sticks cannot easily penetrate. The change of the relative surface height against the stick is determined twice a year.

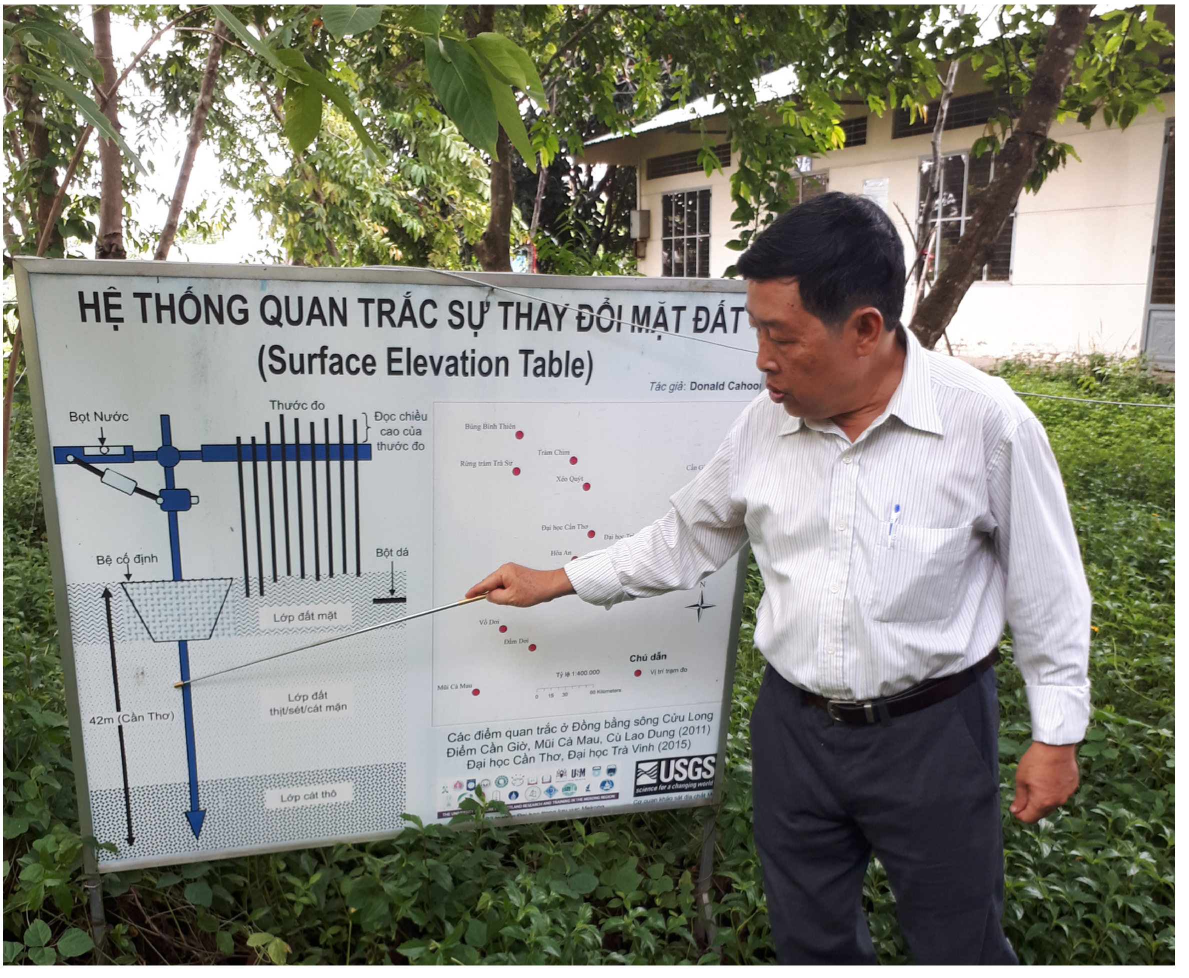


Figure 4: Professor Duong Van Ni in Can Tho University explaining how shallow land subsidence is observed

Data collection with this method began in 2015 in Can Tho using a 42 m rod. According to Professor Duong Van Ni, data should be recorded for at least eight years to get robust results. With four years of operation, results are regarded as preliminary. In the compound of Can Tho University the average shallow land subsidence measured by rod is now estimated at 17 mm/year. Nearby, residential buildings sink at a combined total rate of 27 mm/year (data from InSAR by BGR/GIZ. See below). This could be interpreted as 17 mm/year shallow, and 10 mm/year deep subsidence.

Vertical land movements could be measured with the Global Navigation Satellite System (GNSS); however, the accuracy of these instruments is optimized for horizontal location detection and vertical movements are not precisely detected[34]. No such measurements in the Mekong Delta have been published.

Vertical land movements may be observed from space with sensors mounted on satellites. The satellites send out a radar beam and detect the reflection with a sensor. When satellites on its orbit pass by again and again, they measure the point repeatedly and the reflection will be slightly different if the object has moved a little bit. The sensor of the satellite is very sensitive and records very small differences at ranges of less than a millimetre of movement on the earth. After certain time spans scientists calculate vertical velocities for a period of a year, which is the commonly used reference period. This method is called Interferometric Synthetic Aperture Radar (InSAR) and there are a number of such satellites circulating around earth. Different radar satellites have different resolutions or how many data they can collect for a certain area. Mostly these data cover an area of some square metres with a side length of several metres to tens of metres. However, not every data point collected by the satellite is usable for height detection.

Vegetation, for example, does not give meaningful height data as it is constantly changing. The points suitable for height change detection are called Persistent Scatterers (PS). They are mostly buildings and infrastructure, such as bridges or high voltage electrical pylons.

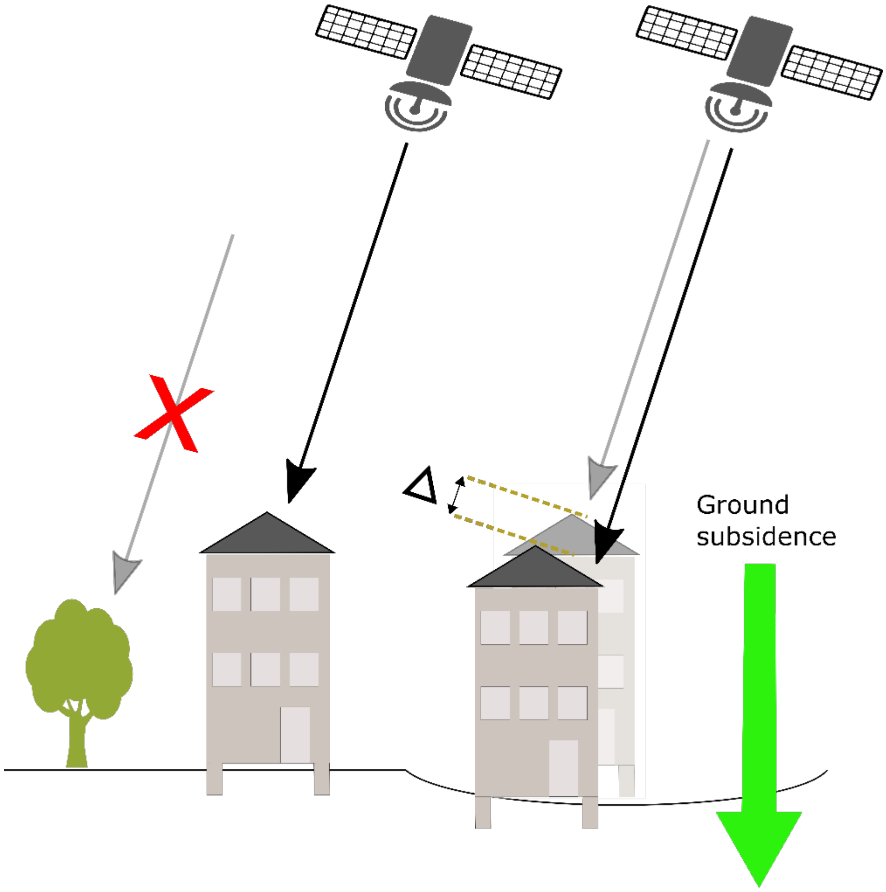


Figure 5: Schematic principle of InSAR technology. The difference in height of a hard structure (e.g. building) changes the radar beam returning to the satellite.

In cooperation with the German Federal Office of Civil Protection and Disaster Assistance (BBK), GIZ and the German Federal Institute for Geosciences and Natural Resources (BGR), initiated InSAR-based research carried out by the Copernicus program of the European Union in early 2019[35]. Data from the Sentinel 1 satellites were used to estimate vertical movements of the PS. About 750,000 points suitable for estimating vertical movements from the end of 2014 to early 2019 were identified. The satellite data covered the entire southernmost part of Vietnam except for very small areas in the very south and west. This covers most of the Southern Plain (the Mekong Delta plus the Ho Chi Minh City area).

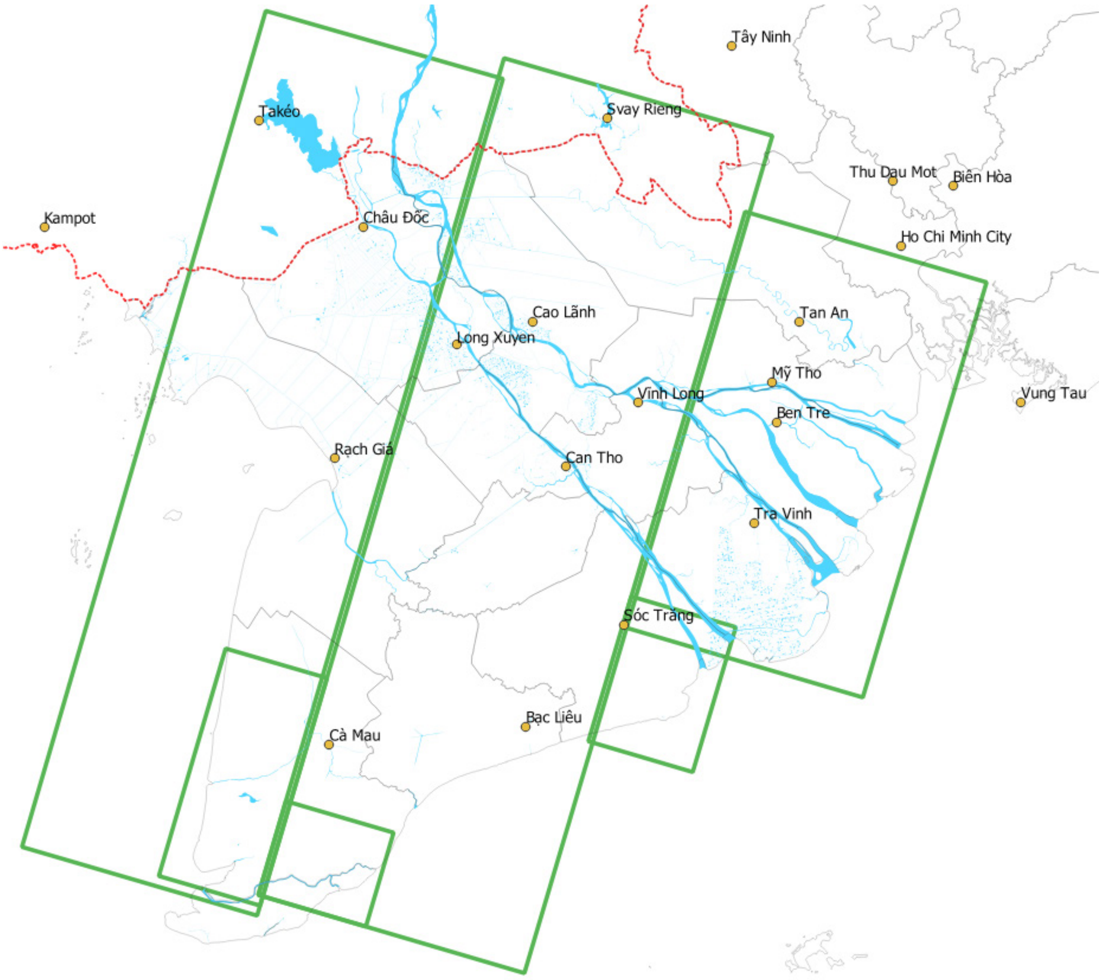


Figure 6: Coverage of the InSAR data.

Processing was carried out in batches indicated with green rectangles. Waterways, provincial and international boundaries for geographical orientation. The average movement rates over more than four years were calculated.

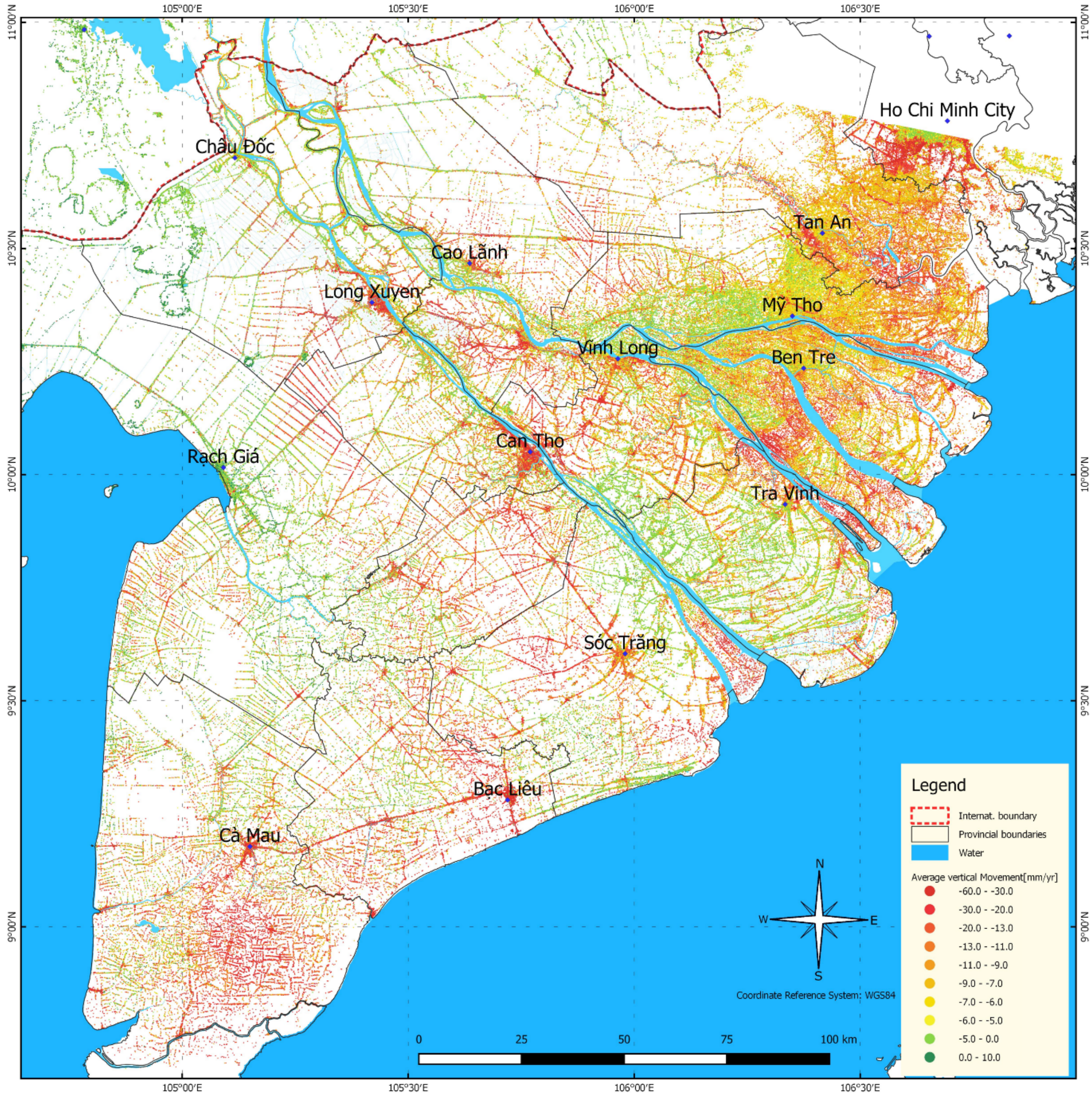


Figure 7: InSAR data points in the Mekong Delta.

The resulting map with the Persistent Scatterers (PS) shows patterns. There are many points in densely populated areas because the PS depend on buildings or other fixed structures. In forested or crop areas there are very few buildings and thus points. These PS may move faster, at the same speed, or slower than the ground. The observed vertical movements therefore do not necessarily reflect the movements of the surface of the earth.

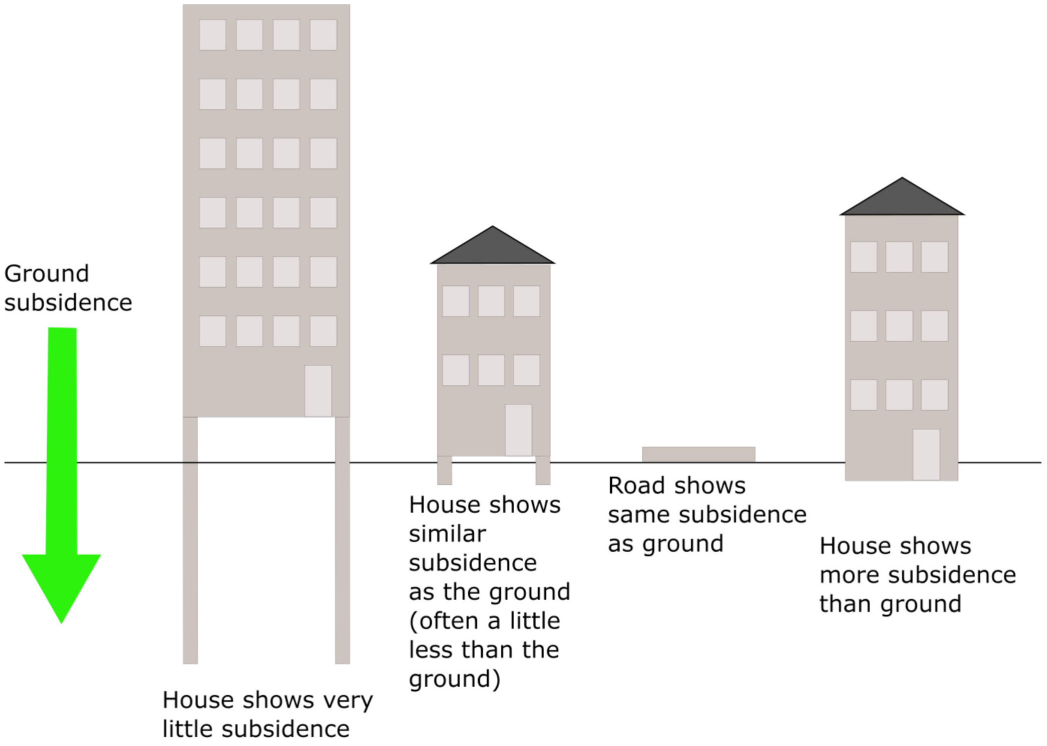


Figure 8: Buildings and infrastructure have different subsidence characteristics depending to a large extent on the depth of their foundation.

In the experience of GIZ, most buildings appear to belong to the category of houses showing similar subsidence as the ground. Large buildings often move very little in the vertical direction. It is assumed that this is the result of deeper foundations while smaller, residential buildings tend to have shallow foundations. Roads have no deep foundation and their sinking rate is more or less the same as the ground around them. The last category of buildings is very rare. Very few buildings sink faster than the surrounding ground surface. It is suspected that heavier buildings normally have a corresponding, deep foundation and thus reduced sinking rates. It is interesting to know that the rate of vertical movements of buildings versus the rate of sinking of the ground is the key to understanding land subsidence. This means describing land subsidence in a spatial sense should disregard InSAR points belonging to structures with considerably different subsidence rates than the ground. Typically, these structures are bridges, high voltage power pylons, and big buildings. These structures were identified with high resolution satellite images (Google Earth, Bing) wherever possible, and PS on or near the structures were filtered out and not used to compute land subsidence rates of areas. The mean value of all PS before filtering was -11.29 mm/year average vertical movement and after filtering decreased slightly to -11.42 mm/year. The number of PS was reduced from 752,406 to 619,138. Based on area (after interpolation), the average annual vertical movement was 10.33 mm/year before filtering and 10.43 mm/year after filtering.

The collected data are provided as points but for practical purposes one needs to know the land subsidence between the points as well. Moving from individual points to areas is challenging as it can introduce a significant amount of error, especially when the distances between actual observations are large (low point density), or when point values vary strongly and in a non-gradual manner (high heterogeneity). Interpolation commonly assumes that the area between points is a flush connection between the points and an interpolation results in a seamless area. The interpolation may be done in different ways and different levels of evenness. For local land subsidence assessments, evening is applied on low levels while stronger evening reveals bigger patterns in the Delta more clearly.

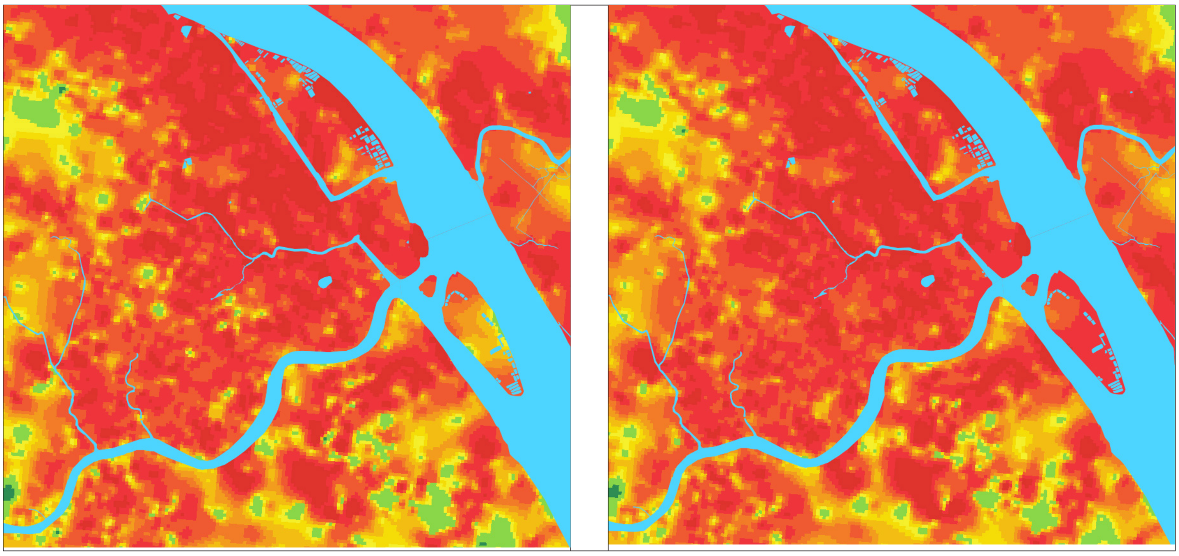


**Figure 9: Interpolated subsidence in Can Tho [mm/year].
Left: based on raw data. Right: based on filtered data.**

Some slow moving points were eliminated and therefore the land subsidence rate increased in these places.

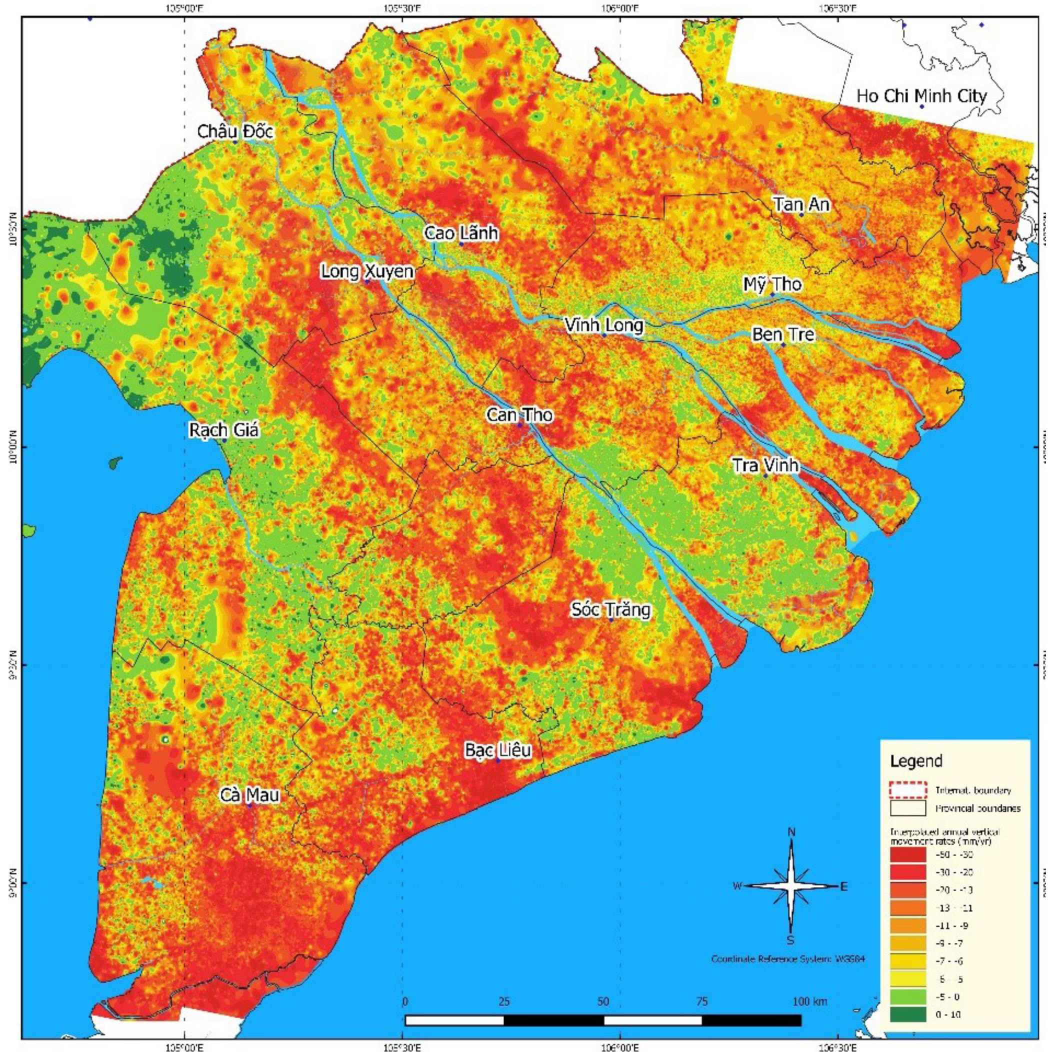


Figure 10: Land subsidence with low level smoothing showing details of vertical ground motion

It is clear that the estimated vertical movements are not uniformly distributed. There are strong, very local variations and also patterns of larger areas exhibiting similar vertical movements. Many urban areas show large negative vertical movements while many rural areas move downward at a lesser rate. However, there are exceptions and some cities experience relatively little sinking while some rural areas sink relatively fast.

The observed variations on much localized levels might reflect reality but they may also result from inaccuracies of the InSAR method which might be producing noise. ‘Noise’ is an effect of randomly distributed values which are too high or too low, and hence constitute measurement errors which do not reflect reality. Determining this will be subject to future research. If technical noise (measurement errors) is the main reason for a high degree of variation, smoothing of the results may reveal subsidence patterns more clearly. In contrast, if high variability is an actual reflection of reality – i.e. pronounced local differences in ground movement do exist – then smoothing will lead to a considerable loss of information and provide a false impression of uniformity. The following map is the output from calculations generalizing vertical ground movements.

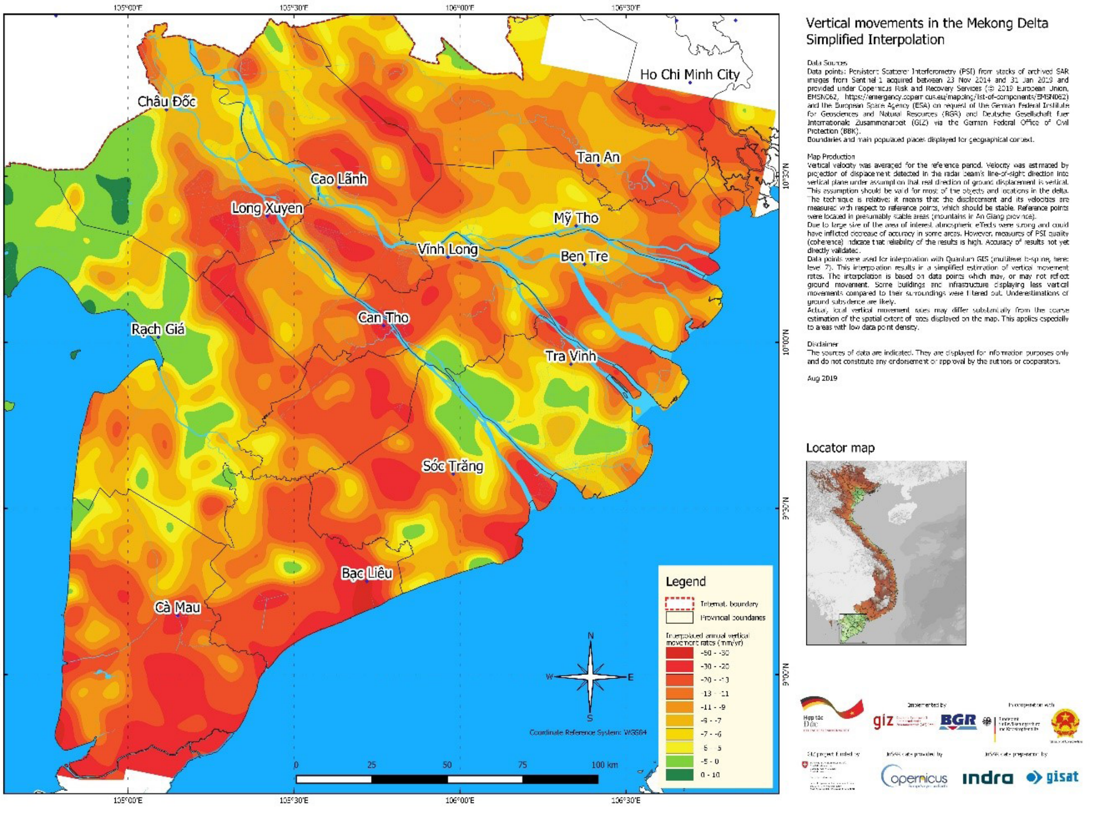


Figure 11: Vertical movements in the Mekong Delta, simplified interpolation.

Land subsidence displayed with strong smoothing. In the north west of the map some, spots are visible with very little ground movements. These places are mostly rocky mountains, which are regarded to be much more stable with respect to vertical movements than the alluvial soils in other parts of the Mekong Delta.

The interpolated vertical movement rates are suitable to assess the composition of the values. A histogram of the data shows this. The distribution of values is estimated by displaying the annual vertical velocity values in a histogram. This means the high density of PS in urban areas and the low density in rural areas are not reflected. It is based on the velocity values of the whole covered area. PS clearly identifiable with structures showing significantly less subsidence than their surrounding area were omitted for this

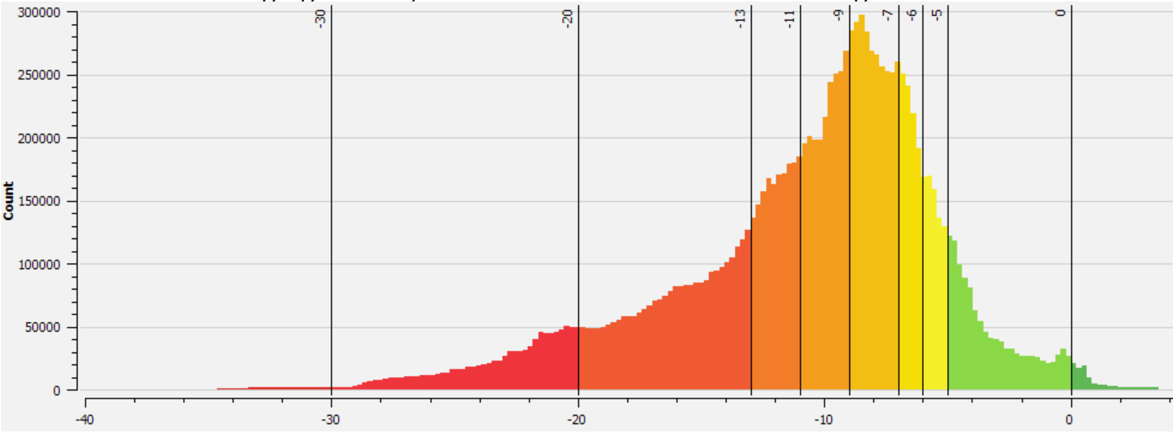


Figure 12: X-axis: annual vertical movement [mm/year], y-axis: number of points with the respective value. The colours reflect the scheme used in the maps above. The average is 10.43 mm/year.

Relatively few points show positive (upward movement) values and there is a heavy concentration of values between -17 to - 3 mm/year. About two thirds of all values are in this range. The collected data have a high spatial and temporal resolution. This permits the display of local land subsidence variations and time series revealing trends over time.

Figure 13: Power pylons marked with pink crosses and PS (circles with colours according to vertical velocity) displayed on Google Earth image as background.

Inset: enlarged detail. The pylon is visible as a white area pointing south-west while the shadow is dark and pointing north-west. The centre of the foundation of the pylon is 11 m from the PS for the pylon in the enlarged area.

Figure 14: Centre of the foundation of pylons marked with crosses, PSI with coloured dots. The distances are between 40 to 50m.

In summary, the horizontal location of a data point is accurate within a range of some metres in some areas and tens of metres in other areas. In many places, the PS are shifted to the east, south-east and south. Within an area, the shift direction and shift distance are quite similar. However, as shift direction and distance vary from one area to the other, corrections are not easy and may be carried out in a small areas but not for the whole Mekong Delta.

Notwithstanding these inaccuracies, the PS for lone reflecting objects in vegetation or agricultural areas as well as bigger buildings in densely built up areas is possible. Smaller structures may have PS but attributing the data to a specific structure proves difficult if many such structures are near to each other.

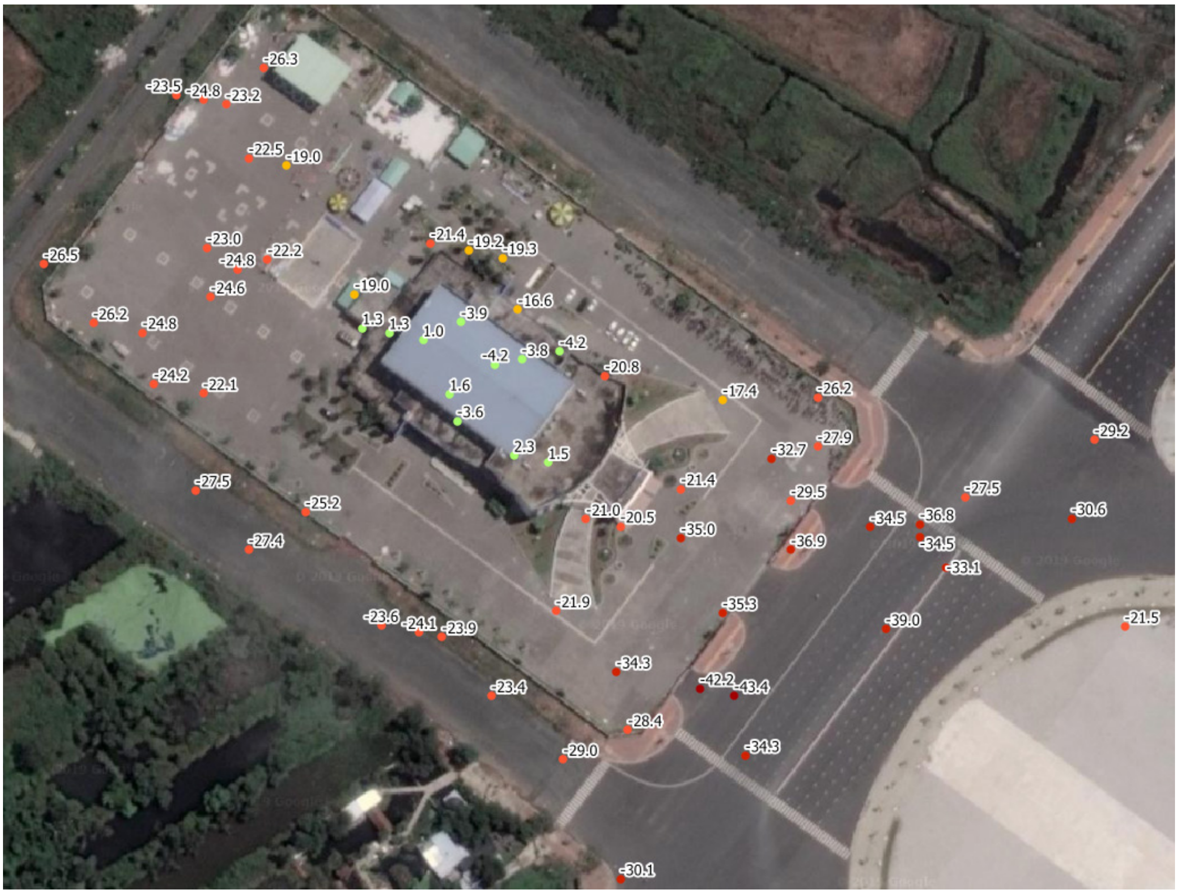


Figure 15: Average vertical velocity in mm per year[36], displayed on Google Earth image as background.

The building in the middle exhibits very little vertical movement while the surrounding streets and parking area shows sinking at several cm per year. The building is a meeting hall in Ca Mau City.

Figure 16: Average vertical velocity in mm per year[37], displayed on Google Earth image as background.

The big building in the centre is a supermarket in Long Xuyen. It does not move significantly, while smaller buildings in the vicinity have negative vertical movement in the cm range.

High temporal resolution

Previously, data on vertical movements in the Mekong Delta were collected every few years. This was sufficient to estimate annual averages but it was difficult to see the dynamics of land movements, such as acceleration or deceleration. The new InSAR data consist of a time series of 180 points each. This means about every eight days a value is collected. These values are displayed in a graph. Time series were produced by setting the first value at "0". Further data are displayed as the difference to the first point. Apart from the annual vertical movement rate, a value quantifying the coherence of the series was produced. A coherence of 1 means all data are exactly on one straight line, while lower values indicate how far values diverge from the calculated line. A large number of points show a straight linear negative trend with a high coherence.

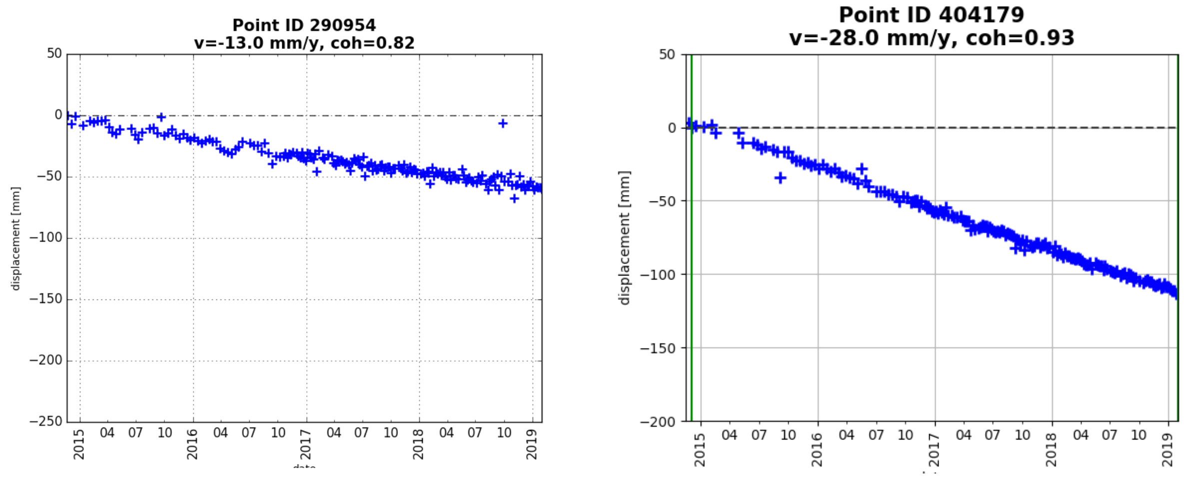


Figure 17: Very few points divert from the linear trend. Some of them show an increase while other points show a decrease of vertical movement rates.

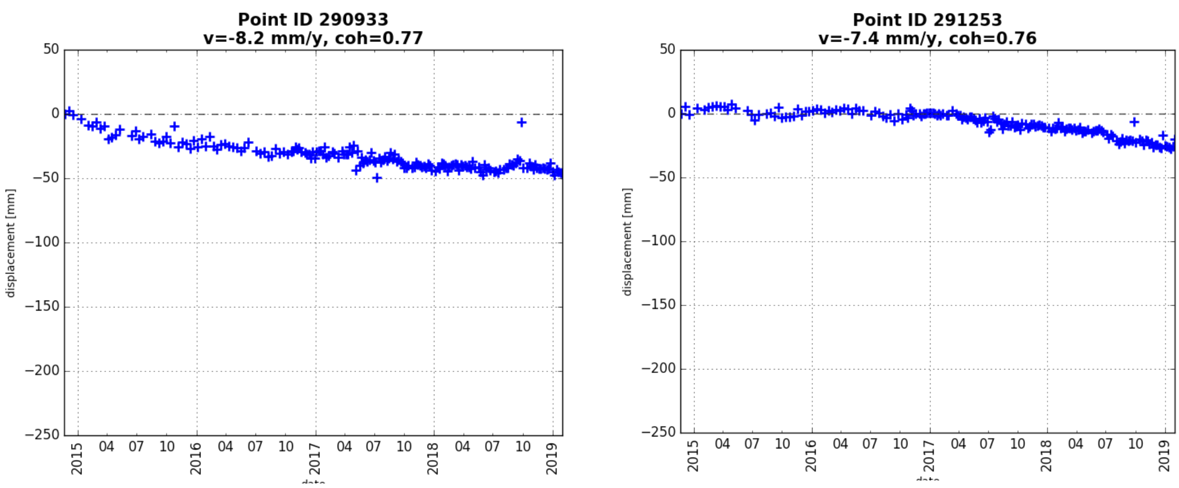


Figure 18: Left: Deceleration. Right: Acceleration of land subsidence.

As a rule of thumb it is common to predict future trends based on historical data up to the same time period historical data are available. This means with four years of past data, a projection of four years ahead will provide quite reliable forecasts, while the error beyond this period might be bigger.

4.2. Understanding causes of land subsidence

There are significant differences in vertical movement rates in the Mekong Delta. Some areas show strong downward movement while in others it is relatively moderate. At the local level, different buildings in the same area move at substantially different rates. Obviously, it is interesting to know how these discrepancies may be explained. What processes underground were responsible for land sinking and why do we see such big differences?

Land subsidence happens in many places in the world and some research has investigated the causes in settings similar to those in the Mekong Delta. Some researchers have already worked on the issue in the Mekong Delta[38]. They identified natural and anthropogenic drivers of the observed land subsidence.

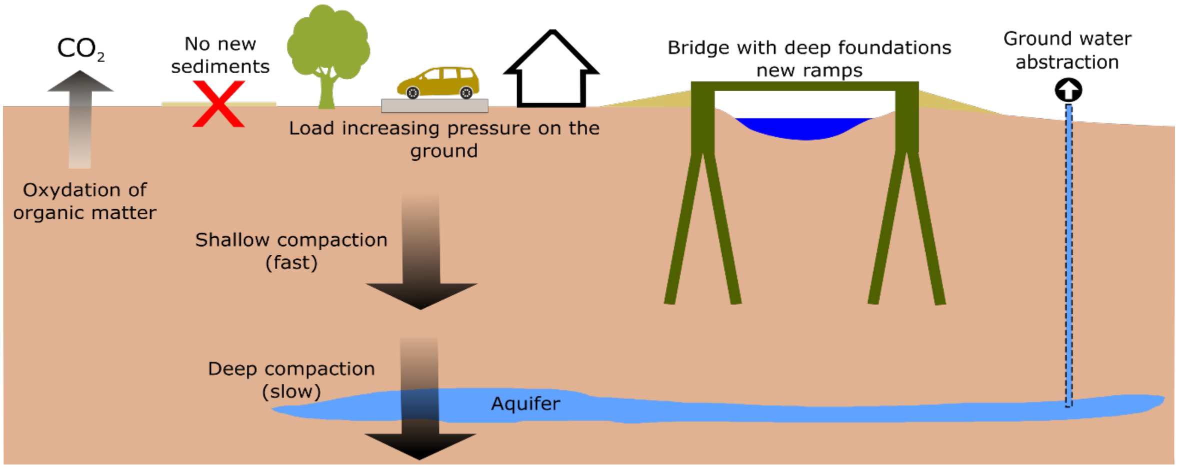


Figure 19: Simplified processes resulting in land subsidence in the Mekong Delta

Compaction of the fresh and soft sediments deposited during the flooding season is a natural process largely compensated by annual replenishment with new sediments. Although the soil was continuously compacting, it did not result in significant changes in the height of the surface. Such a process does not apply in areas converted to settlements. Paved roads cannot gain height from mud and sand settling on their surface. Flooding of crop fields was strongly reduced by building dykes in order to facilitate three annual harvests. Ground compaction continues in urban and rural areas without the compensation of new sediments.

Apart from the strong reduction of sedimentation on land, human-built houses and infrastructure added load to the soil. Though not well quantified yet, it is clear that this accelerates compaction and increases subsidence rates.

The Mekong Delta is full of surface freshwater but this water is often polluted, and nearer to the sea this water is increasingly brackish. Therefore, drilling wells and pumping groundwater is an alternative for providing water for households, businesses, and agricultural activities.

Figure 20: Water pump for supplying freshwater to a shrimp farm in Bac Lieu (photo credit: Sophie Krüger)

Unfortunately, there is very little reliable data about the volume, locations, and sources of groundwater abstraction in the Delta, which makes the correlation with observed land subsidence rates rather difficult. Data from the national groundwater monitoring network shows sustained declining groundwater levels for many aquifers and areas. Groundwater is an indicator of heavy pumping activities beyond levels of natural replenishment. Such data have been used to model the influence of water pumping on subsidence[39]. The observation network density is, however, rather low, and large gaps exist between individual observation points. Also, the Delta is characterized by highly complex sedimentation, containing up to seven overlying aquifers, each of which is subject to different patterns of utilization and partially separated by non-permeable layers with widely unknown properties. All previous models and studies on the impact of groundwater abstraction on land subsidence in the Delta are hence invariably built on a significant degree of assumptions, which may or may not reflect reality on the ground.

The new InSAR data have a high spatial and temporal resolution and it is expected they will contribute to an understanding of why the model and actual data appear to differ. BGR and its Vietnamese partners will target detailed studies on groundwater abstraction and dynamics on areas showing higher land subsidence in the InSAR data. Once abstraction points and quantities are located, localized assessments of PS values and groundwater parameters can be performed.

Another way of utilizing the new data to reveal causes of land subsidence is determining the sinking rates of buildings or infrastructure. If the vertical location of compaction can be determined, the possible causes may be narrowed down to processes known to happen at the respective depth.

The data for almost all bigger structures (big buildings, bridges, power pylons) reveal a surprising trend. While one would assume that the weight of a heavy object presses strongly on the ground and thus sinks faster than lighter and smaller structures, in contrast the opposite is usually found. High and big structures sink more slowly than small structures. Though not finally verified, there are strong indications that the depth of building foundations is a key factor determining subsidence rates. Deeper foundations appear to mean slower sinking while shallow foundations result in faster sinking.

Figure 21: Left: Foundation of a pillar of a residential building in Can Tho. Depth approx. 1 m. Right: The walls have no foundation at all.

High rise buildings and bigger buildings often have more than 40 m deep foundations. The big bridges across the Mekong River have foundations of more than 100 m in depth.

4.3. Understanding the impact of land subsidence

There are a number of effects land subsidence has on the Delta. First of all, the Mekong Delta sinks at an average rate of about 1.0 cm per year[40] bringing it closer to sea level, which currently rises at 4 mm per year in the south of Vietnam[41]. Many scientists expect that the rate of sea level rise will increase over the next decades[42]. Both trends result in an increased relative sea level. The average sink rate of the whole Delta is composed of the rate for agricultural and urban areas (and others), and the rates for different forms of land use vary considerably. Many urban areas lose 3-5 cm of height per year bringing street level towards the sea level faster than, for example, rice paddies.

4.3.1 DEM projections

Digital Elevation Models (DEM) represent the height of the elevation of the earth, normally expressed in metres above mean sea level. They are also called Digital Terrain Models (DTM) and they are distinguished from Digital Surface Models (DSM), which include objects on the earth, such as buildings. For practical purposes it is important to know how high the ground will be in the future. This is especially true for land close to sea level. Ultimately, rising seas and sinking land will meet and result in inundation, but before this happens various effects of these two developments are likely to take place: increased coastal and river bank erosion, flooding, and salt water intrusion. This will increase over the next decades in a considerable number of areas in the Mekong Delta. Although there is a small chance of mitigating land subsidence by reducing or stopping groundwater abstraction, the worst-case scenario would be a continuation of subsidence with rates we see today. Almost all time series of the points from the InSAR research show a linear negative trend. There is no indication of the subsidence slowing down during the four years of data collection. This period is too short to predict vertical movements for the next decades with certainty, but as other data with a similar spatial resolution are not available, the InSAR data are used by GIZ to forecast DTMs for the next decades. Currently, land subsidence appears to continue unabated but as there are physical limits to compaction it has to slow down gradually. In an attempt to facilitate this, GIZ assumes that land subsidence slows by 1% per year. However, it is difficult to judge whether this assumption is practical.

Forecasting how high land will be in the future requires knowledge of how high the ground is now. There were nine different DEMs covering the whole Mekong Delta at the disposal of GIZ[43]. They had different resolutions and many of them have many unacceptable characteristics. The model based on topographic maps of the Vietnamese Government[44] was used for further processing on a regional level. It is a DTM with a pixel size of 500 m. This is acceptable for overview maps and projections. More detailed DEMs need to be used for forecasting the development of ground heights in cities.

The DTM appears to use a vertical datum which is higher than the datum used by the Vietnamese Government (though it is derived from Vietnamese Government topo maps). Using this, many height values of the DTM are lower than geodetic point values of the Government used by GIZ[45].

Currently, it appears difficult to find reliable height references in the Mekong Delta. The geodetic reference points or coordinate control points are subject to an unknown amount of land subsidence and with rising sea levels the traditional reference of "mean sea level" becomes a dynamic value too. The Government decided to shift from this approach to using a quasi-geoid based on the WGS84 ellipsoid[46]. However, this is not yet complete. Once this is done there will be a zero-height value independent of the sea level and sinking land.

A comparison of the 2014 DTM with the estimated 2050 DTM shows that the region south-west of the Hau River approaches "0" or "sea level" faster than the north-eastern part of the Delta. Keeping the above mentioned factors in mind, it is problematic to predict DEM heights in relation to sea level on a Delta-wide scale; however, trends are most likely reflected correctly.

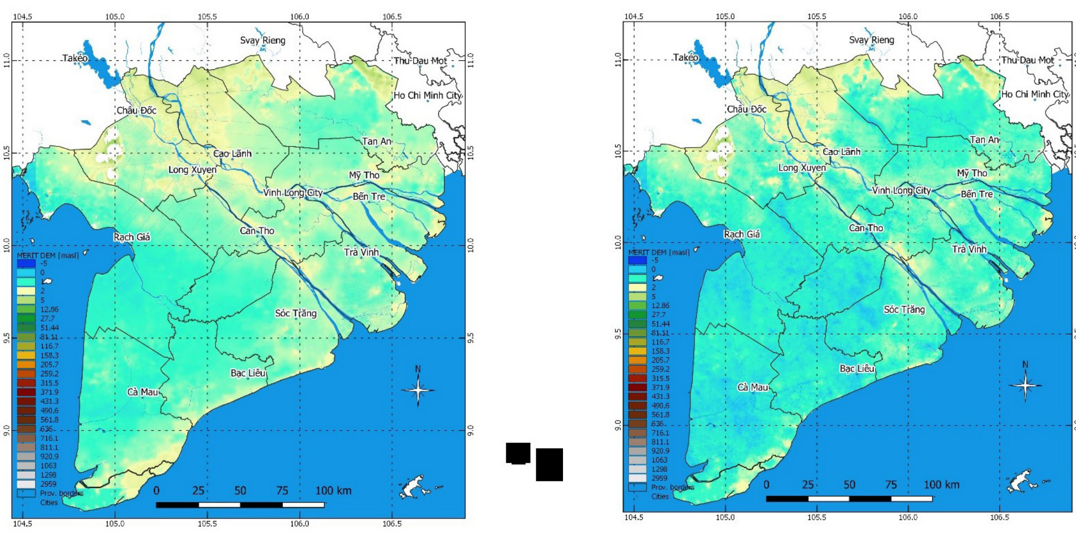


Figure 22: Left: Elevation of the Mekong Delta in 2014 and estimation for 2050 (right). Locally one can use water level gauge data to estimate relative water level rises.

4.3.2. Relative water height increases

Almost all impacts of combined land subsidence and sea level rise appear to be undesirable from the perspective of humans. These impacts include:

- Loss of land by inundation
- Increased exposure to river induced flooding
- Increased exposure to storm surges and tsunamis at coastal areas
- Accelerated erosion along the coasts and rivers
- Increased salinization

Predicting when these impacts take effect in which place is difficult. Many processes are very slow and gradual, although a strong storm, exceptional high water in the river, or combination of such events with a very high tide may speed their development.

One problem in connection to sea level rise and land subsidence is defining the zero value (see previous chapter). However, this problem may be mitigated if local water levels are connected to the height of the ground (e.g. roads) near such gauging stations. In this case, it does not matter where "0" is exactly. To estimate when water and road level will meet, readings from the gauge and observation of road level changes are sufficient. This is explained in the following example from Ca Mau City. Ca Mau is located near sea level. Using the official benchmark of the Vietnamese Government in the city, the average land height of the city centre is 1.43 metres and the lowest surveyed point is 1.03 metres[47]. Several waterways traverse the city and connect to the sea in the west and the east. The water level in the water bodies is not influenced by the Mekong River but strongly by tides and rain.

The annual increase of the water level in Ca Mau averaged 8 mm per year in the period 1988 to 2017. This is higher than sea level rise reported for nearby ocean level observation stations, which for similar time periods recorded 3 to 5 mm per year[48]. This leaves a difference of about 4 mm per year. Natural or man-made reasons (e.g. construction of dykes) for higher water levels in Ca Mau in relation to the tide gauges are not obvious and it is suspected that the higher rate in Ca Mau is caused by land subsidence. Surface land subsidence in Ca Mau was most likely higher than 4 mm per year but if the gauge station in Ca Mau has a relatively deep foundation, a rate of 4 mm per year would be consistent with the range of rates for some bigger buildings in the city.

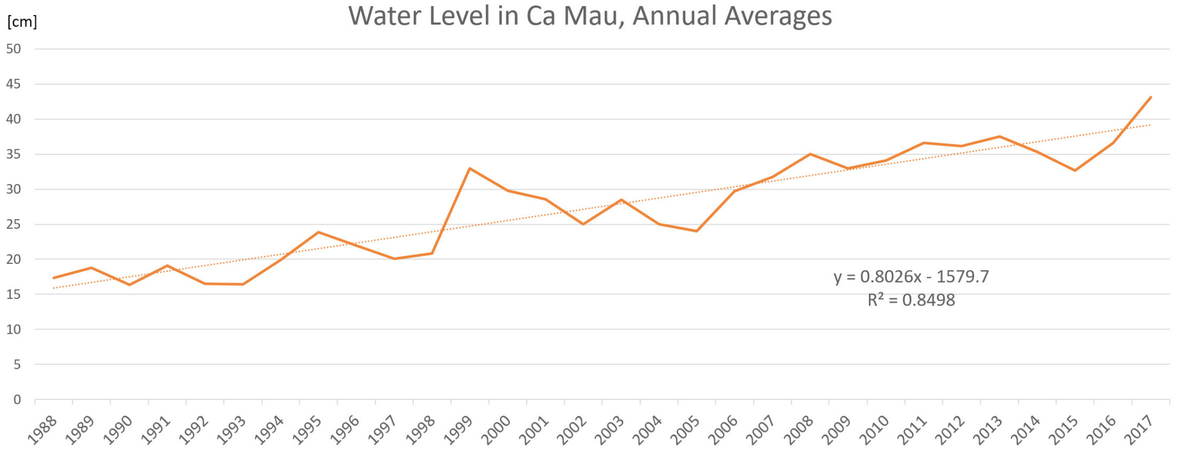


Figure 23: Water level in Ca Mau: Annual averages

Assuming that the land subsidence rate is slower (by 1% per year) and water level rise is constant (though many believe that annual sea level rise rates will increase over the next decades) we see land and water approaching each other. It will probably take less than a decade before water enters some downtown roads during high tide.

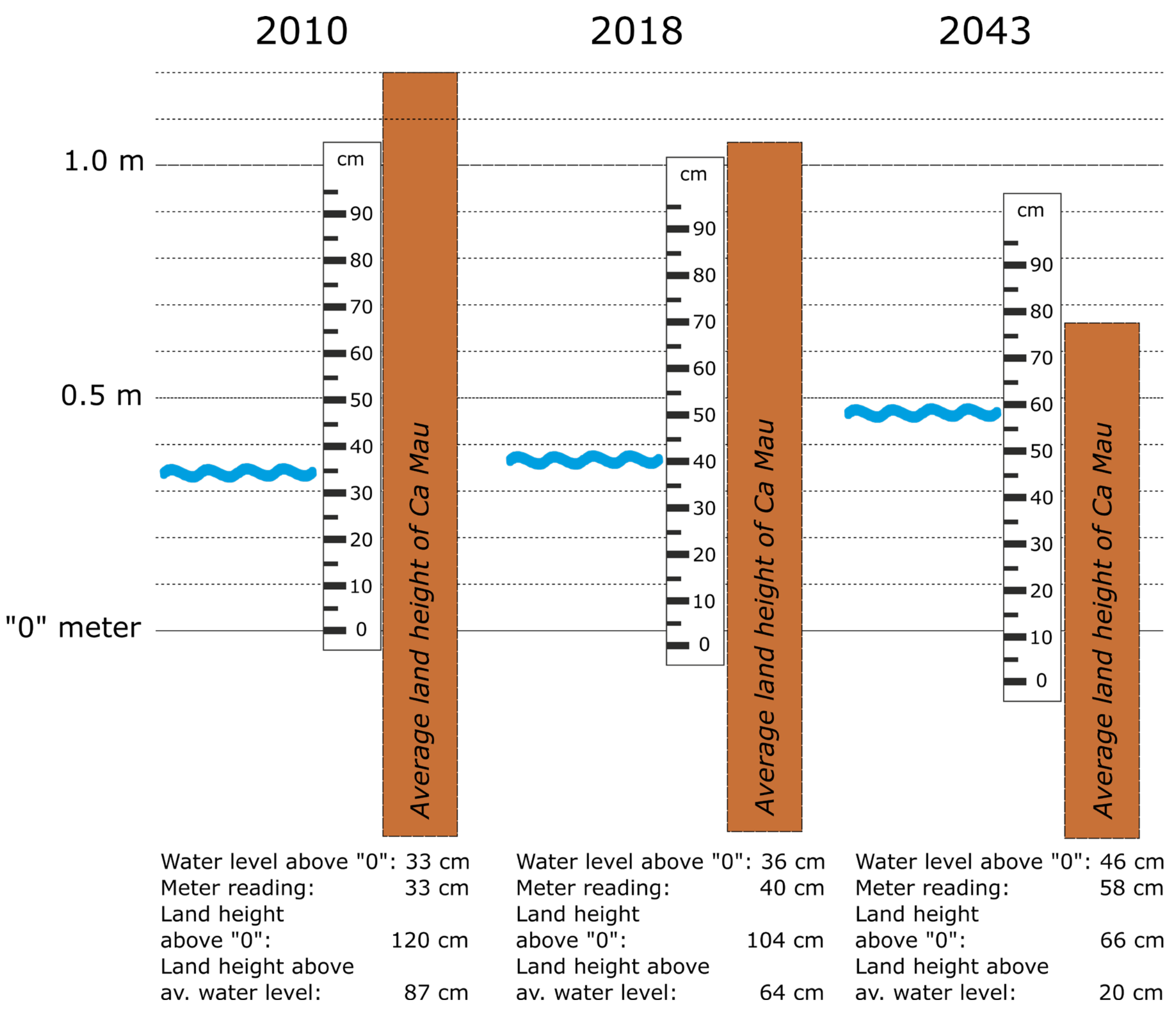


Figure 24: Water level and land height in Ca Mau City from 2010 to 2043

Data from a topographic map of the city with data from 2010 indicated a land height of about 1.2 m in the inner city near the water level gauge. The land subsidence rate at this location was 2 cm/year (based on InSAR data). A straight-line calculation results in 1.04 m height for 2018. At the same time, sea level induced water level rise was estimated at 4 mm/year. The water was slightly more than 3 cm higher in 2018 compared to 2010. The water level gauge shows 8 mm water level increase per year. 4 mm/year is attributed to land subsidence. For 2043 (25 years later), land subsidence is assumed to slow. Therefore, instead of 50 cm, only 38 cm is deducted from the land height. For 25 years the sea level rises 10 cm while the sink rate of the gauge is about 3 mm/year (= 7.5 cm in 25 years).

The graph shows how the water level and the road height are getting closer to each other. The values selected for display are average annual water levels and the road height is near the water level gauge. The maximum water level observed every year is much higher (around 0.8 m above “0”) and some parts of Ca Mau are lower than the roads near the water level gauge. In addition, the annual sea level rise was assumed to be 4 mm. The actual value might be rather higher. This means it is likely that over the next decades, parts of the city will experience temporal inundation during high tides and/or heavy rain events.

4.3.3 Building/infrastructure instability

The impacts of land subsidence in combination with sea level rise have already been described by many authors[49]. This report focuses on other effects of land subsidence, which impact infrastructure and buildings independent of sea level rise:

- Disconnection of bridges from roads requiring ramp adjustment
- Disconnection of utility lines (water, sewerage) from buildings
- Disconnection of ramps, stairs of buildings
- Tilting of buildings (in case of uneven land subsidence)
- Cracks in buildings (in case of uneven land subsidence)

Some of the most obvious places to observe the subsidence of land are bridges. When bridges are constructed they connect flush to roads.

Figure 25: Recently completed bridge with flush transition to the connecting road. No land subsidence visible yet.

Recently completed bridge with flush transition to the connecting road. No land subsidence visible yet. After bridges have been in service for a couple years there are usually signs of the connecting road sinking relative to the bridge. An example is the Cau Cai Son Bridge in the west of Can Tho City. On a historic satellite image, the construction phase is clearly visible.

**Figure 26: Google Earth image of Cau Cai Son Bridge from 08.12.2009.
Ten years later the bridge is approx. 35 cm higher than the connecting road.
On average the road sank 3.5 cm/year relative to the bridge.**

In 2018, a temporary ramp adjusting the road to the higher bridge can be seen. The pedestrian sidewalk is not connected to the bridge side structure and sinks as well as tilts towards the road. The initial height of the sidewalk left marks on the bridge structure.

Figure 27: Image of Cau Cai Son Bridge from 13.05.2018

Figure 28: Image of Cau Cai Son Bridge from early 2019

After May 2018, the temporary ramp was replaced by a more even construction and the sidewalk received repairs and was levelled a lower height in relation to the bridge. InSAR measurements of the bridge indicate 0.3 cm/year sinking, while the PS of smaller buildings nearby are sinking at an average rate of 3 – 4 cm/year.

Buildings often experience problems because of land subsidence. Larger, stable buildings with small subsidence rates face challenges with the ground around them sinking considerably faster. Pipes may be damaged and need to be repaired. Entrances for people and vehicles are damaged and need height adjustments. If subsidence is unevenly distributed under a building it might tilt or develop cracks.

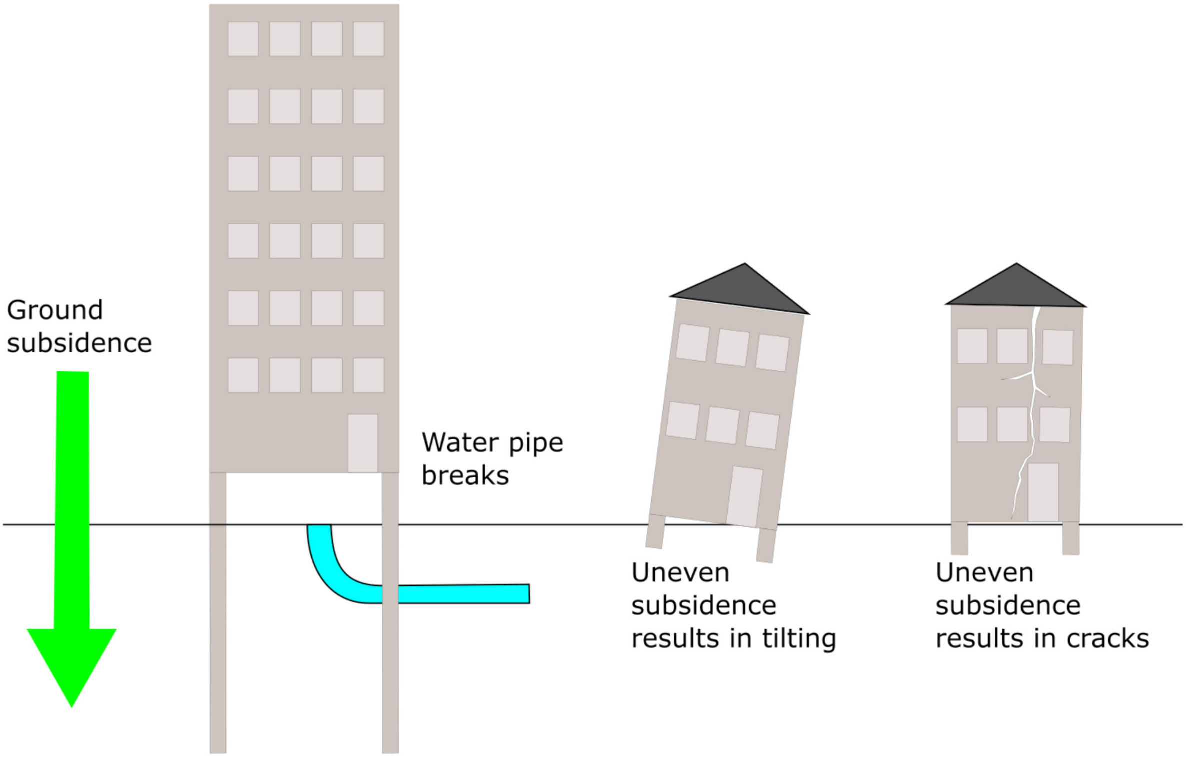


Figure 29: Possible damages on buildings caused by land subsidence

When the ground near a building sinks faster than the building water and sewerage pipes may be disconnected from the building requiring repairs after some years.

Figure 30: Disconnected rain drainage pipe (hospital in Ca Mau).
The structure of buildings may be compromised by land subsidence.

Figure 31: The centre of the ground floor is sinking faster than the walls, resulting in gaps between the window divider, the door, and the floor (a hospital in Ca Mau).

Figure 32: The floor on the right and on the left were on the same level when this hospital in Long Xuyen was built

The part on the left was completed first. The right side is an extension of the original building. The right side is sinking faster than the left side and a ramp was constructed to facilitate access. A new crack indicates that the right side continues to sink faster and eventually the ramp will need to be adjusted again.

A very common sign of land subsidence can be seen at entrances of older, large buildings.

Figure 33: Left: A meeting hall in Ca Mau City. Right: An Giang University in Long Xuyen City.

Figure 34: Left: A supermarket in Long Xuyen City. Right: A hospital in Ca Mau City.

The picture is the same everywhere. The ground descends in relation to the building and leads to damage at the convergence of the two. The observed height differences are largely consistent with InSAR data. The (in some cases estimated) age of buildings multiplied with the annual subsidence rates agree with the total observed height differences between buildings and surrounding ground.

4.3.4 Salt water intrusion

Coastal areas always experience brackish water at the mouths of rivers. Salt may also enter coastal areas if the land is very low and the fresh water discharge is small during dry periods (low rainfall, drought). In the Mekong Delta, relative sea level rise together with low water levels in the waterways during the dry season regularly result in salt water intrusion and increase the salt content of inland water to levels beyond the tolerance of certain crops and human consumption[50].

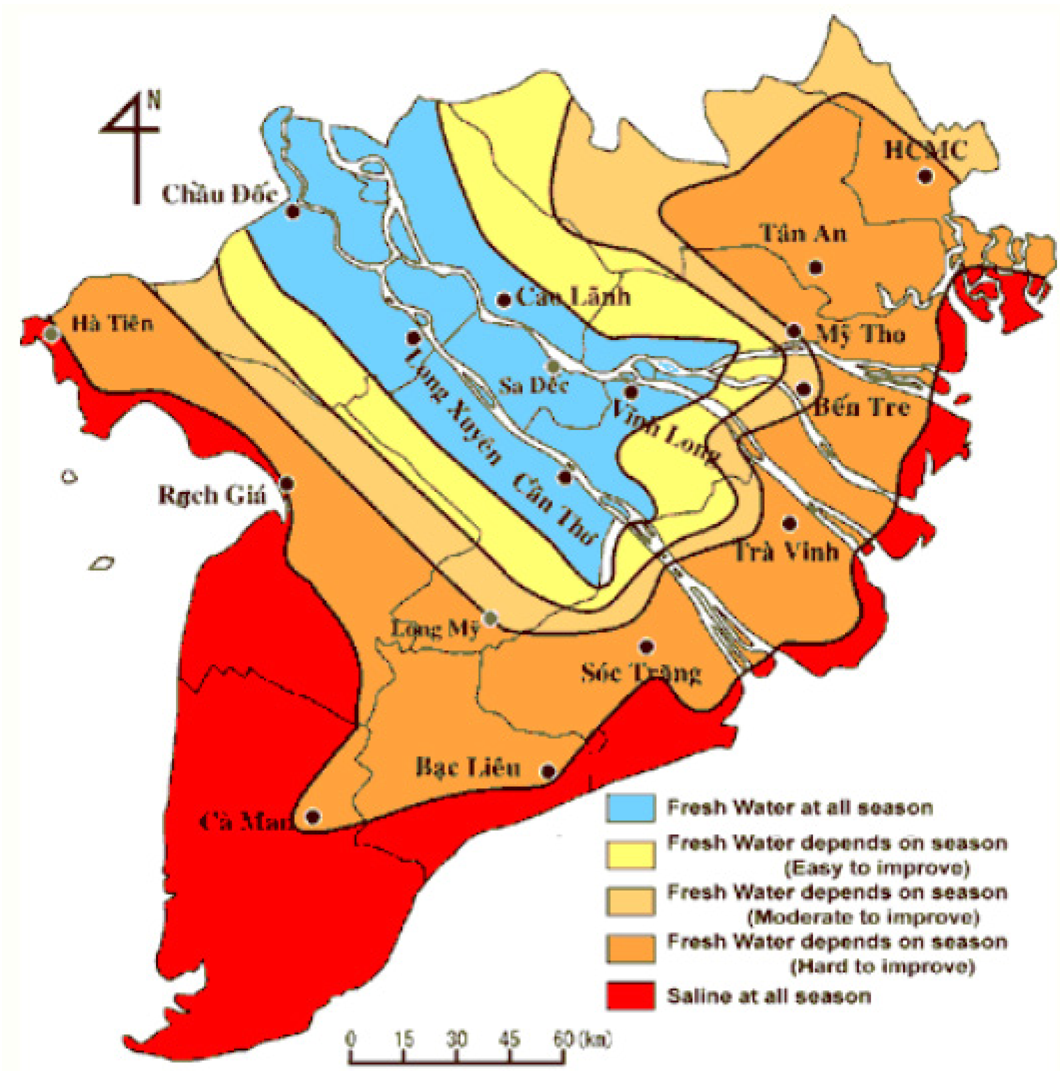


Figure 35: Characteristics of saline intrusion in the Mekong Delta. High salt levels caused varying degrees of damage to agriculture, fisheries, and the livelihoods of people in the region.[51]

4.4. Mitigating land subsidence

Although land subsidence is largely caused by human actions (strongly reduced replenishment of sediments, extraction of groundwater, load from buildings and infrastructure), it is not easy to slow subsidence down or stop it completely.

For agricultural areas, resumption of flooding and the resulting deposits of sediments are an option, but even if flooding was resumed at previous levels, sediments settling in the fields would be much smaller than in the past. This is caused by the substantially reduced sediment transported in the Mekong River[52]. The river carries only 50 percent of the sediment load it used to before human actions interfered[53]. There are two main reasons for the observed reduction of sediment load: trapping by dams upstream and sand mining of the river bed.

Hydro-power dams in China, Laos, Thailand, and Cambodia were constructed during the last decades and more are currently under construction or planned. Dams trap sediments and once all planned dams are completed there will be very little sediment remaining downstream in the river. It is estimated that the reduction will be 90[54] to 96[55] percent that of pre-dam times. Sediment deposits in reservoirs are actually an unwanted side effect for the operators of the dams as they reduce the capacity of the reservoirs; however, removing sediments by hydraulic actions (flushing, syphoning) or mechanical removal requires considerable (financial) effort and it appears that dam operators in the Mekong Basin are not actively pursuing these activities. MONRE indicated that the Government of Vietnam is negotiating with countries in the region to reduce hydropower development with the aim of reducing sediment loss[56], but without visible success up to now[67]. In case these efforts are unsuccessful and dams are constructed as planned, further strong reductions of sediments in the Mekong River are likely.

The situation is aggravated by sand mining in the main river channels. Sand is extracted for construction purposes and with the current levels of economic growth in Vietnam as well as in upstream countries, local sand demand is high and growing. In the past, sand was also exported abroad[58]. Although sand extraction is regulated in Vietnam, regulations are not thoroughly implemented and enforced. This was criticized by the World Bank in June 2019[59].

Figure 36: Sand mining in the Mekong River

Therefore, replenishment of lost land height in agricultural areas by resuming previous flooding levels does not seem to be a viable option.

Another option for reducing land subsidence is reducing groundwater abstraction. In many parts of the world, a strong connection between pumping water from the ground and sinking land has been documented[60]. Volume data concerning groundwater abstraction in the Mekong Delta are not systematically collected and estimations are educated guesses by experts based on groundwater tables and other proxies, such as the number of wells or estimated per capita consumption[61]. Based on these estimations and assumptions, many model calculations have been performed and correlated with observed land subsidence data[62].

Figure 37: Groundwater pump connection for commercial drinking water supply in Ca Mau (Photo credit: BGR)

Model calculations conclude that more than two thirds of detected land subsidence is caused by groundwater pumping[63]. One can safely assume that groundwater extraction is not evenly distributed throughout the Delta and the composition of local drivers of land subsidence may vary strongly. It is not clear whether the models are applicable in all locations.

As model calculations come with some uncertainty and estimating the local contribution of water pumping is challenging, it is difficult to estimate the potential effects of reducing or stopping groundwater extraction and hence the success of any such mitigation policy. What is clear is that reducing groundwater abstraction will have serious repercussions on water supply and economic activities in the coastal delta and it will also be met with resistance by groundwater users. Taking decisive action will clearly benefit from a reasonable degree of evidence, but in the view of BGR and GIZ, remaining uncertainties should not be used to delay measures and perpetuate ultimately unsustainable practices. While a complete halt of groundwater extraction seems hardly realistic in the short term, it is important that technical, institutional and legal preconditions for targeted and effective groundwater regulation be put in place without further delay. In parallel, efforts to collect data and evidence for causal analysis and groundwater management – for example, through wide-spread groundwater extraction metering and monitoring – need to be intensified so that uncertainty can be gradually removed. Regulatory measures can then be prioritized and targeted to areas and depths particularly sensitive to land subsidence, or to areas with strategically important groundwater resources.

A more ambitious approach to mitigating land subsidence lies in designs to not only halt but reverse compaction induced by groundwater extraction. This is thought to be achieved by artificial and managed aquifer recharge, essentially a refilling of the aquifers by pumping and injecting surface water at depth. It is, however, unclear whether the underlying processes leading to compaction – presumably the collapse of clay structures from reduced groundwater pressure – can really be reversed. Even if it could technically work, the cost would be prohibitively high and this option does not appear to be very practical.

4.5. Adapting to land subsidence

Options to reduce or stop land subsidence are very limited. If it is not possible to reduce land subsidence effectively, the next best option is to live with it and cope with its impact. Up to now, the impacts of land subsidence in the Mekong Delta have not been strongly felt (no part of the Delta is under sea level) and few adaptation measures have been implemented. However, some are in the planning stage, such as the construction of an embankment around Can Tho City[64].

Settlements are sinking much faster than agricultural areas in the Mekong Delta. Therefore, it is expected that many towns and cities will experience serious water intrusion problems before farmland areas. The concentration of people and assets in settlements is much higher than in the countryside. These factors call for adaptation measures in cities as a high priority.

Land subsidence near the coast is not a new phenomenon in the world. Many places have experience, and have designed and implemented adaption measures. The most prominent include the Netherlands with about a third of its land area below sea level and no major disasters recorded in recent decades. Another example is New Orleans in the USA. It also lies under sea level to a large extent and the city is protected by dykes. When hurricane Katrina struck the city in 2005, levees and floodwalls broke and flooded the city leaving 1,500 dead and causing enormous economic damage[65]. There are also examples closer to the Mekong Delta. Tokyo, Bangkok, Jakarta, and Semarang are well known examples of places with strong land subsidence problems. They have all taken steps to adapt to land subsidence aggravated by sea level rise.

Figure 38: Floating pier (image courtesy of http://www.bfsa.eu/en/home/)

The most common measure to combat the relative rise of water is constructing dykes or embankments around areas requiring protection. Usually this includes a system of sluice gates and pumps to keep out or remove water from low-lying areas. This is technically and financially demanding and in the Mekong Delta only suitable for settlements and industrial areas – agriculture cannot be protected with such massive and expensive infrastructure.

Harbours need to be outside dyke-protected areas as they need direct access to deep seawater. In Indonesia and Japan, relative sea level rise was compensated by adding layers of concrete or similar materials on top of piers[66]. This is expensive and not a sustainable solution as additional relative sea level rise/land subsidence will require the same intervention after some decades. A more feasible and practical solution might be floating harbours. Piers would be floating and connected via flexible bridges to elevated roads on land. In addition to regular level changes from tides, this infrastructure could handle metres of relative sea level rise.

There is a lot of construction occurring in the Mekong Delta. GIZ strongly recommends adjusting the base height of settlements, industrial zones, roads, and similar objects to a height that guarantees these constructions will still be above water at the end of the century.

One of the impacts of land subsidence is saline intrusion in coastal regions. In addition to strategies already mentioned (e.g. dike, gate construction), there are some options that are currently being implemented[67]:

- Crop calendar adjustments
- Switching from rice to saline tolerant agriculture, such as shrimp farming
- Deepening of aquaculture ponds and use of material to increase embankment heights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05 Conclusions

In recent years, there have been considerable advances in understanding land subsidence and its consequences on socio-economic development and the environment in the Mekong Delta. Establishing the status of land subsidence, the causes of the problem, and the development of practical and sustainable solutions is a priority for the Government. There are significant challenges for the Government. For example, gaps and inconsistencies in the legal and policy framework; unclear roles and responsibilities across ministries and provinces; gaps in the data and available evidence; and limited state budget allocation for land subsidence adaptation and mitigation.

The new InSAR based data on vertical movements of the land surface and buildings provide a wealth of data still to be fully exploited. However, even with the data processing and analysis of drivers of land subsidence conducted so far, the new data clearly indicates the magnitude of the problem across the Delta and observations confirm alarming subsidence rates outpacing sea level rise many times. It is particularly worrying that the time series of almost all new data points show a straight linear trend. This means land subsidence does not show signs of slowing down. As the Delta is only just above sea level this will ultimately lead to a high risk of inundation in large parts of the Delta unless actions are taken to reverse this trend and slow land subsidence considerably. The zero reference height ("mean sea level") appears to be different from one map (or Digital Elevation Model) to the other. Because of this, forecasts of when certain effects of land subsidence will unfold more strongly is difficult. However, it is certainly only a matter of years or decades until more serious consequences of land subsidence in synergy with sea level rise will increase the negative impacts already apparent today. Salt water intrusion will progress affecting agriculture, and temporary floods will become more frequent and cover larger areas impacting urban and rural development. Public and private buildings as well as infrastructure stability will be compromised.

Currently, options to mitigate land subsidence appear to be quite limited. Reducing or stopping groundwater usage or an increase of sediment deposits would certainly delay some effects for some years. However, many government officials and scientists expect sea level rise rates to increase. This would mitigate possible gains from slowing down land subsidence by applying these options. An alternative option of coping with land subsidence is adapting to it and finding ways to live with rising waters. For agriculture, this will mean switching to more salt tolerant species. Urban areas, which are sinking much faster than agricultural land, might need infrastructure solutions in the form of ring dykes, sluice gates, and pumping stations to keep water out of affected urban centres.

06 Recommended actions

Much research still needs to be done to understand the phenomenon and to develop viable coping strategies to counter the "double trouble" of sea level rise and land subsidence. In the long run, the very existence of the Mekong Delta region is at stake. There are some short-term interventions at hand but the far reaching long-term strategy on how to save the Delta from ultimate inundation is still to be developed.

GIZ has the following recommendations, which are divided into two parts. The first is general policy recommendations and the second refers to specific actions to be taken in the five land subsidence management steps.

General recommendations for policy makers:

1. **Integrate land subsidence adaptation activities into the legal and policy framework**
   Key areas for updating the legal and policy framework include the following:
   - Irrigation
   - Meteorology and Hydrology
   - Construction
   - Urban Planning
   - Decree 80 on Drainage and Treatment of Waste Water

2. **State budget allocation**
   - Assess the status of budget allocation for ground subsidence adaptation and mitigation at national and provincial levels
   - Assess the role of the private sector, PPP, and socialization
   - Establish budget estimations for options for adaptation and mitigation of land subsidence
   - State allocation of budget for selected option/s

3. **Clear Roles and Responsibilities of Ministries and Provinces**
   - Institutional assessment of relevant ministries and provinces
   - Options presented to key decision makers
   - Clear roles and responsibilities approved by the Government

4. **Integrating land subsidence into the upcoming Mekong Delta Master Plan**
   - Assessment on integrating land subsidence into the upcoming Mekong Delta Master Plan (in accordance with the Law on Planning)
   - Cooperation with MPI and other relevant ministries

Specific recommendations for land subsidence management steps:

1. **Measure land subsidence (ground motion data collection)**
   - Build or increase human resource capacities in Vietnam to convert freely available radar satellite data to vertical ground motion data (research and development of the method)
   - Establish a regular InSAR ground motion observation service for high risk areas in Vietnam
   - Increase the number of satellite radar reflectors. They should be installed at locations where other land subsidence observations are taking place (to be able to compare different methods)
   - Continue/expand GNSS with instruments at locations of other observations
   - Drill a number of holes to measure compaction of various depths (extensometer, etc.)
   - Measure relative vertical motion differences between infrastructure/buildings and ground surface
   - Verify “0” height (geoid) as a reference for other measurements
   - Include provisions to measure land subsidence in the Law on Survey and Mapping
   - Publish land subsidence data in accordance with the Law on Access to Information

2. **Understand the causes (research on the drivers of land subsidence).**

   - Correlate available ground motion data with other data (soil type, structural geology, age, aquifers, groundwater extraction, land use, etc.)
   - Conduct specific research of suspected drivers (geology & tectonics, hydrology, soil mechanics, loading by buildings, etc.)
   - Further develop regular groundwater observation capacities, including background and extraction monitoring (improve spatial coverage, network density and aquifer inclusion)
   - Include the term “land subsidence” in tasks for MONRE in the Law on Natural Disaster Prevention and Control

3. **Understand the (negative) consequences**

   - Develop or fine tune methods for DEM forecasting
   - Develop or fine tune methods for relative sea level rise forecasting
   - Develop or fine tune methods for saline intrusion forecasting

- Conduct research into the impacts of land subsidence on buildings and infrastructure
- Include the term “land subsidence” in tasks for MARD as part of the National Natural Disaster Prevention and Control Plan in the Law on Natural Disaster Prevention and Control

4. **Mitigate (reduce the speed).**

- Develop methods to increase sediment deposition in crop areas
- Promote alternatives to groundwater extraction
- Test aquifer recharging
- Strengthen technical, institutional and legal capacities for groundwater regulation
- Operationalize existing regulations for groundwater extraction in view of land subsidence (i.e. define clear thresholds and criteria for groundwater registration and restriction areas)

5. **Adapt (live with it).**

- Conduct feasibility studies to protect cities with infrastructure (dykes, gates, pumps)
- Define minimum heights above “0” (mean sea level) for new settlements, industrial areas, and infrastructure to be above local water levels by the end of the century
- Develop/refine methods of agricultural adaption (shift to salt resistant crops, shift to aquaculture, deepen aquaculture ponds, and use material to increase embankment height, etc.)

DÁN XE

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