Spatial analysis for simulation the changing of inland water depth

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Abstract: Vietnam is one of the most affected countries by the global sea-level rise, in which the Mekong Delta is the most heavily impacted area due to the low-lying position. The study aims to simulate and delineate the changing of elevation by combining spatial geostatistics and Kriging interpolation techniques. The assumption of inland water level increases at different sea-level rise scenarios by interpolating 967 elevations geo-rectified data from the topographic map at 1/250,000 scale. The result showed that the exponential is the best model for interpolation of elevation data, distance A_0 = 585,900 m; coefficient R^2 = 0.985; and residue sum of square = 0.0011. Inland inundated water levels maps with sea-level rise scenarios from 0.2 to 2.8 m were delineated. The submersion started when the water level rose to 0.6 m and the total submerged area gradually increasing; until the water levels rose to 2.8 m, the whole region completely flooded. The submerged areas increase, resulting in the loss of cultivated land and food production. However, further research needs to be considered a more detailed study on population, food production, and tidal due to land loss. This study proved that spatial analysis is an effective tool for simulating surface water levels. It is of great significance for controlling water levels changes in the Delta.

Keywords: submersion, elevation, flooding, spatial interpolation

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1 Introduction

Water is an essential resource for all people and a requirement for good health and sanitation. It is a critical input for almost all production and necessary for sustainable growth and poverty reduction (Grey and Sadoff, 2007). The location of water around the world is a critical determinant of livelihoods. Globally, around 70% of all freshwater supply is used for irrigating crops and providing food, and 22% is used for manufacturing and energy (cooling power stations and producing hydroelectric power). In comparison, only 8% is used directly by households and businesses for drinking, sanitation, and recreation (Tran Thuc et al., 2016; UNCEF and WHO, 2019; U.N. Water, 2020). Moreover, in recent decades, the impacts of climate variability and change have become more evident as the region struggles with intense droughts and floods and changes in rainfall and temperature patterns, which are taking a toll on rural and urban areas (Lebel et al., 2014).

Sea level (S.L.) is an average height level of the Earth's surface of water bodies from which elevation heights may be measured. A common and relatively straightforward S.L. standard is the midpoint between a mean low and high tide at a particular location. S.L. can be affected by many factors and is significantly varied over geological time scales. However, 20th century and current millennium sea level rise (SLR) are presumed to be caused by climate change (Sweet et al., 2017), and careful measurement of

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variations in MSL can offer insights into ongoing climate change (Smears et al., 2018).

According to Hens et al. (2018), the hazards of SLR-related floods increase fastest in urban areas. It is related to the increasing surface of cities expected to occur during the decades to come and the increasing of coastal population. In particular, Asia and its megacities in the southern part of the continent are increasingly at risk. The Vietnamese government (2011) recognized the Mekong Delta as the largest rice basket in Vietnam. About 40% of the Vietnamese population lives in this area, so the effects of climate change through the sea-level rise in this region will affect society and the great economy for Vietnam. Besides, climate change has been concerning to the livelihoods of communities in the coastal plain of the Mekong Delta. Surface water management in the coastal plain was limited, especially in enforcement (Linh et al., 2018). Even as the Mekong Region continues to undergo rapid socioeconomic development and regional integration along with a liberalized market economy, it is facing more intense ecological degradation and damage to its natural ecosystems ever.

The Mekong Delta is fundamentally linked to sea surface levels and changes in the hydrology of the Mekong River. Some 8,000 years ago, at the start of the Holocene, sea levels were in the order of 4.5 m above present levels (ICEM, 2012). Now, sea-level rise (SLR) due to climate change is a serious global threat. The continued increase of greenhouse gas emissions and associated global warming could well promote SLR of 1-3 m in this century, and the unexpectedly rapid breakup of the Greenland and West Antarctic ice sheets might produce a 5 m SLR (Dasgupta et al., 2009). Measurements of sea-level rise are complicated and require precise instrumentation and careful data collection over decades. MONRE (2009), summarizing available data, reports that the rate of SLR in Vietnam has been about 3 mm year^{-1} over the last 15 years. It would be similar to the average global increase in SLR documented by the IPCC. Michael Doyle,et al. (2010) used a 1.8 mm year^{-1} rate for the East Sea for the historical SLR resulting only from estuary (thermal expansion of the ocean), based on data analyses from several stations in the region.

Improved understanding and narrowing of the uncertainties of projected increase at both the global and regional/local level and its impacts are critical elements in assisting society (Church et al., 2010). For example, there are currently many research and models to simulate the rising sea levels that affect flooding in the Mekong Delta. However, those techniques require so much data and complicated methods. In contrast, geostatistics and spatial interpolation are promising techniques in developing the assumptions of changes due to rising water levels, positively evaluating climate change in the Mekong Delta. Otherwise, according to Maroufpoor et al. (2020), humans have always sought to obtain enough information about natural phenomena. In this regard, essential tools were created. However, the restrictions of the tools are important factors that affect the amount of exact gathered information. Efficient mathematical models (e.g., geostatistical and deterministic methods) were developed and recommended to overcome the limitations.

According to Murphy et al. (2010), spatial interpolation methods often apply to estimate values of physical or chemical components in locations where they are not measured. However, very little research has been conducted to investigate the relative performance of different interpolation methods in surface waters. Rakhmatullaev et al. (2011) used the geostatistical approach includes a (semi-) variogram analysis and interpolation (Kriging and simulations -turning bands). In addition, techniques predicting values at unsampled locations for generating digital bathymetric surface models of reservoir bottom conditions for estimating the volume and surface area at a given water elevation are also considered.

The objectives aimed to (1) simulate the changing of elevation by using geostatistics and Kriging interpolation techniques, as the assumption of inland water level changes under sea-level rise. Then, (2) assess the spatial distribution and the impact of the increase of water levels with different assumptions from the simulated results, affecting agricultural land in the Mekong delta. This can assist the decision-maker to have other views in predicting the water level as levels rise.

2 Methods

2.1 Data collection

The Mekong Delta in Vietnam (Figure 1) covers 39,000 km^2 and is home to more than 17 million inhabitants. Despite the rapid economic growth of Vietnam in recent years and essential improvements in agricultural systems in the region. Water can also be directly and indirectly a threat to these livelihoods as, for example, large portions of the Delta are flooding annually. Although people have adapted to this flooding cycle, extreme floods can be highly destructive (Renaud and Kuenzer, 2012).

To simulate the spatial distribution of submerged areas in Mekong Delta for spatial analysis, the collection include:

The collection of elevation data of 967 locations from the topographic map of the Mekong delta at 1:250,000 scale (Vietnam People's Army, 1983). In each elevation location, the data of X and Y in UTM coordinates were recorded.

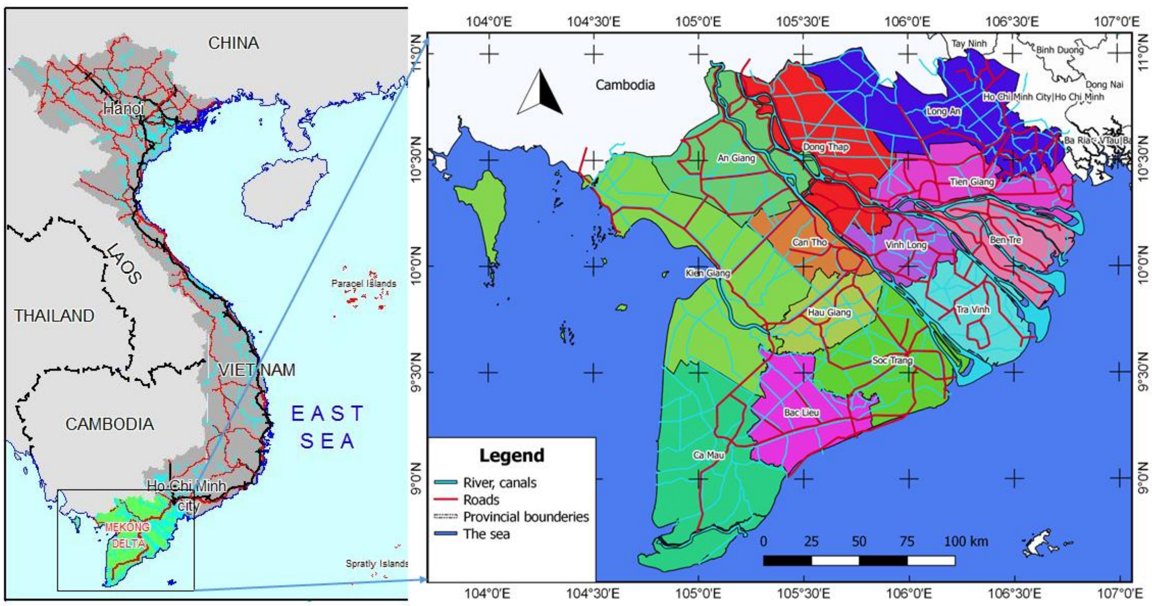


Figure 1 Administrative map of the Mekong Delta in Vietnam

The maps of administrative boundary, land uses of the Mekong Delta (2008) at the scale of 1:250.000 (Sources: Department of Land Resources, Cantho University), collect to overlay with interpolated maps for estimation the extend of the submerged area by changing of water levels.

The statistical data on the population of 13 provinces in 2006, 2007, 2008 was collected (Statistics Office, 2008); for estimating the affected issues.

2.2 Data processing

Maps must be homogeneously registered using the Universal Transverse Mercator grid (WGS 84) at UTM Zone 48, Northern Hemisphere (WGS 84) study area to rectify the simulation and spatial delineation elevation data.

The theoretical variogram describes the spatial dependence of a spatial random field or stochastic process in spatial statistics. The appropriate model was selected by matching the shape of the curve of the experimental variogram with the shape of the mathematical process.

The semivariogram $\gamma(h)$ was first defined by Matheron (1963) as half the average squared difference between the values at points (S_1 and S_2) separated at distance h. Formally:

$$\gamma(h) = \frac{1}{2v}\iiint_v [f(M+h) - f(M)]^2 dV \qquad (1)$$

Where M is a point in the geometric field V, and $f(M)$ is the value at that point. The triple integral is over three dimensions. h is the separation distance (e.g., in m or km) of interest. In practice, it is unsuitable for sampling everywhere, so the empirical variogram is used instead.

The variogram is twice the semivariogram and can be defined, equivalently, as the variance of the difference between field values at two locations (S_1 and S_2, note change of notation from M to s and f to Z) across realizations of the field (Cressie, 1993):

$$2\gamma(s_1, s_2) = Var(Z(s_1) - Z(s_2)) \\ = E[((z(s_1) - \mu(s_1)) - (z(s_2) - \mu(s_2))^2] \quad (2)$$

A variogram measure how much two samples taken from the height vary in water depth depending on the distance between those samples in a study from the field of elevation. Samples taken far apart will change more than samples close to each other.

Using spatial interpolation, data were processed using GS+ software to determine the variogram (variation model) of elevation data.

Kriging is the essential method in geostatistics and is applied widely in many natural science fields. Kriging was initially developed in geostatistics by the South African mining engineer called Krige. The mathematics was further developed by Matheron (1963). The emphasized point of Kriging is the estimation of the variogram. Depending on the general principle of Kriging, the steps are: calculate the experimental discrete variogram in different points, then fit the discrete experiment points with a mathematical model which is designed as the model variogram.

Spatial interpolation uses points with known values and coordinates to estimate values at other unknown locations. We use only the collected data cover the entire region to make an elevation map. Because of high costs and limited resources, data collection is usually conducted only in a limited number of selected point locations. Spatial interpolation can estimate the elevation at locations without recorded data using known elevation readings at nearby weather stations. The Kriging and direct measurement calculations fall within the range of minimum and maximum simulation values as identified by Rakhmatullaev et al. (2011).

In this study, the kriging technique applies to simulate the changing of inland distribution underwater levels height at different scenarios, assuming from 0.2 m to 2.8 m with the interval of 0.2 m.

Combination of interpolated maps with administrative, transportation, rivers networks, and land use status maps allowed computing water levels' impact at different scenarios.

3 Results and discussion

To generate a continuous map, a digital elevation map from elevation points measured with a GPS device, or rectified data, an interpolation method must optimally estimate the values at those locations where no samples or measurements are taken. The interpolation results were then used for analyses of the whole area and show below.

Table 1 Parameters of different spatial variation models of elevation data

Model	(Co)	(Co + C)	(A)	(RSS)	R^2	(C / [Co + C])
Linear	0.472	0.702	147 371	0.0019	0.973	0.328
Exponential	0.452	0.905	585,900	0.0011	0.985	0.501
Spherical	0.006	0.602	12,700	0.0491	0.313	0.990
Gaussian	0.066	0.602	10,912	0.0489	0.316	0.890

Note: (Co): start threshold fluctuations; (Co + C): the threshold value changes; (A): distance changes also took part in most; (RSS): the squared deviation; ($R^{2)}$: coefficient of determination; (C / [Co + C]): percentage changes.

3.1 Variogram of the elevation spatial variation in Mekong Delta

A suitable model is needed based on the high reliability of coefficient of determination (R^2) and the minimum of total squared deviation (RSS) to identify the spatial variation and the models' reliability for interpolating the elevation data. Therefore, four variogram models with different parameters were determined (Table 1). The exponential model select for interpolation due to its highest coefficient of determination (R^2 = 0.985) and the smallest RSS = 0.0011.

The principal source of error and deviation reflected within the dataset is related to the sample points' density and spatial configuration (Johnston, 2003).

3.2 Simulation of the spatial distribution of elevation in Mekong Delta

After the variogram analysis, the interpolation carries out using a kriging method (Rakhmatullaev et al., 2011).

Over 967 elevation points collect from the Mekong Delta topographic maps (Figure 2), the spatial interpolation delineates the spatial distribution of different elevation levels based on the selected variogram. In addition, the kriging technique applies to simulate the changing of inland underwater distribution levels height at various scenarios, assuming from 0.2 m to 2.8 m with an interval of 0.2 m.

Interpolation results (Figures 3 and 4) showed that the current Delta's elevation changed from 0.4 to 2.8 m above sea level (not including the mountains) and divide into 12 classes. Generally, the whole area is relatively flat, with more than half (57.2%) high ranging from 1.8 to 2.4 m. However, with the distribution covering 13 provinces/cities, the remaining area is low and has high mounds. In particular, some areas of Bac Lieu, Kien Giang, Tien Giang, and Ca Mau provinces have less than 1-m height elevation, occupying 1.6% of the region that can be submerged when water levels in the area increased.

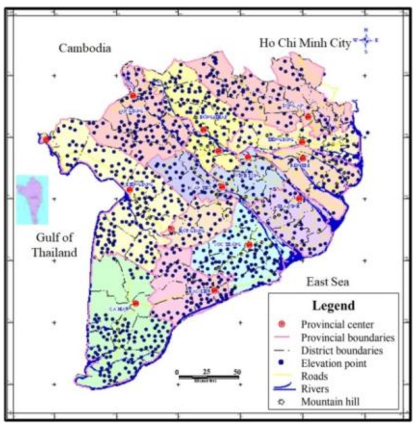


Figure 2 Location of elevation data collected in the Mekong Delta

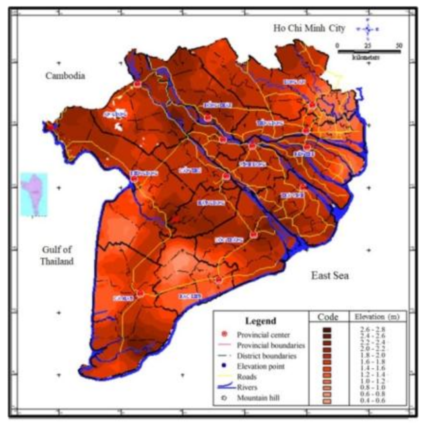


Figure 3 Spatial distribution of the height of current elevation in the Mekong Delta

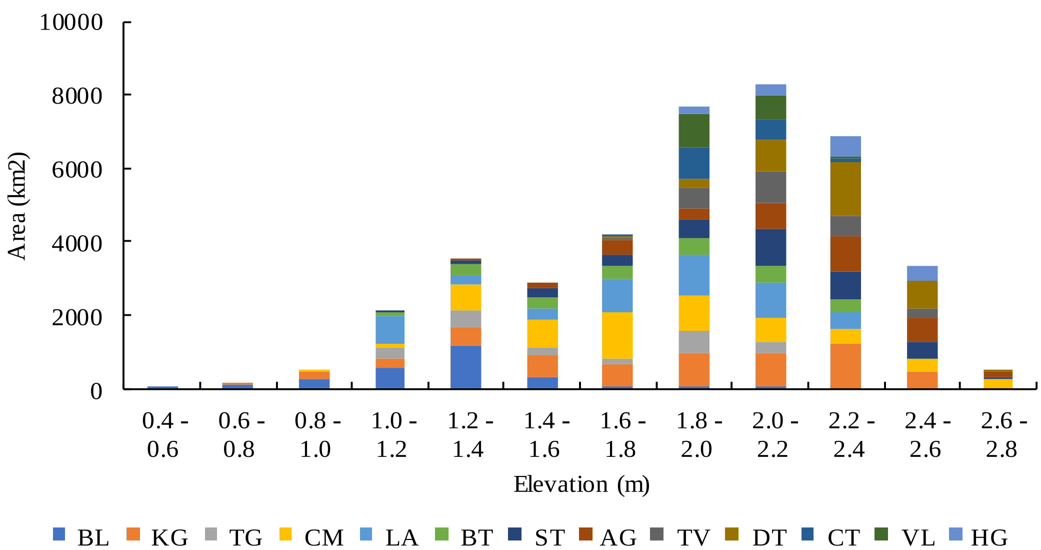
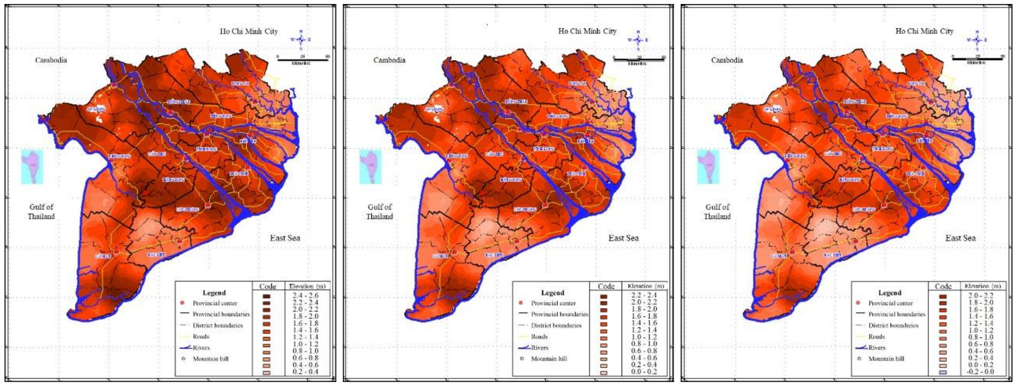
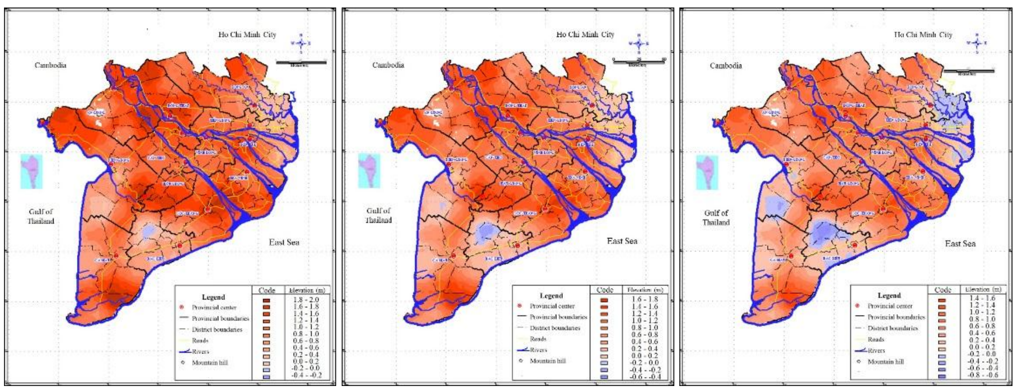


Figure 4 The extent of elevation in different Mekong Delta provinces (km^2)

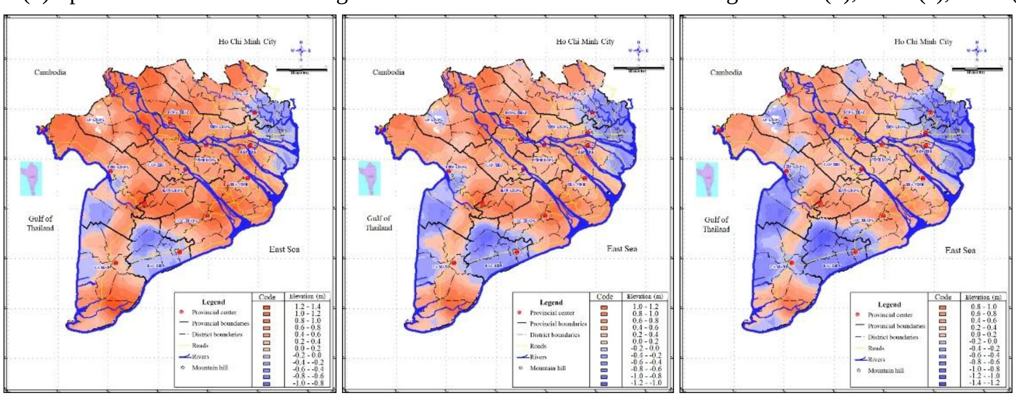
Notes: AG: An Giang; BL: Bac Lieu; BT: Ben Tre; CM Ca Mau; CT: tho; DT: Dong Thap; HG: Hau Giang; KG: Kien Giang; LA: Long An, ST: Soc Trang; TG: Tien Giang; TV: Tra Vinh VL: Vinh Long.



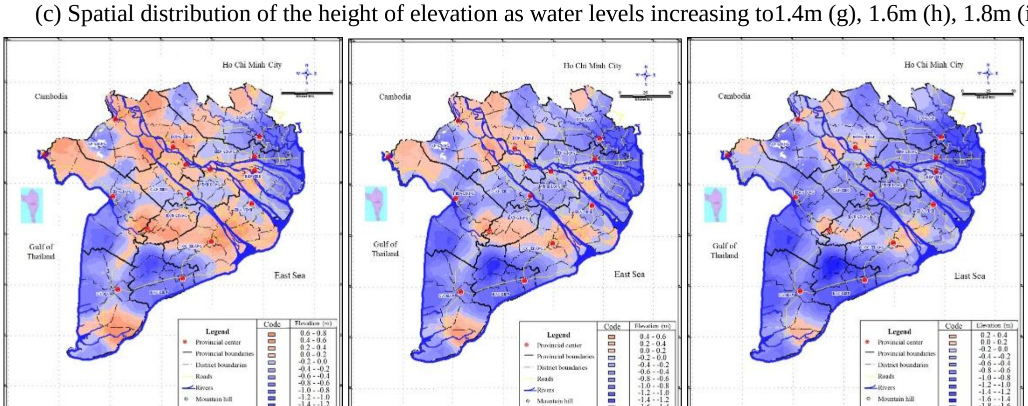
(a) Spatial distribution of the height of elevation as water levels increasing to 0.2m (a), 0.4m (b), 0.6m (c)



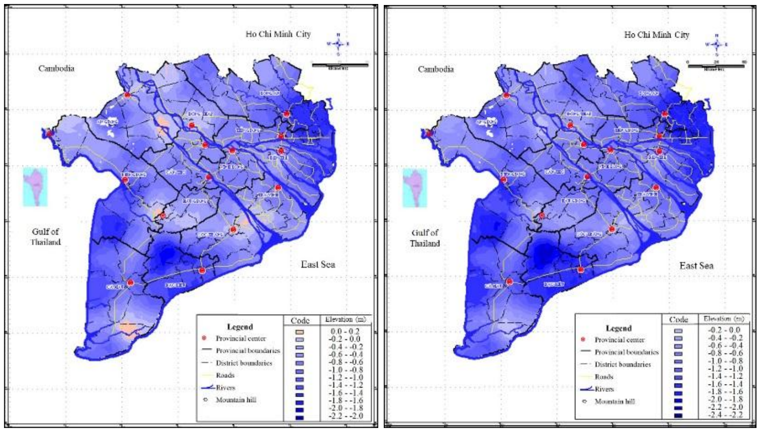
(b) Spatial distribution of the height of elevation as water levels increasing to 0.8m (d), 1.0m (e), 1.2m (f)



(c) Spatial distribution of the height of elevation as water levels increasing to1.4m (g), 1.6m (h), 1.8m (i)



(d) Spatial distribution of the height of elevation as water levels increasing to 2.0m (m), 2.2m (n), 2.4m (o)



(e) Spatial distribution of the height of elevation as water levels increasing to 2.6m (p), 2.8m (q)

Figure 5 Spatial distribution of the height of elevation as water levels increasing to different heights

3.3 Simulation of the spatial distribution of the height of elevation at different water levels in the Mekong delta

Each region has different topographical and hydrological conditions. Therefore, it is not easy to assume the water level in other areas to use the average water level on rivers. Consequently, we used the elevation value above sea level as the benchmark to assume the increase of water level in the region.

The assumptions developed based on the Mekong Delta's current elevation, increasing to 2.8 m. Thus, the lower elevation above sea level at each level of flooding was 0.2 m high, including 12 classes of the corresponding water level. The spatial distribution of the height at different water levels show in Figure 5a-eas the higher the water levels, the larger area of surface water, and then larger areas of land lost.

The simulation assumed that the flooding affected the Mekong Delta region when the water level rose (or lower elevation) was 0.6 m. Thus, the total unsubmerged area of the Delta gradually reduced by increasing the water level until the water level rose to 2.8 m. Then, the high regions' elevation drops to 0, and the whole area submerges in water (not the mountains). The changing surface water (or submerged by increasing the water levels in different provinces) results from overlaying interpolated maps at different assumptions with administrative maps.

Generally, the Ca Mau peninsula (Bac Lieu, Ca Mau, and Kien Giang) was affected mainly by inundation. Bac Lieu province is beginning submerged when the water level reaches 0.8 m; half of these provinces submerge when water levels rise to 1.2 m. Most of the plains are submerged when water levels rise to 2.0 m. Water levels rising to 2.6 m almost provinces of Ca Mau peninsula flooded(Figures 6).

3.4 Effect of the increasing water level on some social-economic factors in the Mekong Delta

The simulation results showed that the Mekong Delta is seriously affected when the inland water level rises as the sea level rises. The Mekong Delta's elevation distribution assumption started to be concerned when water level rising to 0.6 m, the affected seriously by water level up to 1.4 m with 14.9% submerged area and the region's population affected was approximately 2,682,455 people.

The assumption of each hectare of rice cultivation cycle in the Delta is turned into an average of 2 crops per year, meaning that each 1 ha area of land planted at least two turns of sowing area (Statistics Office, 2008). As a result, 1 ha of rice revolved around 2 ha each year (from 2crops), with an average yield of 4.8 tons ha^{-1} (Statistical Office, 2008); the annual revenue could plan up to around 9.6 tons year^{-1}. Then, suppose the water in this area rose to 0.6 m. In that case, the lost area is 2 km^2 (about 200 ha) or 400 ha (200 ha × 2 crops) of sowing area of rice approximately (two rice cropping season/year) lost and then affecting 1,920 tons of rice in this region.

Table 2 and Figure 6 show the effects of water levels on population, rice cultivation area, and total food production in the Mekong Delta region. Assuming the water level rises to 0.6 m, there are no or minimal effects, but if the water level rises 1 m, there is 6,036 ha lost (in which 278,219 people are affected, 380 km^2 rice area loss 364,800 tons of food production loss). If the water level is up to 2.6 m, most of the land in this region submerged on 20,719 km^2 (or 4,142,800 ha cultivated rice land), and then 19,890,240 tons of rice production loss per year. Under this assumption, if water levels rise to 2.6 m, nearly most rice areas and people were affected.

In general, the above results show the suitable method to simulate elevation changing by using geostatistics and Kriging interpolation techniques and assess the spatial distribution and the impact of the increase of water levels with different assumptions. Moreover, the Kriging interpolation method is a good approximation as suitable to the assessment of Rakhmatullaev et al. (2011). According to the results, the geostatistical approach is a very helpful, reliable, and efficient method to process for increasing the number of measurement points at unsampled places. Otherwise, the variogram analysis use to examine the structural relationship of data for physical process anisotropy analysis, which have changed characteristics in the direction and space over traditional methods for bathymetric or topographic surveys as described by Bernert and Sullivan (1998), Ortt et al. (2000), Marache et al. (2002), Soler-López (2003, 2004), Furnans and Austin (2008).

The simulation interpolation introduces a range of volumes and surface areas in contrast to traditional estimates. As a result, it believes that there would be possibilities to react appropriately in the decision-making process.

Table 2 Assumptions of social and economic factors affected by the increasing of inland water level in Mekong Delta

Water level rise assumptions	0.6 m	1m	1.4 m	1.8 m	2.2 m	2.6 m
Total current area: 40,600 km^2						
Lost area (km^2)	2	626	6,036	12,867	28,034	37,629
Total current population: 17,695,000 people						
Population affected (people)	713	278,219	2,682,455	5,718,124	12,458,456	16,722,412
Total current rice area: 20,855.2 km^2						
Lost area (km^2)	2	380	3,027	6,541	14,920	20,719
Total current food production: 20,021,016 tons						
Lost production (tons) (Assumption for 2 rice cropping/year)	1,920	364,800	2,905,920	6,279,360	14,323,200	19,890,240

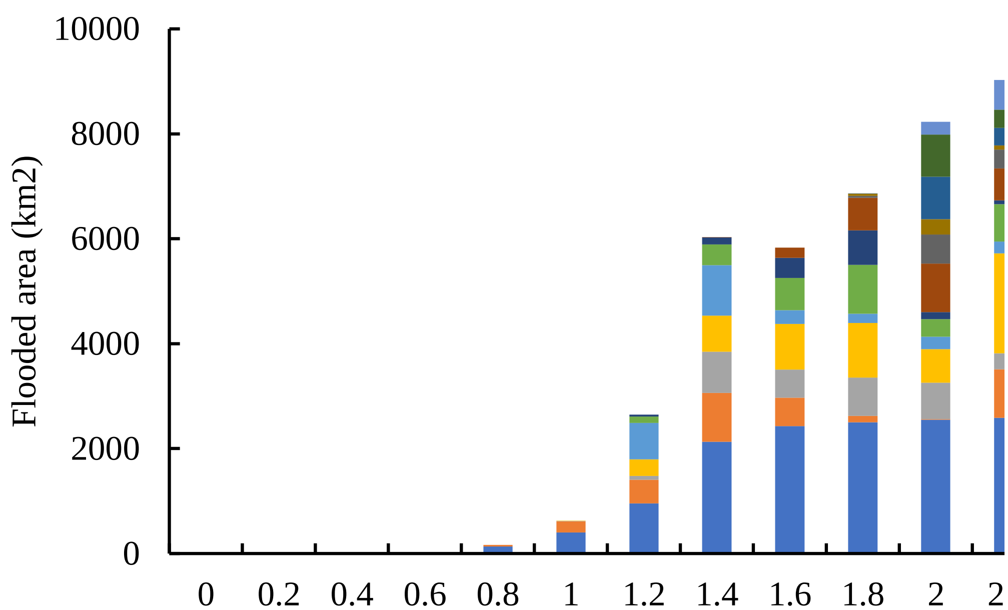


Figure 6 Changing of surface water (flooded) area under changing of difference inland water levels in different provinces

Note: AG: An Giang; B.L.: Bac Lieu; B.T.: Ben Tre; CM Ca Mau; CT: tho; D.T.: Dong Thap; HG: Hau Giang; K.G.: Kien Giang; LA: Long An, S.T.: Soc Trang; T.G.: Tien Giang; T.V.: Tra Vinh; V.L.: Vinh Long

4 Conclusion

This study applied the geostatistical and Kriging interpolation techniques as a tool to simulate the changing of elevation, as the assumption of inland water level changes under sea-level rise. Four variogram models with other parameters were estimated, in which the exponential model was selected for interpolation due to its better performance (R^2 = 0.985, RSS = 0.001108). The geostatistical approach successfully outlined this model,

Using the selected variogram model to simulate and interpolate the inland water levels changes at different scenarios, the spatial distribution of the flooding that impacted the Mekong Delta region was delineated. When the water level started rising to 0.6 m, the total affected area of the region gradually increased until the water level rose to 2.8 m. The Ca Mau peninsula is mainly submerged under this condition. Generally, the whole area is relatively flat, with more than half (57.2%) area ranging from 1.8 to 2.4 m in height. Bac Lieu province is beginning to be submerged when water level higher than 0.8 m, half of these provinces are submerged when water levels rise to 1.2 m. Otherwise, when water levels rise to 2.6 m, almost all Ca Mau peninsula is submerged. Most of the plains are submerged when water levels rise to 2.0 m. In general, the submerged starts when the water increases to 0.6 m. The total area gradually reduces until the water levels rise to 2.8 m that the whole region is completely submerged.

By assumption, when the water level rises to 2.6 m, nearly most of the land, rice area (380 km^2), food production (364,800 tons) are lost, and most of the people (278,219 inhabitants) are affected.

The spatial analysis using variogram and interpolation techniques can simulate the changing of elevation by changing water levels at locations without recorded data using known height. This procedure can assist the decision-maker to have another view in predicting the water level as sea-level rise. However, the other affected factors, such as roads, rivers, infrastructures, tidal, etc., need to be considered in further analysis.

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