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Subsidence and Shoreline Retreat in the Ca Mau Province – Vietnam Causes, Consequences and Mitigation Options

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ABSTRACT: In the past decades, the Ca Mau province located at the southern end of Vietnam, has experienced significant land-loss. Satellite data suggest that a loss of land, or a retreat of the shoreline, ranging from about 100 m to 1.4 km have occurred over the past 20 years or so. In addition to the retreating coastline, the Ca Mau coastline has experienced loss of mangrove forests and salt-water intrusion into canals and rivers in the region. A study undertaken in collaboration between Vietnamese and Norwegian institutions has tentatively concluded that the main cause of the land-loss is subsidence of the ground surface as a result of ongoing groundwater pumping. The experienced land-loss may be further enhanced by a climate change related sea-level rise.

Large parts of the land area in Ca Mau lie less than 1.5 m above sea-level. The subsidence settlements may already have reached 40 to 80 cm in some places, and the present subsidence rates may correspond to 2-4 cm/year. Recent satellite based data using InSAR technology (Interferometry Synthetic Aperture Radar) confirm that significant subsidence is on-going in all provinces in Vietnam from Ho Chi Minh City and southwards. If no actions are taken soon, the implication will be that these provinces are lost to the sea within a time frame of a few decades. The only realistic way to prevent such subsidence settlements is to greatly reduce groundwater pumping in the area, and replace it with water from other sources. Also in light predicted climate-change related sea-level rise, some physical barriers may also be required to protect the region against flooding.

It is recommended to immediately initiate an observational program and supplementary analyses to verify the present and future subsidence of the ground surface in Ca Mau. This is to ensure that remedial actions are planned for and implemented before it is too late.

KEYWORDS: Shoreline retreat, Subsidence, Sea-level rise, Coastal erosion

1. INTRODUCTION

Through the Norwegian Ministry of Foreign Affairs (MFA) in Oslo, the Norwegian Geotechnical Institute (NGI) was in 2012 requested to assist the Ministry of Agriculture and Rural Development (MARD) in Vietnam to assess apparent "land-loss" problems observed along the coastline of the Ca Mau province located south in Vietnam, Figure 1.

Figure 1 Map showing the southern part of Vietnam and the Ca Mau province

It was indicated to NGI that the apparent "land-loss" was associated with a combination of enhanced coastal erosion and retreat of the shoreline, a possible general subsidence (sinking) of the ground surface relative to the sea-level, or possibly also a rising sea-level induced by climate changes. The enhanced shoreline erosion caused loss of Mangrove forest which contributes to protect the coastline against erosion.

Increasing salt water intrusion into canals and rivers in the region was also suggested to be a consequence and part of the "land-loss" problem, and had already some impact on agricultural farming (rice production) as well as shrimp and fish farming in the province.

2. IDENTIFICATION OF SHORELINE RETREAT

2.1 From field inspections

MARD had information from local people and staff that suggested significant retreat (1-2 km) of the shoreline along the southern end and west coast of Ca Mau in the past 20 years. It was suggested that the cause could be enhanced coastal erosion, possibly combined with some sea-level rise.

NGIs field trips to the region in 2012, and interviews with local inhabitants, confirmed a significant retreat of the shoreline in many places. It was also apparent that the mangrove forest was in strong retreat in places, which made the coastline even more vulnerable to erosion by waves and currents.

Some test areas to study ways of protecting the mangrove forest, and thereby reducing erosion, were established by the Vietnamese. An example was using small rock dikes constructed in the sea outside the shoreline. These test dikes were built in relatively shallow water (1-2 m). The rock fill was wrapped in a robust geotextile to prevent the rock from mixing in with the soft seabed silts and clays. Visually, it was clear that the these small rock dikes reduced wave action and erosion on the inside of the dikes, but the authors are not informed how they have performed over a longer period of time.

The German Development Cooperation (Deutsche Gesellshaft für Internationale Zusammenarbeite, GIZ) in cooperation with Australian AID, have assisted the Vietnamese with assessing the severe ongoing coastal erosion and shoreline retreat taking place along the west coast of the Kien Giang province north of Ca Mau (Figure 1). In this connection, they proposed and tested out a cost-effective system for protecting against erosion and loss of Mangrove forest. The main element of the system was to build double rows of fences made of Melaleuca trees in shallow water some tens of meters into the sea.

The test areas performed well, reduced coastal erosion, and allowed re-establishment of mangrove seedlings on the inside of the fences, GIZ (2012).

2.2 From satellite imagery

NGI used Landsat satellite data to map coastline change in the Ca Mau area. A total of 203 Landsat TM and Landsat ETM+ scenes from the period 1989-2012 were analyzed. The ground spatial resolution of this data is 30 m. Coastline change between Jan. 31, 1989, Sept. 8, 1999 and March 3, 2012 were assessed.

Table 1 summarizes interpreted coastline changes for some typical locations shown in Figure 2). The pattern of change is diverse, however, with generally considerable shoreline retreat along the eastern, southern and south-western shores, and locally accretion or land gain along the north-western side of the Mui Ca Mau peninsula defining the western tip of Ca Mau and Vietnam (Figures 1 and 3). This accretion is clearly a result of sediment transport along the coastline. In the outset, it is also possible that some of the shoreline retreat could be due to coastal erosion.

It should be noted that the data in Table 2 may contain some inaccuracies due to unknown sea state (tidal fluctuations, beach slope) at image capture time.

Table 1 Summary of average coastline changes in Ca Mau

Location	Average coastline change 2012-1989 (in m)
1	-1100 to -1400
2	-600 to -900
3	-400 to -500
4	-300 to -400
5	+550
6	-100 to -150
7	-100 to -150
8	+1300 to +1700
9	+1200
10	+10 to +50 (oscillating)
11	+10 to +15 (oscillating)
12	-100 to -200
13	-200 to -240

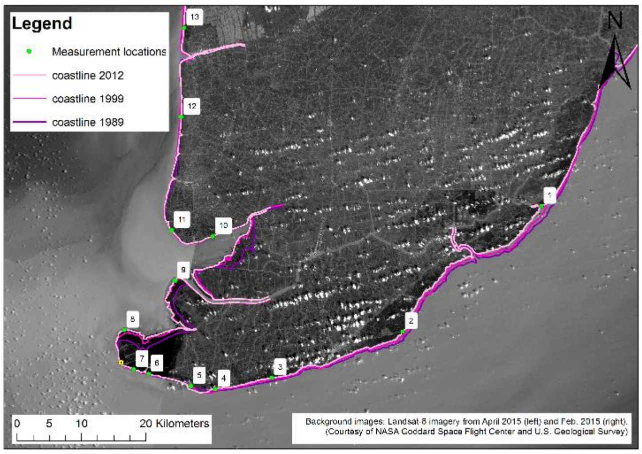


Figure 2 Location of positions with quantitative coastline change measurements in Ca Mau given in table 1

3. PROCSSES CONTRIBUTING TO COASTLINE CHANGES

The observed erosion and coastline changes along the Ca Mau coast could have several causes such as: accelerating sea-level rise; land subsidence; more severe storm surges, stronger sea currents. All factors influence coastal morphology by changing sediment flow and suspension leading to erosion or sedimentation. The following discusses briefly the different potential causes.

1) Vietnam is one of the countries in the world that seems most severely affected by an accelerating sea-level rise (Dasgupta et al.. 2007). Measurements at the East coast of Vietnam (Hon Dau) showed a sea-level rise of 3 mm/year between 1993 and 2008 and a rise of 20 cm in the last 50 years (MONRE, 2009). The flat areas in Ca Mau are particularly exposed. In combination with the observed subsidence (see section 4), sea-level rise is assumed to contribute to shoreline retreat, increased salinity or salt water intrusion and apparent rising groundwater tables in Ca Mau's coastal areas.
2) Extreme storm and storm surge events caused by typhoons occur only occasionally, since Ca Mau is not in the main area of the Pacific typhoon tracks. However typhoons in combination with sea-level rise might cause waves up to 4-5 m leading to severe damage, including erosion if they occur (IMHEN, Ca Mau PPC, 2011).
3) A more continuous influence on erosion results from storm surges, mainly caused by surge from seasonal constant monsoon winds and their changing direction. There are two monsoon seasons in southern Vietnam: (i) SW-monsoon (wet, affects the West coast of Ca Mau with north-bound currents) and (ii) NE-monsoon (dry, affects the East coast of Ca Mau). The SW-monsoon causes waves of up to 1 m at the West coast, the NE-monsoon waves of up to 2 m at the East coast of Ca Mau. Sea-level rise is supposed to increase storm surge heights to over 1 m, leading to e.g. overtopping of dikes (IMHEN, Ca Mau PPC, 2011). Since the monsoon causes alternating surge, waves and currents this may lead to erosion along the Ca Mau coastline (Cat et al. 2011). Beyond that Cat et al. (2011) found that besides the monsoon induced sea states, irrigation and flood discharge in canals cause sediment deficits in some areas, increasing coastal erosion rates.
4) It is most likely that the shoreline retreat rate in Ca Mau has recently increased due to a combination of several factors, such as subsidence, sea-level rise, and changing wave and wind climate. As suggested in the next section, subsidence due to groundwater pumping is likely the main cause of the problems. However, also other anthropogenic factors like water management (canals or irrigation) or coastal protection (hard structures) may have local effects on erosion and accretion. Further investigations on the local wave characteristics and sediment dynamics in the near-shore zone (e.g. high resolution modeling) would be required to verify this.
5) With regard to observed changes in salinity, many Ca Mau farmers have converted from rice to shrimp farming, while ignoring the degradation of the aquatic environment. Measurements of the seasonal variations in salt water intrusion in one district indicate that salinity can no longer be washed out completely in one season. It is concluded that salinity and suspended solids in the aquatic environment in the Cai Nuoc district are increased by shrimp monoculture (Tho et al.., 2006).

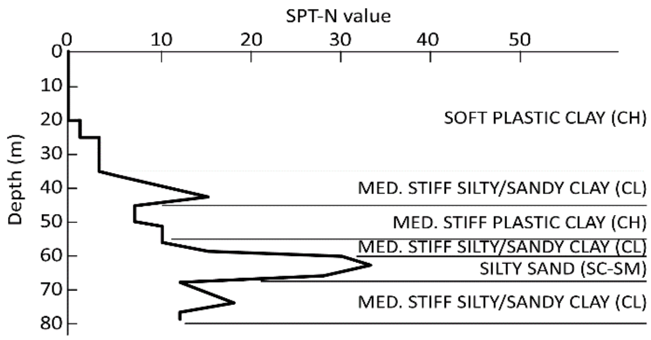


Figure 3 Soil section Sau Nan Bridge Ca Mau (Based on data from Fugro Vietnam, 2012)

Table 2 Selected cases of subsidence due to groundwater pumping

Location	Maximum subsidence (m)	Period	Max. recent subsidence rate (cm/yr)	Reference
Mexico city	> 13 m	≈1900-2010	≈40	Ortiz-Zamora et al. (2010)
Taipei	2 m	1955-88	0	Woo and Moh (1991)
Bangkok	≈ 2 m	1933-2002	3	Phien-wej et al. (2005)
Jakarta	4.1 m	1972-2010	28	Abidin et al. (2011)

4. POTENTIAL SUBSIDENCE DUE TO GROUNDWATER PUMPING

4.1 Past experiences

Subsidence or settlement of the ground surface due to groundwater pumping is a very well known problem that is- or has been-experienced many places around the world. Examples from cities like Mexico City, Taipei, Bangkok, Shanghai, Tokyo, Manila, Jakarta and New Orleans are well known and widely published. Other examples of larger land areas severely affected are the Netherlands, the regions around the outlets of the Brahmaputra and Ganges rivers, and the San Joaquin Valley in California. Table 2 summarizes subsidence data from a few selected cases. The subsidence is as large as up to about 13 m in or around Mexico City, and locally the subsidence rate is still as large as 40 cm/yr. Bangkok and its metropolis has reached a subsidence of up to about 2.0 m, and some areas still subside at a rate of up to 3 cm/yr. The cities of Shanghai, Taipei and Tokyo have experienced subsidence up to 3 to 4 m, but the subsidence was stopped due to enforcement of severe restrictions on groundwater pumping.

Subsidence of so far somewhat smaller magnitude, has also in recent years been observed in and around Hanoi and Ho Chi Minh cities in Vietnam (e.g. Nguyen and Helm, 2000; Tien, 2012). According to Royal- Haskoning-DHV and Deltares (2013), ongoing subsidence in many areas around Ho Chi Minh City is larger than the predicted rate of sea-level rise.

The subsidence problem is often most severe where there are soft compressible clays capping deeper sand or gravel aquifers from which groundwater pumping takes place. Pumping from such confined aquifers will rapidly cause a reduction in pore pressure at the bottom of the capping layer. A reduction in pore pressure at the base of the soft clay layer will with consolidation spread upwards through the layer. The rate of pore pressure reduction and the volume change and settlement it will cause, is a rather classical geotechnical consolidation problem. If the permeability of the clay is constant with depth, and there is some supply of surface water from rainfall or other sources at the top, the final equilibrium pore pressure will be represented by a linear distribution from zero at the upper groundwater level, to whatever drawdown is caused at the bottom of the clay layer.

The amount of, and time for, consolidation settlements to occur, is governed by the thickness of the layer, and variations in volumetric compressibility and permeability of the clay with depth and with effective stress changes imposed.

4.2 Ground conditions in Ca Mau

There exists limited data on soil conditions in Ca Mau, but Fugro Vietnam (2012) provided some information about what they thought could be quite typical general soil conditions, taken from a site at the Sau Nan Bridge in Ca Mau. As illustrated by Figure 3, there is in general an upper capping soft clay layer, which may extend to depths of 20 to 40 m (35 m in Figure 3), underlain by interbedded layers of medium stiff silty/sandy clay and silty sands extending to very large depths (several hundreds of meters).

Fugro Vietnam (2012) have indicated that the upper plastic soft clay layer has a water content in the range of 70-100 %.

4.3 Observed pumping rates and groundwater pressures

MARD and the Division of Water Resource Planning for the South of Vietnam (DWRPIS) have provided some data on the extent of groundwater pumping in the province of Ca Mau in 2012. In total, there are 109,096 wells within Ca Mau, and the total amount of groundwater pumped out corresponds to 373,000 m^3/day (Nguyen et al., 2009). Private shallow wells, pumping just a few m^3/day represents the largest number of wells, but there are also a number of up to about 200 m deep wells that supply water to the most densely populated areas, and local industries.

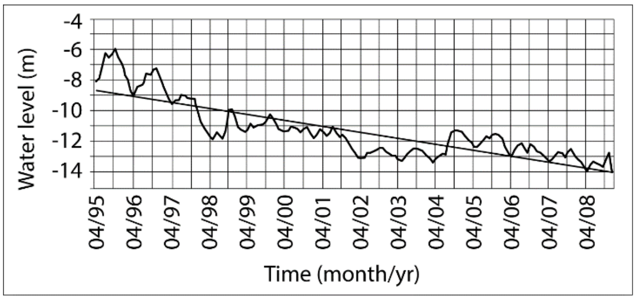
The province of Ca Mau has a total surface area of about 4,350 km^2. The capping soft clay layer will strongly limit vertical recharge of surface water to the aquifers where pumping takes place. The upper capping soft clay layer also seems to extend way beyond (tens of kilometers) the borders to surrounding provinces. Even if the aquifers consist of sands with much higher permeability than the capping clay, the lateral recharge of groundwater through these layers will be small compared to the total rate of extraction. As an upper bound estimate, the average subsidence rate in Ca Mau may therefore, be calculated as the total pumping rate divided by the gross area of the province. That leads to an average subsidence rate of 3.1 cm/yr.

The report by Nguyen et al. (2009) also include data on measured drawdown of water level from within the aquifers that pumping takes place. Figure 4 shows three examples of measured drawdown in observation wells in the aquifers. These three sealed-off observation wells extended to depths of about 90, 136 and 166 m, respectively. The data suggest a rather steady decline in drawdown over the period 1991 through 2008, as indicated by the straight lines in Figure 4. At the end of 2008 the drawdown was measured to lie in the range 10 to 19 m. The charts show, however, that there was a drawdown of 3 to 7 m already at the start of measurements in 1991.

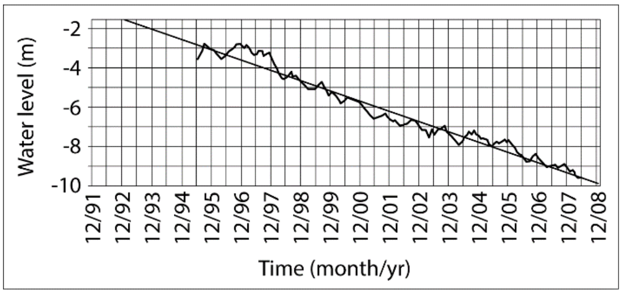
4.4 Calculated consolidation settlements

As part of the study, NGI performed analyses of possible consolidation settlements within the upper capping soft clay layer. The purpose being to get a better estimate of, not only the rate of subsidence settlement, but also the total settlements in the region up until now, and how it may develop in the future. The finite difference based 1-dimensional consolidation program Geosuite-Settlement (Vianova GeoSuite AB, 2013) was used for the analyses. The following main assumptions formed the basis for the analyses:

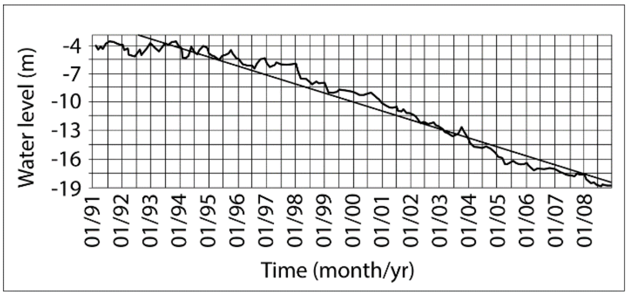
- A thickness of the upper capping soft clay layer was assumed to be 20 or 40 m.
- The clay, below an upper thin crust, was assumed to have a water content of 75 % and total unit weight 15.5 kN/m^3. Figure 5 shows the assumed in-situ pore pressure, u_0, and vertical effective stresses, σ'_{v0}, for a 40 m deep profile.
- The upper soft clay layer is in geologic terms assumed normally consolidated, but is assumed to show an apparent pre-consolidation pressure due to long-term creep effects since deposition (e.g. Bjerrum, 1967) corresponding to an overconsolidation ratio of OCR= σ'_{v0}/p'_c = 1.3.
- The volumetric compressibility characteristics were estimated from empirical correlations to the natural water content presented by Karlsrud, K. and Hernandez-Martinez (2012). The basis for these correlations are oedometer tests on very high quality block samples. The compressibility parameters, as defined in Figure 6, were based on the tangent modulus concept of Janbu (1963). Table 3 presents the settlement parameters actually used, including definitions. Some comments are given to the compressibility parameters. When the reference pressure, p'_r, in Figure 6 deviates from zero, it implies that the classical



a) Observation well Q177020, depth 90m



b) Observation well Q19902, depth 136 m



c) Observation well Q188030, depth 166 m

Figure 4 Example of measured drawdown in water level in observation wells installed in aquifers below the upper soft clay layer (replotted from Nguyễn, K. Q. et al., 2009)

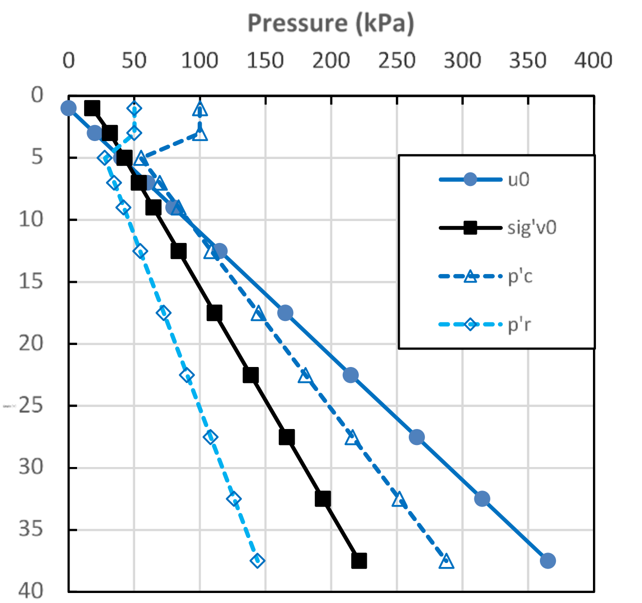


Figure 5 Assumed pore pressure and vertical effective stresses in the settlement analyses (here for 40 m thick capping soft clay layer)

virgin compression index, λ= $C_c/(1+e_0)$, is non-linear when the stress is plotted in the normal log-scale. When p'_r=0, Janbu's modulus number, m, is equal to ln10/λ and λ is constant. The dashed red line in Figure 6 represents an equivalent modulus number, m_0, when it is assumed that p'_r= 0 (meaning also λ is constant) when the applied stress is σ'_{M2}+50 kPa. Data presented by Karlsrud and Hernandez-Martinez (2012) show that all natural marine clays show a rather strong non-linearity when the tested samples are of high quality, which is important to account for in settlement analyses.

- The analyses also include consolidation due to creep, which in the model is assumed occurring in parallel with the primary consolidation process. The Geosuite-Settlement program use the formulations of creep parameters based on the Krycon model by Svanø et al. (1991). A key creep parameter is the time resistance number, m_r, which is related to the more commonly used secondary compression coefficient, C_α, through the expression: $C_\alpha/(1+ e_0)$ = ln10/m_r. Based on empirical creep parameters presented by Mesri and Castro (1987), it was selected a value of $C_\alpha/(1+ e_0)$ = 0.0092.
- The stiffness and permeability of the soil layers below the upper capping soft clay layer is large compared to the upper soft clay layer, and any settlements stemming from these layers was not included in the analyses.
- The reduction (drawdown) in pore water pressure at the base of the soft clay layer was on basis of Figure 4 assumed to have dropped linearly with time to 10 or 20 m reduction after 15 years. Following t = 15 years, the analyses assumes no further drawdown at the base of the soft clay layer. Note in this respect that the data in Figure 4 suggest that the pressure may have continued to drop after 2008. Thus, the settlements predicted could in the future become significantly larger than given by these preliminary settlement analyses.

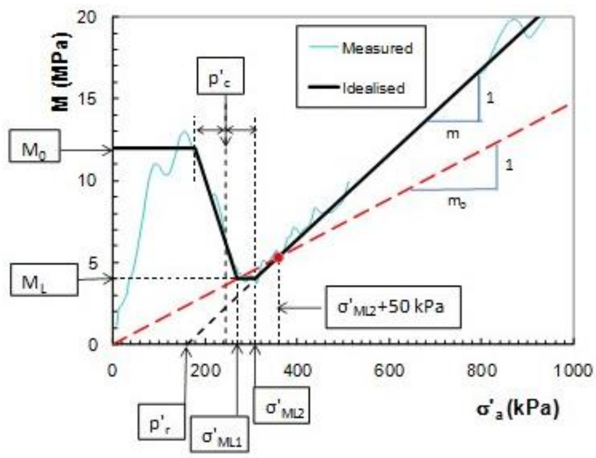


Figure 6 Definition of relationship between tangent oedometer modulus and imposed stress (from Karlsrud & Hernandez-Martinez, 2012)

Table 3 Summary of settlement parameters used in consolidation analyses

Parameter	Value used	Explanation
Modulus in over-consolidated stress range, M_o	$4{\cdot}m{\cdot}p_c$	For loading up to p_c
Modulus number, m	12.5	For loading beyond p_c
Reference pressure, p_r'	$0.5{\cdot}\ p_c$	For loading beyond p_c
In-itu vertical permeability, k_{vi}	10^{-9} m/s	$\beta_k = \dfrac{(log k_1 - log k_2)}{\Delta\varepsilon_a}$
Permeability change index, β_k	4.0	

Figure 7 presents the calculated development of settlement with time for the range of parameters assumed. Figure 8 shows the corresponding calculated average rate of settlement per year. Note that time t=0 in these figures is 15 years back from 2009, i.e. in 1994. The letter H in the figures represents the assumed thickness of the upper soft clay layer and "du" is the assumed reduction in pore water pressure (in m drawdown) after t=15 years and following years.

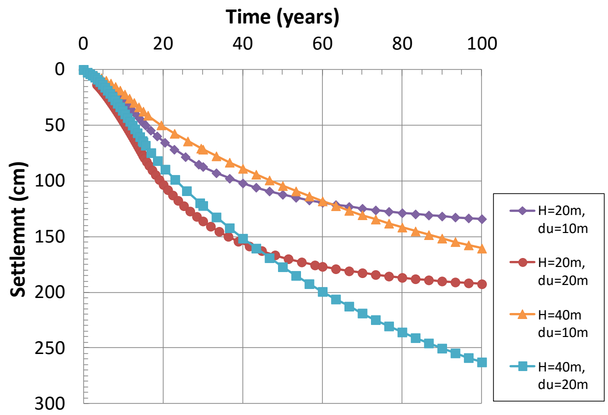


Figure 7 Summary of calculated consolidation settlements versus time for the upper soft clay layer. (Time t=0 represents year 1994)

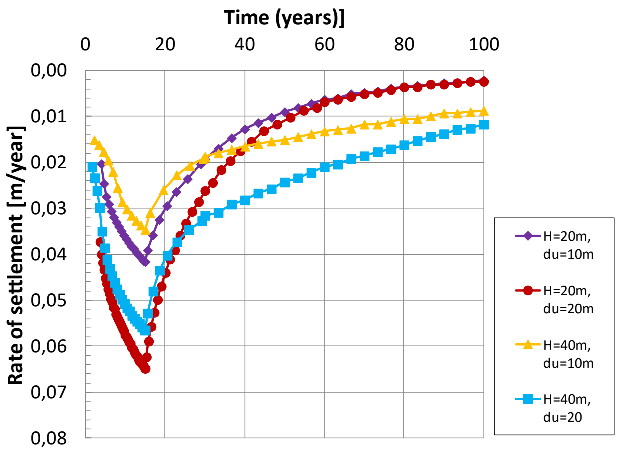


Figure 8 Calculated rate of settlement versus time (Time t=0 represents year 1994)

The analyses show that after t=15 years, the predicted settlement of the ground surface is already as large as 30 to 80 cm. Within the next 25 years (t=40 years in the figure) the predicted settlement will have increased to 90 to 150 cm, and further to 120 to 210 cm 50 years ahead (t=65 years).

There are still significant uncertainties with respect to the predicted consolidation settlements. A main uncertainty lies in if, or to what extent, the drawdown measured in the aquifers from where pumping takes place, have already reached the bottom of the upper soft clay layer. New piezometer installations to measure groundwater pressures at different levels, coupled with settlement measurements, are essential to verify the situation. Such a measurement program should not only cover representative locations across the Ca Mau province, but all the southern provinces in Vietnam shown in Figure1.

The lower range of predicted settlements in Figures 7 and 8 may be most representative for the present situation. Note however, that any settlement arising from soil strata below the capping soft clay layer are so far neglected, which would add to the predicted settlements. With increased rate of groundwater pumping the potential for settlements would also increase significantly beyond the present predictions. There are also likely to be significant local variations in settlements due to variable soil conditions and variable rates of pumping and drawdown across the province.

In a recent paper, Erban et al. (2014) have also presented an assessment of subsidence settlements, and tied that to observed average drawdown rates in the aquifers (e.g. Figure 4), They also used 1-D models to assess settlement rates, but assumed that all settlement occur in parallel with the drawdown. The soil parameters used in these analyses were based on empirical and simplistic constant modulus values as often used for aquifer "compaction analyses" by geologists (meaning consolidation analyses in geotechnical terminology). On this basis, they predicted a subsidence rate in Ca Mau province ranging from about 1.5 to 3.0 cm/yr for the average rate of drawdown experienced in the different observation wells.

Across the province of Ca Mau there may be significant variations in soil stratigraphy and in the compressibility and permeability of the different main soil units. In a paper by IUCN (20111) it was shown a cross section along the Bassac River about 50 km NE of the province of Ca Mau. Here sandy soils were dominating down to depths of about 400 m, but included continuous "capping" clay layers in between the sandy layers.

When a better picture of the variations in soil stratigraphy across Ca Mau, as well as the other provinces in southern Vietnam is established, one will be in position to undertake more comprehensive geo-hydrological aquifer modelling of the impact of the ongoing groundwater pumping. Minderhoud et al (2015) suggested a framework for such aquifer modelling. It is important to calibrate such models against subsidence and reduction in groundwater pressures observed so far. The model can then be used to predict future scenarios, and how they depend on the future rate of pumping in different areas. It is still a shortcoming of most geo-hydrological models that they do not correctly model the time-dependent consolidation of soft soils. To get a correct prediction of subsidence it is necessary to supplement geo-hydrological modelling with soil mechanics based consolidation analyses.

4.5 Verification of subsidence from InSAR data

Erban et al. (2014) also presented assessment of ongoing settlements using satellite based InSAR technology (Interferometric Synthetic Aperture Radar). The SAR technology is based on registration of travel time for radar arrays sent from a satellite to reach the ground, and being reflected back and registered at the satellite. Changes in travel time registered during different passes of the satellite over the area of interest, makes it possible to calculate changes in elevation of an area of the ground. Use of InSAR for detecting ground movements has increased considerably over the past 20 years or so, partly due to improved accuracy and more satellite operators offering such data.

Figure 9 presents the InSAR results from Erban et al. (2014) in the form of average settlement rates based on satellite data for the period 2006-2010. The data confirm that significant subsidence is on-going, not only in Ca Mau, but in all southern provinces in Vietnam from Ho Chi Minh City and southwards to Ca Mau. The maximum subsidence rate observed in the Ca Mau province is according to Figure 9 about 3 cm/yr, which is of the same order as estimated above from analyses of effects of groundwater pumping. Note in Figure 9 that areas only depicted in gray colors are without reliable data. This is due to poor backscatter from rural areas with limited "hard" surfaces to reflect the radar arrays.

4.6 Potential consequences of predicted subsidence

The ground surface elevation across large parts of the Ca Mau province lies below Elevation +1.0 and +1.5. The consequences of settlements of the order as indicated above would therefore within a few years time be catastrophic for the Ca Mau province, and the whole area would eventually be lost to the sea if counteracting measures are not rapidly implemented.

The calculated subsidence settlements are most likely the main explanation for the apparent shoreline retreat observed along part of the Ca Mau coastline in recent years. The same applies to enhanced salt water intrusion and loss of Mangrove forest.

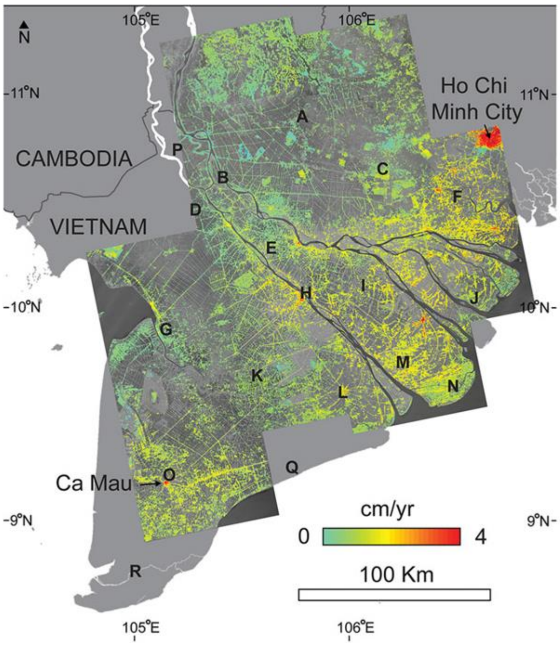


Figure 9 InSAR based average rates of land subsidence in southern Vietnam, time period 2006- 2010. Data © JAXA, METI 2011 (After Erban et al., 2014)

The severity of this potentially catastrophic scenario enhances by the likelihood that all the southern provinces in South Vietnam (Figure1), south of Ho Chi Min City, probably suffer from similar groundwater pumping and subsidence. At present about 24 million people live in these provinces. Without expedient actions to reduce groundwater pumping and the ongoing subsidence, the livelihood in these areas are at high risk. At present, the southern provinces stand for a very large portion of Vietnam's total agriculture and aquaculture production, as well as export of such products. With such a large loss of fertile land, Vietnam as a nation would also suffer severely.

5. RECOMMENDED ACTIONS

As part of the study presented herein, NGI has proposed a series of activities to get a verification of past and expected future subsidence caused by the on-going groundwater pumping. This included the following main activities:

1) To undertake a program of ground investigations to identify major soil units down to a depth of about 200 m, and how the thickness of the units vary across the Ca Mau region. The site investigations should be based on a combination of Standard Penetration Tests (SPT), piezocone tests (CPTU) and Shelby tube sampling. Retrieved soil samples should be subjected to routine type classification tests as well as oedometer test to determine compressibility and permeability characteristics of the different soil units.
2) Implementation of a monitoring system to document on-going subsidence settlements, as well as to get data on pore pressures within the main soil units affected by groundwater pumping across the region. Subsidence measurements could primarily be based on collection of InSAR data, but it should be coupled with physical measurements at selected locations. This will require installation of deep benchmarks (to about 200 m depth) combined with surface settlement platforms. Vertical extensometers would also be useful to identify or verify what soil units that contribute mostly to settlements.
3) Undertake 3-D global and local time-dependent aquifer analyses. This should be based on the soil data established from activity 2) and available groundwater pumping data. The aquifer analyses should be supplemented by 1-D consolidation analyses with focus on determination of time-settlement response of the upper capping soft clay layer.

Due to the rapid developing subsidence settlement, the Vietnamese authorities are encouraged to continue its efforts to implement remedial measures. The authors are aware of the concern that the Vietnamese government has in terms of sustainability of the current land use in Ca Mau and the livelihood of its people. Remedial measures that are on the list include: alternative sources of fresh water supply, introducing water-saving techniques to aquaculture farmers and introduction of pricing mechanism for fresh water supply including extraction of groundwater.

Monitoring, processing and dissemination of land subsidence information are demanding tasks. This because it needs an integrated approach to reach a diverse group of stakeholders and decision makers. Land subsidence has clearly a multi-sector perspective. The proposed monitoring system will provide the authorities with a tool that can quantify the subsidence development by concrete numbers and thereby be a useful tool in policy decisions for designing the necessary remedial measures.

In the opinion of the authors, only restriction on groundwater extraction can in the long run, save the region from a very unfavorable development. Supply of alternative clean water is certainly a challenge. Supplying water to farmers via pipelines or canals as a part of the Mekong Delta Irrigation Plan has been introduced as a possible option. On a scale like this, construction of a series of water purification plants along the existing rivers and canals might be another solution. Both solutions will be challenging in terms of cost, logistics and time to get the water distributed to local farmers, people and industries. The time element in itself is of great concern, considering the rapid unfavorable subsidence development.

If groundwater extraction continues at the present level, the only realistic alternative to save Ca Mau will be to start constructing dikes and polders along the coast and throughout the region like in the Netherlands. This will require large pumping facilities, and probably large tidal locks at some of the Mekong river delta outlets.

The problems with subsidence and shoreline retreat due to groundwater pumping that Vietnam is facing, are further enhanced by the expected climate change driven sea-level rise. The most recent report from the climate panel (IPCC, 2014) indicate that the sea-level around Vietnam by 2100 may increase by about 40 cm if actions are taken to limit global temperature increase to 2^0C, and about 80 cm if nothing is done to reduce present emission levels. To save the southern provinces of Vietnam from the impact of sea-level rise may therefore, in any case require planning for construction of some protection dikes and polders in the region, but at a much smaller scale than if subsidence induced by groundwater pumping is allowed to continue.

6. CONCLUSIONS

The study presented herein suggest that the Ca Mau province has experienced a retreat of the shoreline ranging from about 100 m to 1.4 km over the past 20 years or so. In addition, the Ca Mau coastline has experienced loss of mangrove forests and salt-water intrusion into canals and rivers in the region.

There is strong evidence that the ongoing groundwater pumping causes significant subsidence settlements in the entire Ca Mau province. Both InSAR data, and settlement analyses suggest that the present rate of settlement is at least up to 2-4 cm/yr, and that total subsidence settlements already may reached up to 40-80 cm in places. Such settlements may largely explain the observed retreat of the shoreline. Climate change related sea-level rise would add further to the subsidence related changes.

If the ongoing extensive groundwater pumping continues, in a few decades the subsidence may exceed 1.5 m. As large parts of the land areas in Ca Mau lie less than 1.5 m above sea-level, such subsidence will have very serious consequences. The severity of this scenario enhances by the likelihood that all the provinces south of Ho Chi Minh City probably suffer from similar groundwater pumping and subsidence. At present, about 24 million people live in these provinces. Without expedient actions to reduce groundwater pumping and the ongoing subsidence, the livelihood in these areas are at high risk. The only realistic way to prevent such subsidence settlements is to greatly reduce groundwater pumping in the area, and replace it with water from other sources, for instance purification plants. In addition, also in light of expected sea-level rise due to future climate-change, physical barriers and dikes to protect the region will likely be required.

Establishing an observational program, combined with soil investigations and more in-depth analyses of present and future subsidence settlements should be undertaken to verify the situation. This to ensure that remedial actions are planned for, and implemented, before it is too late.

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