PROBABILISTIC FLOOD MAPPING OF STORM SURGES DUE TO TROPICAL CYCLONES WITH SEA-LEVEL RISE ALONG MEKONG DELTA

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ABSTRACT: Mekong delta is severe-vulnerable for fluvial flood. Though frequency of coastal flood is low frequency, we should know the risk. This paper shows the extreme heights of storm surges calculated by extreme theory and hindcast of storm surge heights past 60 years. Based on the extreme heights, probabilistic flood area was calculated by physical process model of shallow water flow. And more, impact of rising sea-level is also considered with storm surges. The results were quantified as area of flood and affected population. Reducing of capacity of dykes due to rising in sea-level also was shown at the end of this paper.

Keywords: Storm surges, extreme value, vulnerability, adaptation, global warming, dyke.

MOTIVATION AND PURPOSE

On characteristic of floods, Mekong delta can be separated into two area. The one is fluvial flood at upper stream area of Mekong rivers (V. P. Dang, et al., 2012) as like the event in the year of 2000 and 2011. The other must be coastal flood at the downstream area as like the event by Typhoon Linda in the year of 1997 and the event in the year of 2012. Later case occurred on 17 and 18th September, authors looked a flood situation in Can Tho city. Inhabitants people along the Bassac River did not have experience of flood in the year of 2011. However this situation of the river reported in Mekong River commission (2012) is that the water level at the observation station of Chau Doc, where is upper stream in Viet Nam, was lower than that in the long-term average and significantly affected by effect of astronomical tide.

Nobuoka et al. (2011) showed vulnerability of Mekong delta due to coastal impact and adaptation capacity. However, as these results based on the level comparing method between heights of extreme water level at coastal line and altitude, coastal flood areas were expanded too much.

The purpose of this study is to calculate probabilistic hazard area of coastal flood due to storm surges in the condition of dike systems and rising in sea-level by use of numerical simulation.

METHODOLOGY

Hindcast of Storm Surges

For past water rising anomaly due to tropical cyclones, typhoons, along the Viet Names coasts during the year of 1951 to 2011, hindcast of storm surges was implemented by use of best track data provided by RSMC Tokyo-Typhoon Center. The time of analysis, location, and central pressure in the data were used to solve the pressure fields and wind fields expressed by Equation-1 by Myers (1961) and Equation 2.

\[ P(r) = P_c + \Delta p \cdot \exp\left(-\frac{r_0}{r}\right) \]  

(1),

where \( r \) is distance from center of typhoon, \( P(r) \) is barometric pressure at the position of distance \( r, P_c \) is pressure at center of typhoon, \( r0 \) is radius of typhoon defined as distance from center of typhoon to the highest wind position as a parameter.

Wind velocity at 10m above mean sea-level is

\[ V(r) = c_1 V_{gr}(r) + c_2 \frac{c_1 V_{gr}(r_0)}{c_1 V_{gr}(r_0)} U_r \]  

(2),

where gradient wind \( V_{gr} \) is expressed by following equation,

\[ V_{gr} = \sqrt{\left(\frac{rf}{2}\right)^2 + \frac{\Delta p \cdot r_0}{\rho_a} \exp\left(-\frac{r_0}{r}\right) - \frac{rf}{2}} \]  

(3),

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and $C_1$ and $C_2$ are coefficient 0.7. $U_T$ is a movement speed of a typhoon. In addition, angle of gathering the wind to the center of typhoon/cyclone is set as 20 degree. Each radius of the cyclones was calculated by use of empirical equation by Kato (2005), Equation 4, which was derived from analyzing the relationship between central pressure of cyclone and that radius in Northwest Pacific region,

$$r_0 = \begin{cases} 0.769 \times Pc - 650.55 & (Pc \leq 950 \text{ hPa}) \\ 1.633 \times Pc - 1471.35 & (Pc > 950 \text{ hPa}) \end{cases} \quad (4).$$

The governing equations of storm surges are equation 5 to 7.

$$\frac{\partial M}{\partial t} + \frac{1}{R \cos \phi} \left( \frac{\partial}{\partial \lambda} \left( \rho M \frac{\partial \phi}{\partial \lambda} \right) + \frac{\partial}{\partial \phi} \left( \tau M \cos \phi \right) \right) = -2 \Omega N \sin \phi + \frac{gh}{R \cos \phi} \frac{\partial \eta}{\partial \lambda} = \frac{h}{\rho_w} \frac{\partial \phi}{\partial \lambda} + \frac{\tau^{(s)}}{\rho_w} - \frac{\tau^{(b)}}{\rho_w},$$

$$\frac{\partial N}{\partial t} + \frac{1}{R \cos \phi} \left( \frac{\partial}{\partial \lambda} \left( \rho N \sin \phi \right) + \frac{\partial}{\partial \phi} \left( \tau N \cos \phi \right) \right) + 2 \Omega M \sin \phi + \frac{gh}{R} \frac{\partial \eta}{\partial \phi} = \frac{h}{\rho_w} \frac{\partial \phi}{\partial \phi} + \frac{\tau^{(s)}}{\rho_w} - \frac{\tau^{(b)}}{\rho_w},$$

$$\frac{\partial \eta}{\partial t} + \frac{1}{R \cos \phi} \frac{\partial M}{\partial \lambda} = \frac{1}{R \cos \phi} \frac{\partial (N \cos \phi)}{\partial \phi} = 0 \quad (7),$$

where $M$ and $N$ are flux for direction of longitude and latitude axis ($\lambda$ and $\phi$), $\eta$ and $h$ are sea surface elevation and water depth, $\Omega$ is Coriolis parameter, $p$ is barometric pressure on sea surface, $\tau_s$ and $\tau_b$ are friction of sea surface and sea bottom, $R$ is radius of earth, $g$ and $\rho_w$ are gravitational acceleration and mass density of sea water. Friction coefficient on wind stresses acting on the sea surface are calculated by use of Mitsuyasu and Hond (1982), equations 8.

$$C_D = \begin{cases} -(1.290 - 0.024 \times W) \times 10^3 & (W \leq 8 \text{ m/s}) \\ (0.581 + 0.063 \times W) \times 10^3 & (W > 8 \text{ m/s}) \end{cases} \quad (8),$$

and on the sea bottom, Manning rough coefficient 0.025 was set in the calculation. The ADI method of difference method was employed for solution of these governing equations. Spatial size of grid was two arc-minutes. It is assumed that astronomical tides were mean sea-level in all of cases, which means astronomical tides were ignored in this study.

**Return Period of Storm Surges**

The storm surges of 1/10 to 1/1000 return periods were calculated by use of an extreme value theory. That sampling data is the hindcasted storm surges.

Values of annual maximum heights at each gird on coastal lines were collected. Using distribution function of extreme value are the Fisher-Tippett type I (Gumbel),

$$F(X) = \exp\left(-\exp\left[-(x - B)/A\right]\right) \quad (9)$$

the Fisher-Tippett type II and

$$F(X) = \exp\left[-(1 + (x - B)/kA)^k\right] \quad (10)$$

of which shape parameter are $k=2.5, 3.33, 5.5$ and 10.0, and Weibull distribution (three parameter),

$$F(X) = 1 - \exp\left[-(x - B)/A\right]^k \quad (11)$$

of which shape parameter $k=0.7, 1.0, 1.4, 2.0$. These parameters and rejection of unfitted distribution functions in this study were the method proposed by Goda (1988).

**Probabilistic Flood and Vulnerability Assessment**

One of the typical storm surges in Mekong delta was caused by Typhoon Linda, 1997. Track and time-change of central pressure of Typhoon Linda was used for calculating probabilistic flood in this study. The constant rate for change in intensity of the pressure was set to become that the simulated maximum height is same as the maximum height on each return period in Mekong Delta.

By use of these tracks changed in intensity of pressure, the numerical simulations as same as the hindcasting simulation were carried out including flood on the land. The topography in the simulation was made from GTOPO30 (USGS) and SRTM30 (NASA), that combined method was described in Nobuoka (2007). Moving boundary of the simulation for expanding the flood area was set by threshold of minimum water level at the latest time steps.

Rising in Sea-level due to global warming in the year of 2100 was set as 100 cm according to Viet Nam national scenario (Ministry of Natural resource and Environment, 2009). Intensities of typhoons that were adjusted the height of each return period were assumed not to change due to global warming. For social scenario, national population growth according to SRES scenario provided by CIESIN (2002a) was used with the distribution of population database GPW (CIESIN 2002b). It is assumed that the design level of coastal dyke constructed along all of coastal lines was same as a chosen return period of the storm surges at each grids.
Fig. 1 Calculated distribution of height of 100-year storm surges in Viet Nam.

**DISTRIBUTION OF RETURN PERIODS OF STORM SURGES IN VIETNAM**

Figure 1 shows the calculated distribution of height of storm surges, of which return period is 100-year. The 0 to 2 m of the heights is paint in blue to purple at coastal line. The over 2 m heights are also in purple. There are no painted coastal lines along half of Bac Bo Gulf. Because the extreme function on hindcasted storm surges was rejected. The storm surge of 100-year in north of Viet Nam is higher than the other area. The maximum heights of storm surge achieved 2m in top of circles in the figure. This results must be accorded by the number of landfall of strong typhoons. The height around the river mouth of Mekong river, second bottom circle, is also high as around 1.5 m.

Figure 2 shows the relation of return periods and heights at the 4 points, where are shown by black circles. Though the line of north points shows high water level comparing with other points, the rate in a increase is small. The highest rate of increasing is around river mouth of Mekong river. One higher value, sometime, generates high extreme value of the function. It is assumed that this high result came from the storm surge heights due to typhoon Linda. The typhoon passed the south of Bassac River and strong onshore winds blew also around the river mouth, where quite shallow area expanding. It is easy for these sea bottom topographies to generate higher storm surges.

**PROBABILISTIC FLOOD HAZARD IN MEKONG DELTA**

Figure 3 shows the probabilistic flood map due to a typhoon, of which intensity was changed and track was same as that of typhoon Linda. Painted colors from sky-blue to purple show the 0 to 4 m of flood heights above mean sea water level. In the case of 10-year return period, flood area is limited to some closed coastal zones. The flood area expands according to increase in return period. In the case of 100-year, edges of flood reach 30 km far or more from costal lines. The flood area reached inland of Mekong delta in case of 500-year or longer.

Figure 4 is the results of flood map due to the typhoon which is same as that in figure 3 with 100 cm of sea-level rise. The flood map of 10-year with the sea-level rise is similar to the results of 100-year in figure3. Similarly, the result of 50-year return period with rising in sea-level is same as 1000-year in Figure 3.

The quantities of these results shows in Figure 5. Figure 5 (a), (b) and (c) are the maximum water level at coastal line, area of flood and affected population due to storm surge of each return periods. The black line is the case of no sea-level rise and red line is the case of 100cm rising in sea-level as the results of figure 4. The dotted and broken lines are the results including social change; population growth (degrease) according to SRES scenario. In the condition of this study, the impacts of 30-year to 100 year affect to expanding flood area and increase in affected population much comparing to the rising water in water level of storm surges.

Impact of sea level rise due to global warming is also large. The effect of population growth due to
global warming is also large so that large uncertainties remain in these results of this study.

**PROBABILISTIC STORM SURGES AND DYKES SYSTEM ON COASTAL FLOOD IN MEKONG DELTA**

Capacity of dykes to reduce flood area is shown in Figure 6, which design level and impact scale of storm surges are 100-year return periods. Figure 6 (a) which is the case of no sea-level rise shows no flood area, which means that the dykes defend all of coastal zones against the storm surges. On the other hands, when sea-level rise becomes 100 cm, there are almost no effect of the dykes for defense of the delta as shown in Figure 6(b).

**REMARKABLE SUMMARY**

According to hindcast of storm surges and extreme static analysis base on the hindcast results, a frequency of storm surges is low in Mekong delta, but it is possible to generate high storm surge and wide coastal flood one times during one century. The hazard area due to storm surge which is 100-year return periods is 8 times larger than that due to 10-year impacts. The results in this study suggest that even if better dykes than those in present are constructed in Mekong delta, the flood area due to storm surge as 100-year return period may become vast, in case sea-level rise becomes to 100 cm.
Probabilistic Flood Mapping of Storm Surges Due to Tropical Cyclones With Sea-Level Rise Along Mekong Delta

Fig. 4  flood area due to probabilistic storm surges with sea level rise 100 cm in Mekong delta (no dykes)

Fig. 5  maximum water level, flood area and affected population of return periods
Tough these results hold many uncertainty, we must care not only fluvial flood but also coastal flood in downstream area of Mekong delta, under the global warming conditions.

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