Can Tho University Journal of Science
website: sj.ctu.edu.vn

DOI: 10.22144/ctu.jen.2018.023

Land subsidence modeling in the Mekong Delta: A case study in Soc Trang and Can Tho city

Nguyen Dinh Giang Nam[1*], Goto Akira[2] and Osawa Kazutoshi[2]

[1]*College of Environment and Natural Resources, CanTho University, Viet Nam*

[2]*Department of Hydrological and Environmental Engineering, Utsunomiya University, Japan*

**Correspondence: Nguyen Dinh Giang Nam (email: ndgnam@ctu.edu.vn)*

Article info.

Received 29 Nov 2017
Revised 14 Apr 2018
Accepted 20 Jul 2018

Keywords

Land subsidence, Mekong Delta, Rheology model, Three factors

ABSTRACT

In this study, the three-factor rheology model was applied to simulate land subsidence associated to the groundwater decline in the urban area (Can Tho) and the coastal area (Soc Trang) of the Mekong Delta (of Viet Nam). The considered three factors including (1) the elasticity coefficient, (2) the viscosity coefficient of the Voigt part, and (3) the viscosity coefficient of the Damper part, were calibrated to get the matching with limited observed values. As the results, the long-term transient simulation in the period of 2000-2013 showed that the land subsidence rate in Can Tho city was around 2.6 cm/year. For the coastal area, transient simulation showed that the cumulated subsidence for the period of 1994-2014 was 65 cm which means around 3 cm per year. To maintain the groundwater pumping under future rainfall condition, another 60 cm of land subsidence was expected over the next 21 years in the coastal area. To understand the subsidence under increase in pumping (1.8% per year), the cumulative land subsidence in the period of 2014-2035 was estimated around 71.4 cm at the coastal area of the Mekong Delta.

Cited as: Nam, N.D.G., Akira, G. and Kazutoshi, O., 2018. Land subsidence modeling in the Mekong Delta: A case study in Soc Trang and Can Tho city. Can Tho University Journal of Science. 54(5): 45-51.

1 INTRODUCTION

It has been reported that most of land subsidence in the low-lying land have been caused by excessive groundwater (GW) extraction. From 1960s to 1970s in Japan, a huge amount of GW was taken to satisfy the growing water demands for industrial and domestic water use, and it had resulted in serious land subsidence in the urban areas such as Tokyo and its surroundings (Nakajama *et al*., 2010). In order to avoid the risk of the land subsidence, the Japanese government implemented the regulation on GW use in the urban areas, in which the national government tried to control major GW use, and the surface water use was promoted, such as lake, water storage and water saving technologies. After this regulation, land subsidence has now mostly stopped in Japan.

When looking at the Mekong Delta of Viet Nam, it is most likely that the rapidly growing GW use may cause serious land subsidence also in Mekong Delta (Philip *et al*., 2017). Particularly because of its vast low-lying land feature, land subsidence in the Mekong Delta may lead to decisively serious devastation. Relationship between GW level decline and the rate of subsidence has been observed for recent five years in various places in the Mekong Delta. GW pumping is resulting in subsidence at levels affecting the existing management area and additional land use planning (Phien-wej *et al*., 2006). The land subsidence can cause other associated problems, such as changes in elevation and gradient of stream channels, ill drainage, other water transporting facilities, damage to civil engineering structures, private and public buildings. Especially, the salt intrusion in the coastal area, sea level rise along the east coastal area of the Mekong Delta have also been observed for several times and has averaged 2.9 mm/year (MONRE, 2012). A combination of sea level rise and land subsidence could cause a serious increase in frequent flood inundation and result in tidal encroachment onto lowlands in a coastal community (MONRE, 2012).

For such serious risk of land subsidence, observation of land subsidence in the Mekong Delta has so far been very poor (Minderhoud *et al.*, 2017). Thus, to understand the land subsidence issue, the first attempt in this study performed the modeling of land subsidence due to GW withdrawal and its application to the Mekong Delta.

A three-factors Rheology modeling of subsidence has been performed, with particularly concerning the case study in the middle and coastal areas of the Mekong Delta. The areas of modeling, Can Tho city and Soc Trang city, are interested cases by a lot of water supply wells. GW withdrawal for domestic, industrial and agricultural employment has induced remarkable ground surface settlements (Phien-wej *et al*., 2006). The model parameters were optimized by the Interferometric SAR (InSAR) for 5 years (2006-2010) (Minderhoud *et al*., 2017).

2 METHODOLOGY

2.1 Modeling approaches

The thickness of a confined aquifer is maintained with the balance between the outer pressure from the gravity of the upper soil layers and the inner pressure of the aquifer water. Therefore, the reduction in the inner pressure caused by the extraction of GW from the confined aquifer will cause the contraction of the thickness of the aquifer. That is the process of land subsidence, and it is considered a phenomenon containing both reversible and irreversible factors. Namely, the recovery of land surface elevation cannot catch up with the recovery of GW level to the past level. For example, in the correspondence between the seasonal fluctuation of GW level and that of land surface elevation, even if the GW level returns to the same level as the past, the land surface elevation cannot be back to the past level.

For such partly irreversible phenomena, it is known that the theory of rheology is effectively applicable, where the reversible factor is expressed by elasticity, and the irreversible factor is expressed by plasticity or viscosity. Here in this study, the three-factor Rheology model to be mentioned below was employed to simulate the land subsidence in the Mekong Delta.

2.2 Rheology theory

The aim of rheology is to examine the influence of a load on work of various materials considering also of the duration of such a load. The name rheology originates from Greek words rheo (flow) and logos (science). Sometimes rheology is treated as an independent field of science that encompasses such special issues as resilience theory, plasticity theory, or mechanics of viscous liquids. Models of the aforementioned ideal materials are treated as special cases of a more general rheological model. Such a division is a result of the interdisciplinary significance of rheology.

Materials exhibiting rheological properties are subjected to the same general laws of mechanics as the rest of materials. Differences in their mathematical description lie in formulating appropriate constitutive equations which include an additional independent variable: real time.

Rheology is of a huge practical significance in numerous fields of technology, including compression of soil analysis. Therefore, Rheological properties are exhibited by soil characteristics. Those properties become visible to various degrees depending on the type of soil and conditions of any given soil or land.

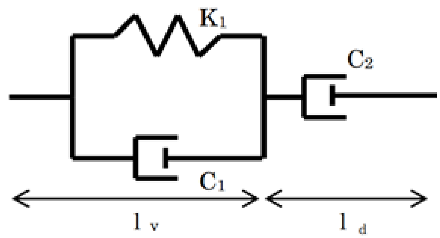

Fig. 1: Three factor Rheology Model

2.3 Three factor rheology Model

Rheology model, the simple structural model, which aims to interpret fundamental properties of materials in terms of physics, is used in the literature on rheology. A spring is a model of an elastic material that subjected to the Hooke's law. As a model of viscous liquid, it is possible to consider a silencer, presented as a perforated piston moved in a cylinder filled with viscous liquid. As a result

of the applied force, the silencer performs a movement, velocity of which is proportional to the amount of the force. A parallel combination of an elastic element and a viscous one forms a model of viscous-elastic material (Kelvin-Voigt) (Fig. 1).

A three-factor Rheology model was developed to estimate land subsidence caused by excessive GW exploitation (Nakajama *et al*., 2010; Morita *et al*., 2014). GW-related subsidence is the subsidence (or the sinking) of land resulting from GW extraction, and a major problem in the Mekong Delta as rapid urbanization zones and developing areas without adequate regulation and enforcement, as well as being a common problem in the developing countries. One estimate has 80% of serious land subsidence problems associated with the excessive extraction of GW making it a growing problem throughout the world.

In order to express the characteristics of ground subsidence, using a three-element model that can designate the amount of return displacement and residual displacement independently. The concept of the three-factor model consists of the Voigt part and the damper part, which are characterized by following parameters:

(1) The elasticity coefficient K1 and the viscosity coefficient C1 of the Voigt part;
(2) The viscosity coefficient C2 of the damper part.
The equations of the model are as follows:
The force acting on Voigt section: fv = - K1 (lv - L) – C1 lv
Force acting on damper part: fd = - C2 ld.
Balance of forces: f = fv = fd;

This differential equation was solved using the Euler method. The value of f represents the relationship between the GW level and the ground force with:

f = ground pressure - GW level (pressure head)

Balance of length: L = lv+ ld. = (K1 (L - lv - f)/C1 - f/C2

Where lv (m) is the length of the Voigt part, ld (m) is the length of the damper part and L is the total length (m); For applying it to land subsidence, the thickness of the soil layer is represented by "L"; GW level is interpreted to the working force on the soil layer

2.4 Scenarios setting

To build the scenarios for modeling in Soc Trang, the rainfall series generation was conducted. The rainfall observed at the meteorological station in Soc Trang city was selected as the representative to be used for simulating the GW levels from the past to present (Nam *et al*., 2017). Meanwhile, the precipitation forecast for the future was estimated by the downscaled Global Climate Model (GCM) model for the whole Mekong basin with a resolution of 20 km x 20 km up to 2035, which was downscaled using PRECIS from the GCM by the Southeast Asia START Regional Center. However, there were significant differences between the observed rainfall and the model estimates for the present condition. Therefore, based on the Bias correction method (Piani *et al*., 2009), the rainfall series for the future 21-year period (2015-2035) was adjusted by considering the difference in the present 20-year period (1980-1999) rainfall series.

Table 1 shows the combination of the two GW management options and the two future climate conditions produces 3 possible cases with the following focusing: (i) the current rainfall condition (1994-2014) and GW management of Driver 1 are assumed for baseline case—the status quo scenario (A1); (ii) The future rainfall condition predicted by GCM for the medium emission is assumed with the GW management of Driver 1 for B1, Driver 2 for B2.

Table 1: Drivers and scenario assumptions

Scenario	Driver	Assumption
	Management options	***GW abstraction***
1	Baseline situation	Abstraction is maintained
2	Increased supply	Increasing of 1.8%/year
	Future climate conditions	***Recharged by rainfall***
A	Historical base-case	Recharged by historical rainfall (1994-2014)
B	Future rainfall GCM for medium emssion	Recharge by simulated future rainfall (2015-2035)

3 RESULTS AND DISCUSSION

3.1 Estimation of three factors

To find out the optimized values of three factors: (i) the elasticity coefficient (K1), (ii) the viscosity coefficient (C1) and (iii) the viscosity coefficient (C2) for the model is important to reduce uncertainty in model simulation. In order to estimate these factors for land subsidence model, the type of optimization target is the observed land subsidence of InSAR during the period of five years (2006–2010) for the whole Mekong Delta. Optimization steps are shown in Fig. 2, and Table 2 shows the applicable parameter values of three factors during the adjustment steps.

Table 2: Parameter values at different application

Locations	K1	C1	C2
Previous research in Tochighi, Japan (Morita, 2014)	0.45	0.25	67
Calibrated values for the Mekong Delta, Viet Nam.	0.5	0.35	87

3.2 Simulated land subsidence in the urban area of the Mekong Delta

Fig. 3 shows the relation between GW head, which is measured as GW levels at the long-term observation well in Can Tho city, and subsidence, which is typically analyzed as land subsidence at land surface by the InSAR (Minderhoud *et al.*, 2017). Given the current trend of decreasing GW level, the long-term transient simulation of 14 years (2000-2013) was conducted to find out the current land subsidence situation in Can Tho city. It was found that the cumulative land subsidence in Can Tho city was about 36 cm over the 14 years which means 2.6 cm per year of land subsidence rate.

Because of the limitation of the soil properties testing, a match between simulated and measured subsidence should be improved by the further detailed data for the model (Fig. 4). Thus, it does not necessarily indicate that the factors controlling subsidence are accurately represented by the model

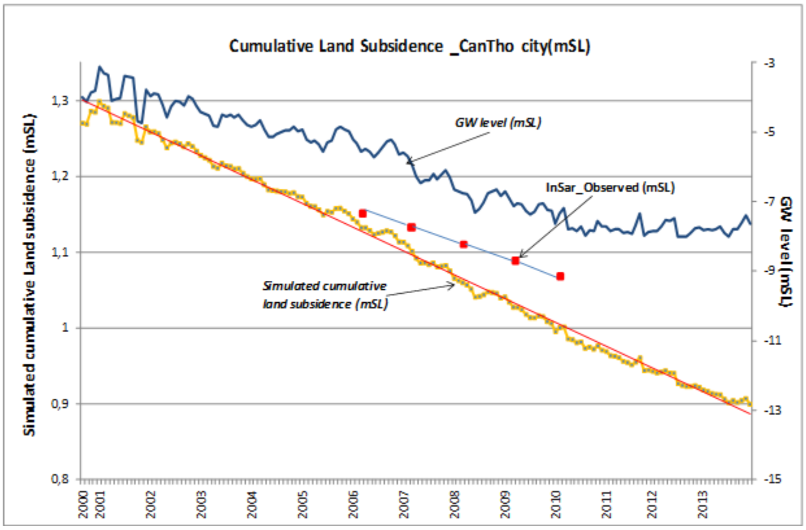

Fig. 3: Long-term transient simulation of cumulative land subsidence in the period of 2000-2013 of Can Tho city

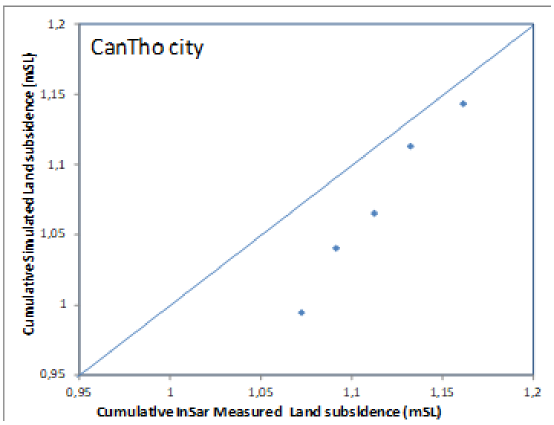

Fig. 4: Cumulative simulated vs. observed land subsidence in Can Tho city

3.3 Simulated Land Subsidence for the coastal area of the Mekong Delta

In the first simulation, the model is applied to estimate land subsidence rate concerning historical observed GW level from 1994 to 2014 and the output modeled GW level of each scenarios in Soc Trang. Fig. 5 shows the current rate of land subsidence is 3 cm per year. It implies that the changes of GW heads in the aquifers, which are confined by thick clay layers, can lead to cumulative land subsidence of about 65 cm. Meanwhile, based on the scenarios development, the simulation for future rainfall (B1) indicated that the land subsidence is lighter than the current by around 2.7 cm per year which means around 60 cm of the cumulative land subsidence. Thus, in increasing recharge condition has smaller subsidence risk than the current. In this case, the model shows a fairly good match between simulation and observed-InSAR from 2006 to 2010 (Fig. 6).

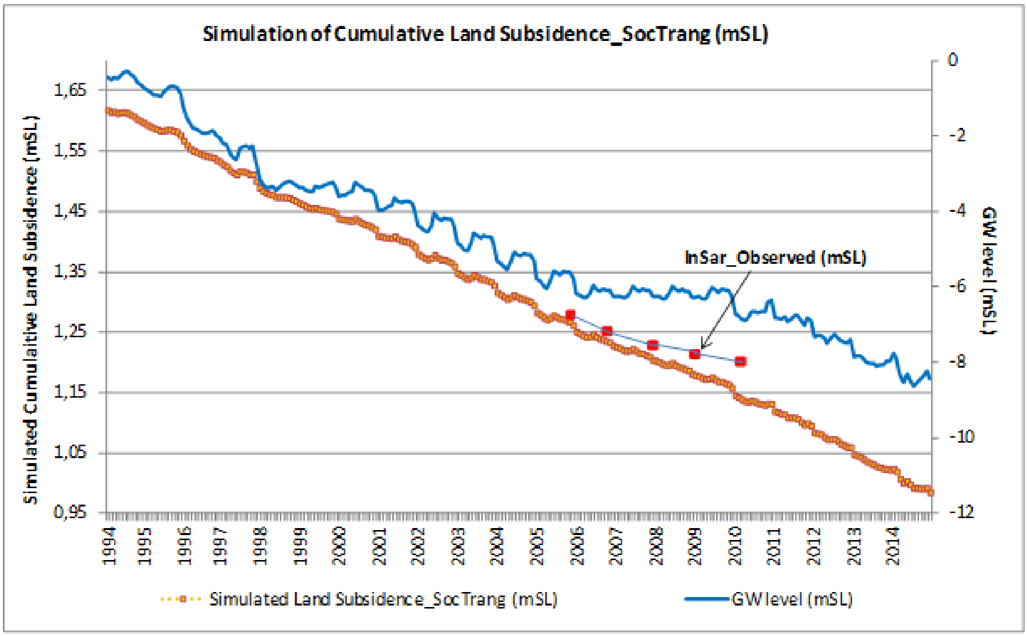

Fig. 5: Cumulative land subsidence in Soc Trang

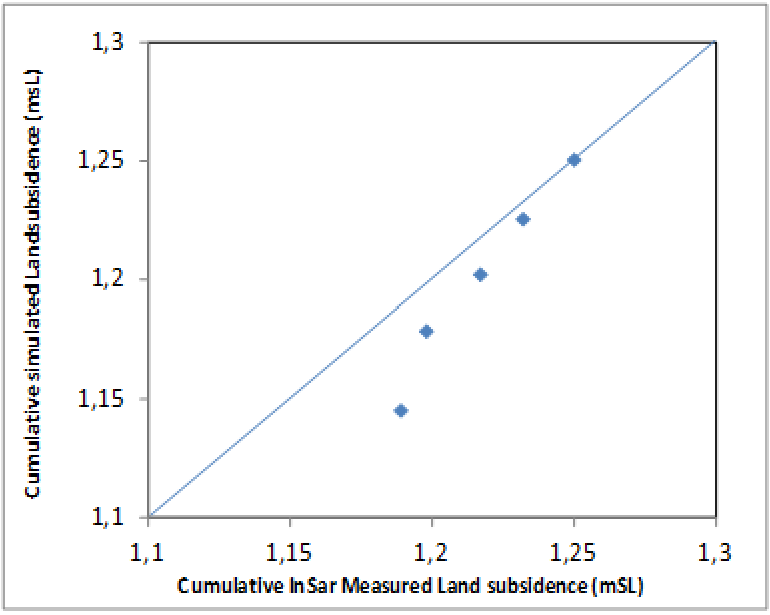

Fig. 6: Cumulative simulated vs. observed land subsidence in Soc Trang city

To evaluate the land subsidence in the next 21 years, the model was applied corresponding simulated GW levels of the scenarios in Table 1 (Nam *et al.*, 2017). For the baseline scenario (A1), if the GW abstraction is kept as the current pumping under current rainfall condition, there will be a land subsidence by around 2.85 cm per year. Meanwhile, the simulation results showed significant land subsidence through the simulation period with the rate of 3.4 cm per year in case of the increasing GW pumping (B2). It implied that if GW abstraction increases, the cumulative land subsidence will be around 71.4 cm in Soc Trang in 2035 (Fig. 7).

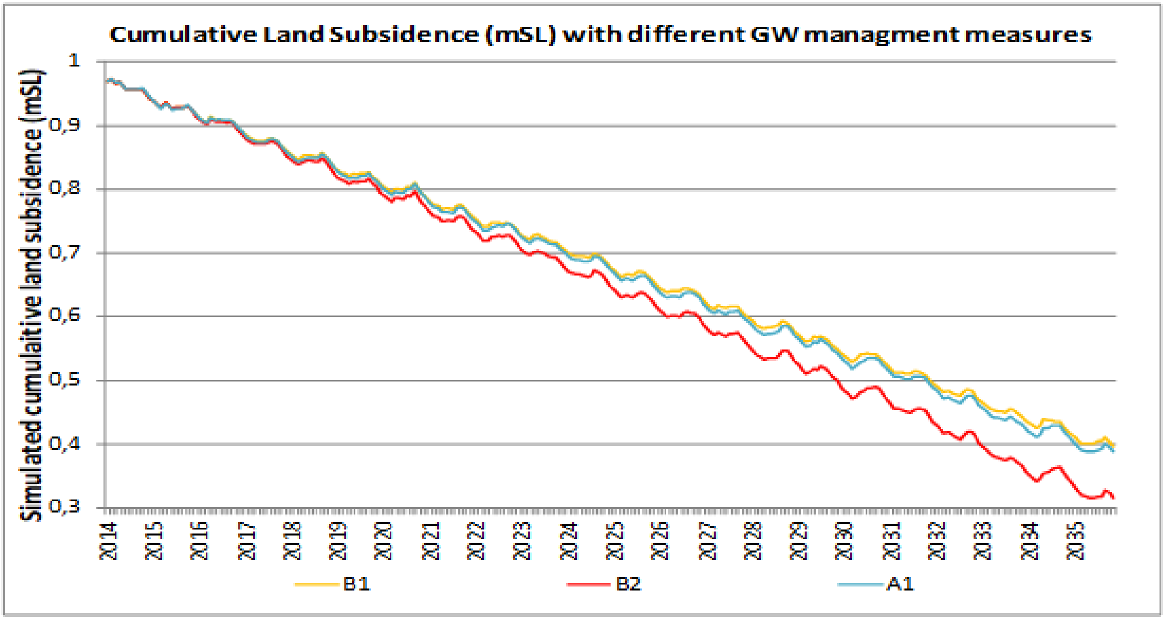

Fig. 7: Simulation of cumulative land subsidence with different GW management and rainfall conditions

From the calculation, it is found that the rate of subsidence is directly controlled by the fall of GW level, the saturated thickness of aquifer, and the hydrogeological characteristics of the aquifers.

As the results, the estimated land subsidence in the coastal area of the Mekong Delta may cause several problems. Potentially the most devastating problem occurs in flat-lying coastal areas where loss of ground elevation may either cause inundation or increase the potential for flooding by tides and storm surges. When flooding becomes severe enough, expensive flood-control works or even abandonment of the affected land become necessary. A second problem may cause when the magnitude of subsidence is large and the subsidence area is small.

3.4 Model limitation

The issues of land modeling are very complex and specific. There is no universal model that would equally consider all properties of the material. Depending on the accepted theoretical model, various models of displacement may be obtained. Land subsidence occurs due to several joint factors such as natural soil compaction, soil compaction due to external load, soil compaction due to water extraction, thickness of the clay, and thickness and content of filling materials. In this study, the model has implemented by theoretical basics of rheological models that are applied when describing vertical land displacements. The simulated rate of land subsidence of the study areas has been calculated based on the lack of observation data. Because of the limitation in availability of the database, the calculation of land subsidence has been done using some average table values as there is a limitation of getting the materials from different depths beneath the surface to test their hydro-geological properties.

4 CONCLUSIONS

The model was calibrated to show the same decline slopes between calculated and observed land surface elevations for each area. The results of model simulation showed that the model can perform well to reproduce the land subsidence though the observed data was very limited. Also, the simulation results as well as the observed data presented well the irreversibility of land subsidence.

However, the model is the first trying of land subsidence evaluation in the Mekong Delta under limited data. Thus, some recommendations are as follows:

(i) Because GW level declines may influence land subsidence, it is important to monitor, test compile, and interpret them in parallel throughout the entire Mekong Delta.

(ii) It is possible that water levels may not yet have declined below the preconsolidation head in areas where subsidence has not occurred. Subsidence can be simulated in the model only where inelastic storage is specified; inelastic storage was specified only for areas where measurements have shown that subsidence has occurred.

(iii) The one-dimensional indicated that the delayed flow of the soil layers is an important process in the occurrence of subsidence. Therefore, the model applied for this study may simulate subsidence before it actually occurs.

(iv) Because of the hydrodynamic lag and the residual compaction, simulated subsidence might not be expected to match measured subsidence.

(v) The subsidence rate should be monitored to address recent and future subsidence issues as well as improve the accuracy of modeling.

Finally, it is expected that the simulation and prediction of subsidence rates in two case studies are helpful for water and land resource managers, planners, regulators, and administrators to utilize, manage, and protect the Mekong Delta resources.

The irreversibility of land subsidence means the difficulty of recovery from the land subsidence that once has happened. Accordingly, countermeasures to cope with the land subsidence must be taken as soon as possible before the serious problems emerge.

ACKNOWLEDGMENTS

The authors would like to acknowledge Rise and Fall project and Department of Natural Resource and Environment of Soc Trang and Can Tho city for providing data and annual reports

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