

Simulation of Inundation Process using 2D Finite Element Method in the Tonle Sap Lake

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Abstract

A 2D-FEM model was used to investigate the flood inundation process in the Tonle Sap lake area and its environs of the Mekong River Basin using the FEM (Finite Element Method) technique with 2-D shallow water equations. The model is based on an explicit two-step, finite element method that is capable of predicting water depth, mean velocities in the vertical direction, and the positions of wet and dry areas during water flow propagation. The study area covers floodplains of the Mekong River from Kratie in Cambodia to near the Vietnamese border. The model was applied to the water flows over the years 1996 through 2003. Simulations results showed real inundation processes of the study area. At first, the model was used to simulate a flood inundation process over the years 1996 through 2003 without considering direct rainfall and evaporation for description of the flows in the river and floodplain system. The simulated results showed little lower compared with the observed water levels and discharges at some important points in the basin. In order to improve the simulation results, a submodule was developed considering rainfall and evaporation and new

simulation was done for the flood inundation process. Computed results water velocity, flow direction, inundation depths, inundation extent, flood arrival times and flood duration within the flood plain were used to construct flood inundation maps. The new simulation results fitted well with observed data compared with the previous simulation results. The simulated results produced a lot of hydrologic information. This information can be used to assist agencies in developing emergency and evacuation plans and analyzing risk potential in the event of flooding. Furthermore, it can be conveniently applied to other river basins.

Keywords: 2-D FEM, flood process, Tonle Sap Lake, Mekong River basin

Introduction

The Mekong River plays an important role in the socio-economic and cultural life of people living in its riparian countries. Therefore, development of a hydrodynamic model to estimate floodplain inundation and its risk is an indispensable aid to integrating the basin management policies of relevant national and local governments in the Mekong River basin. In particular, a peculiar feature of the flow in and around Tonle Sap Lake and its environs in the Mekong River system is the existence of reverse flows into the lake from the Mekong River. This phenomenon occurs annually in May-June, when most of a large water mass from the main Mekong River flows down to the lower Mekong and Bassac Rivers, and at the same time a portion of the water flows upstream into Tonle Sap Lake, where the water level is lower than that of the Mekong River. In September-October, when the water level of Tonle Sap Lake is higher than that of the Mekong River, this stored water starts to drain into the lower Mekong and Bassac Rivers (Masumoto 2000). This natural mechanism provides a peculiar and important balance to the Mekong River downstream from the lake and ensures a freshwater flow into the Mekong Delta in Vietnam during the dry season, protecting the rich agricultural lands of the delta from saltwater intrusion from the South China Sea.

Until recently, with the development of high-speed computer technology, two-dimensional (2D) finite difference and finite element method (FEM) models for floodplain inundation have been developed, which overcome some of the limitations of one-dimensional ones (e.g., Kawahara *et al.* 1976, 1982, 1986;

Kawachi 1987; Leclerc *et al.* 1990; Heniche *et al.* 2000). These two-dimensional models, especially FEM models, have proved to be adapted particularly for modeling complex topography as encountered in natural conditions. However, most of these FEM models developed only for estuaries or small reaches of floodplain areas as for computational cost and capability. This paper presents the results of a study on flood inundation process carried out in the Tonle Sap lake area and its environs of the Mekong River Basin.

In lower part of the Mekong River basin, the Mekong River Commission (MRC) and Mekong Committee (MC) have a long history of using hydrologic and hydraulic models (International Water Management Institute, 2000). Most of these models are one-dimensional models (such as the VRSAP model applied by Dac (1987 and 2004); MIKE11 by MRC (2002) or the coupling of one-dimension in rivers with two-dimension in floodplain model (Dutta *et al.* 2004; MRC 2003). Such one-dimensional or combination of one and two-dimensional models only can describe the river channel and floodplain as a series of cross sections perpendicular to the flow direction and thus they could not characterize water flow directions as real states at confluences and meandering reaches.

In this paper, we present a two-dimensional finite element model using full terms of depth-averaged, shallow-water motion equations. The model was applied to simulate this peculiar flooding process of Mekong River and its floodplains in Cambodia over the years 1996 through 2003. Main roads, dikes, colmatages, and waterway-opening works in the study area, which enable water to be stored, were taken into account in the simulation. We found the simulation model to be capable of explaining the topographical geometric complexity and boundaries of the study area and to produce hydrologic data without gauging. Furthermore, flood regulation function of paddy fields in the study area was then assessed, using the results of the model simulation and land-use data. Namely, the volume of flooded water on paddies was estimated in order to evaluate the impact of flood storage by paddies on floods and water use. The results showed that about one-fifth of the total flood volume is stored on paddies in and around Tonle Sap Lake, and reservoirs which are formed by dikes in paddy areas not only protect the urban areas from floods, but also supply water for downstream areas after floods.

2D-FEM Method in Inundation Process

Governing Equations

The model is based on an explicit two-step, finite element method that is capable of predicting water depth, mean velocities in the vertical direction, and the positions of wet and dry areas during water flow propagation. In simulation the water motion is described by the 2-dimentional St. Venant equations in the following form:

Continuity equation

$$\frac{\partial \eta}{\partial t} + \frac{\partial(Hu)}{\partial x} + \frac{\partial(Hv)}{\partial y} = q_{rain} - q_{eva} \quad (1)$$

Horizontal Momentum equation:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - \varepsilon \frac{\partial^2 u}{\partial x^2} - \varepsilon \frac{\partial^2 u}{\partial y^2} + g \frac{\partial(H+Z)}{\partial x} + \frac{gu(u^2+v^2)^{1/2}}{HC^2} - \frac{K|W|W_x}{H} - fv = 0 \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - \varepsilon \frac{\partial^2 v}{\partial x^2} - \varepsilon \frac{\partial^2 v}{\partial y^2} + g \frac{\partial(H+Z)}{\partial y} + \frac{gv(u^2+v^2)^{1/2}}{HC^2} - \frac{K|W|W_y}{H} + fu = 0 \quad (3)$$

where $H = (\eta+h)$ is total depth of flow, h is the average water depth, η is water surface elevation, t is the time, u and v are the depth averaged velocities in the x and y coordinate directions respectively, ε is the eddy viscosity coefficient; g is the acceleration of gravity; z is the bed elevation; C is the Chezy coefficient of roughness; K is the wind stress coefficient; W is the wind velocity; f is the Coriolis parameter, q_{rain} is the rainfall intensity and q_{eva} is evaporation rate.

DEM Data Conversion and Finite Element Generation

The topographic data used in the model comprise a 100-m x 100-m grid resolution Digital Elevation Map (DEM) provided by the MRC. To cover the study area, we selected data from the upper part of the DEM map downward to the Tan Chau and Chau Doc water-level gauges and used these converted data to generate the meshes and interpolate the bed elevations at FEM nodes. In this study, Mesh Generator software was used to generate unstructured triangular meshes, which were used in the calculation of the 2D FEM simulation model. Outer points of floodplain and main river domains were extracted to create

floodplain and river boundaries. These floodplain and river boundaries were used as external and internal boundaries in the mesh generation processes. Node distributions of the boundaries were modified at meandering parts of rivers to make smoother meshes. Considering the topography, the scale of the study area, and mesh-smoothing conditions, we selected mesh sizes from 2500 m to 5000 m in the floodplain area and sizes from 200 m to 450 m inside the main river areas, thus generating refined FEM meshes. The generated meshes and elements of the whole study area are shown in Figure 1.

The final generated meshes had 52514 nodes and 99998 elements in the floodplain area, and 14550 nodes and 24999 elements inside the main river areas. The bed elevations of grids in the DEM data were used to interpolate the elevations of FEM nodes in the floodplain domain, while more precise and newly updated sound-bathymetry data of the main rivers as bed elevations (MRC, 2003) were utilized to interpolate the elevations of FEM nodes in the domain of the main rivers. In addition, a bilinear interpolation algorithm was used to interpolate the elevations of the FEM nodes in the floodplain areas, and a nearest-point interpolation algorithm was applied to interpolate the elevations of the FEM nodes in the main river areas.

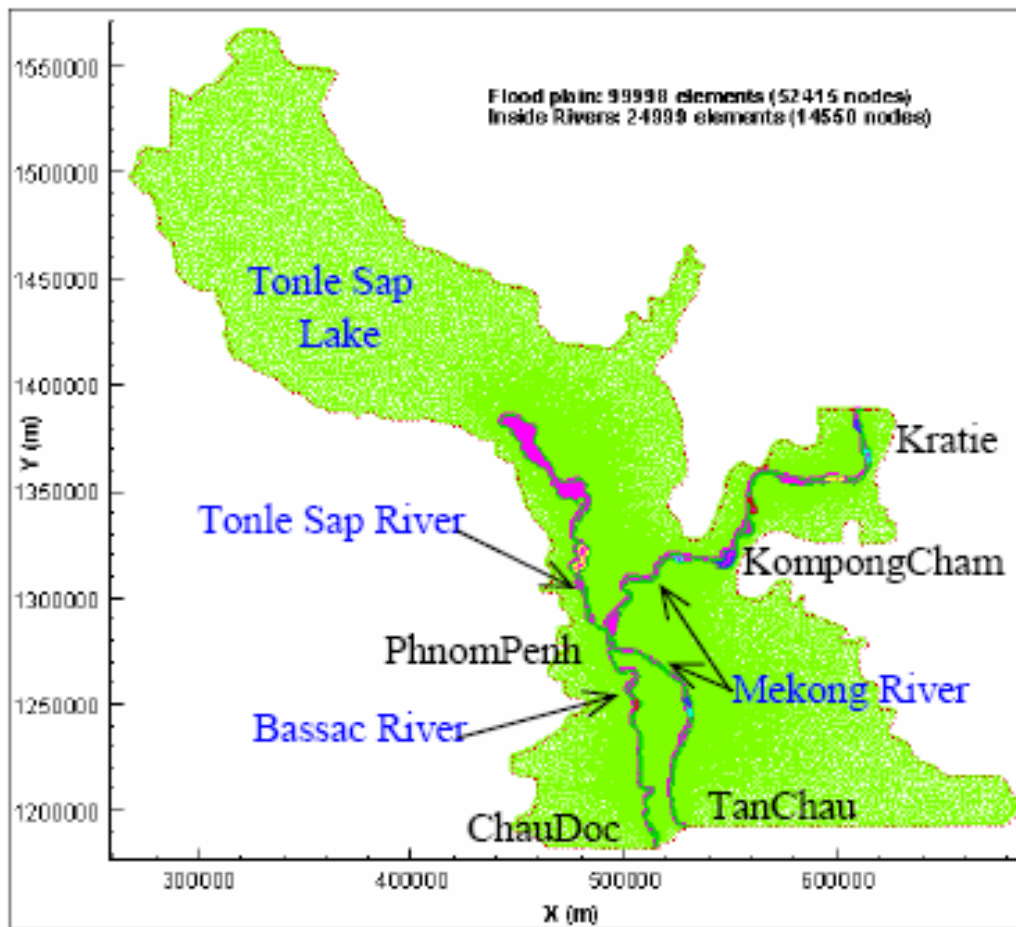


Figure 1: Generated meshes and elements in the study area.

The two-dimensional model uses the finite element method to solve differential equations representing conservation of mass and momentum. Two-dimensional model geometry is characterized by elements and nodes in a finite element network. The final computational mesh was obtained by combining the elements generated for the river and floodplain areas. The final mesh, shown in Figure 1, has approximately 62965 nodes and 124997 elements. Manning roughness coefficients of 0.020 and 0.025 were used for the river and floodplain areas respectively. A computation time-step of 50 sec approximately 10 times the Courant criteria was adopted. This value of time step was chosen as a compromise between maintaining the accuracy of the computations as well as keeping the computation time down to practicable limits. The average computation time, using a Pentium IV 1.20 GHz Processor 248 MB RAM, required for a complete 1 year simulation is about 25 days.

Assigning elevations of Main Roads, Dikes, Colmatages, and Road-opening Works to FEM Domain

The elevations of those construction works that have a significant influence on flow regimes in the study area were assigned to FEM nodes and elements in the model simulation (Figures 2 and 3).

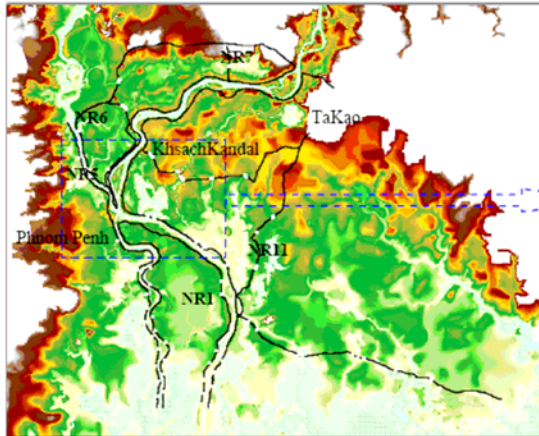


Figure 2: Selected Roads, Dikes, Colmatages and Road-opening Works in the Model Simulation.

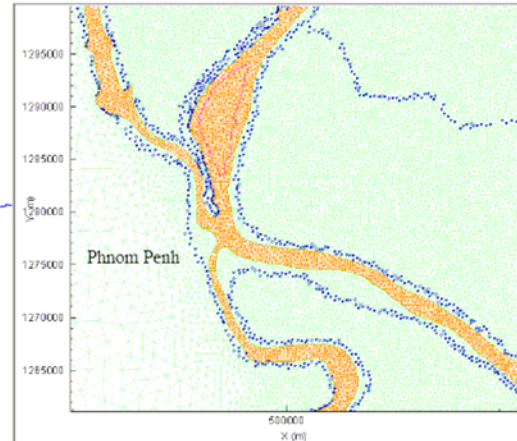


Figure 3: FEM Nodes for the Selected Roads, Dikes, Colmatages, and Road-opening Work.

Construction works were selected based on the MRC “Road Opening Survey” report MRC (2003) and other available data included National-Road 1 (NR1) from Phnom Penh to the Vietnamese border; NR5, NR6, and NR7; a local road on the left bank of the Mekong River, from Khsach Kandal to the junction with NR11 at Ta Kao; dikes on both sides of the Mekong River from Kompong Cham to near Tan Chau; dikes of the Tonle Sap River from Phnom Penh to Prek Dam; dikes on both sides of the Bassac River, from Phnom Penh to near Chau Doc; colmatages, which channel river water into areas behind the levees; and main road-opening works located on the selected roads and dikes. Arc-GIS tool was used to convert the polyline shape data of the selected roads, dikes, colmatages, and road-opening works to point data. Coordinates of these points were used to find the FEM nodes and elements closest to the points, and then assigned the elevations of the selected roads, dikes, colmatages, and road-opening works to those FEM nodes and elements (Figure 3).

Solution of the Inundation Processes by FEM

We applied the weighted residual of the standard Galerkin FEM to 2D shallow-water equations (1) and (2) for spatial discretization, and employed the selective lumping two-step explicit FEM for numerical integration in time, in a

method proposed by Kawahara *et al.* (1986). In the simulation, we used a selective lumping parameter, e , with a value of 0.85~0.9, to reduce the numerical damping effect and to adjust the numerical stability. We used a time increment, $\Delta t = (1\sim 10)$ s, in the calculation because the time stepping scheme employed yielded a stable Courant number. Eddy viscosity coefficient ε , which is expressed by a single variable function of the 4/3rd power of the mesh spacing as:

$$\varepsilon = (0.01 \sim 0.02) \Delta^{4/3},$$

where Δ is the mesh spacing that can be expressed in terms of the element side lengths:

$$\Delta = (l_1 l_2 l_3)^{1/3},$$

based on previous studies (e.g., Kawachi, 1987).

Manning roughness coefficients, $n_R = 0.02$ and $n_F = 0.025$, were used for main rivers and floodplains, respectively.

For the initial values of all the flow variables u , v , and H , the simulation model was coded so that it could either assign values to these variables or use the results of previous solutions as initial conditions, depending on how the simulation was started. In practice, when there was no available information about the flow field, the model was run with a starting velocity of zero ($u = 0$, $v = 0$) and a constant water surface, or, to speed up the convergence of the simulation result, the water surface was set as a linear water surface slope based on observed water level data (WL). This kind of cold-start initial conditions was used whenever a new simulation case was established. Later simulations started with initial conditions resulting from a previous run. The water depth H for each node is calculated by $H = WL - z$ (3), where H is the water depth, WL is the water level, and z is the bed elevation. Slip conditions were imposed along land boundaries so that normal velocities of nodes belonging to land boundaries were set to zero. The observed (or calculated) discharges of 12 tributaries around Tonle Sap Lake were set up as constantly wet nodes; during the dry season these are inflow boundaries, located at the lake's water edge. At each of these 12 nodes, a quantity of augmentative water depth, $\Delta h = (\Delta t Q_i) / A_n$ (where Q_i and A_n are the discharge and affected area of the node on surrounding elements, respectively), was added to the water depth H of the node at every time increment Δt . Upstream inflow conditions were specified by measured water levels as a function of time at the Kratie water level gauge, while water levels at

the Tan Chau and Chau Doc gauges were used to specify downstream outflow conditions.

We adopted the method proposed by Leclerc *et al.* (1990) and Heniche *et al.* (2000) for moving boundaries. Because elements near the water edge may be dry, wet, or partially wet, we used a certain threshold of water depth $dh = (0.03 - 0.05 \text{ m})$ to discriminate these types of nodes: if total water depth $H < dh$, the node was considered dry, and if $H \geq dh$, the node was considered wet. An element was considered entirely dry if $H < dh$ at all three nodes of an element, and such an element was excluded from the computation. If $H < dh$ for only one or two nodes, the element was partially wet, and only the mass balance equation was used and momentum exchange was neglected ($u = v = 0$ was imposed for the dry nodes). To avoid numerically artificial water flow from wet to dry nodes, water depths of the dry nodes of moving boundaries were kept negative ($H < 0$) as in Equation (3), so that water levels at dry nodes would be equivalent to those of wet nodes. If water depth $H \geq dh$ at all three nodes of an element, then the element was assumed to be wet, and the normal finite element formulation was employed. The values of dh provided good results in our study, and we could adjust these values to optimize the solution. This approach proved efficacious in handling the problem of moving boundaries owing to the study area's wetting/drying cycle.

Simulated Flood Inundation Map

By applying the methods and using the parameters as described above, we obtained the following simulation results. Figure 4 displays the simulated results of the maximum flood extent on 28 September 2000, and that on 9 October 2003 as well as inundation processes on the 1st days of June, July, August, September Year 2000.

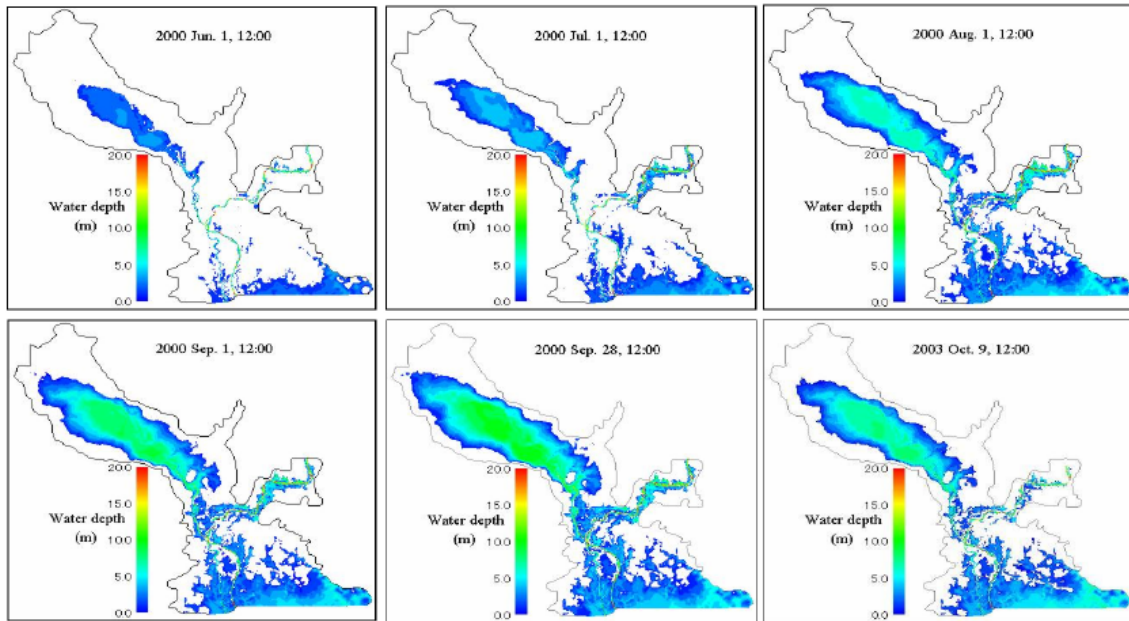


Figure 4: Simulated Flood Extent in 2000 and 2003.

The simulated flow-fields in inundated areas around the confluence near Phnom Penh on 1 September 2000 are shown in Figure 5. It depicts one scene of the simulated flow field in inundated areas around the confluence near Phnom Penh.

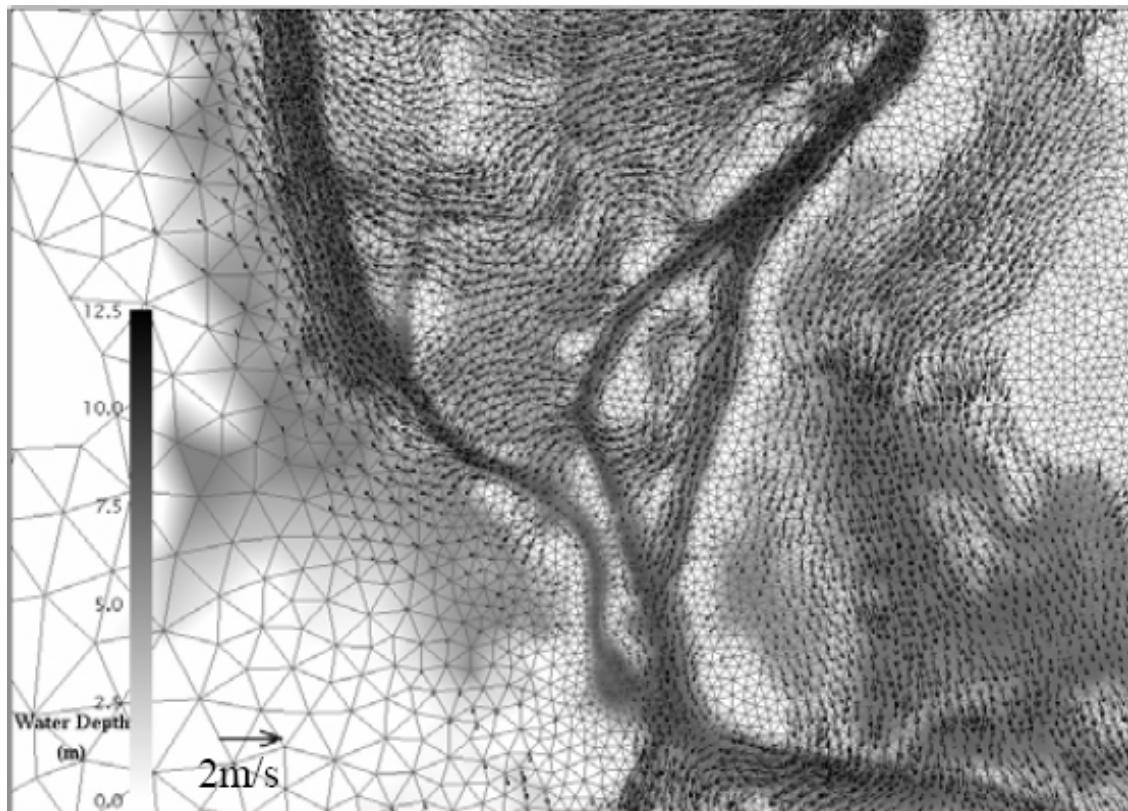


Figure 5: Simulated Flow-Field at the Confluence of the Tonle Sap and Mekong Rivers on 1

September 2000.

Model results described the real features of the area's flood flows; e.g., in the annual monsoonal wet season (from June to October), Mekong River floodwaters flow downstream to the lower Mekong and Bassac Rivers. At the same time, part of this high water reverses its flow and travels upstream, into the Tonle Sap River and towards Tonle Sap Lake, where the water level is lower. This reverse water flow increases the size of the lake. Figure 5 describes these features of the rising stage of the flood flow during the wet season in the study area. Simulated water levels at Kompong Luong in Tonle Sap Lake during wet season were 2.4 m, 4.3 m, 7.4 m, 8.5 m, and 9.8 m, corresponding to the first day of June, July, August, September, and October 2000, respectively.

The simulated results reproduced the inundation processes occurring during the year: At the beginning of wet season (June), water was flowing only in the main rivers; at the onset of the flood (July), flood water spilled out gradually to adjacent areas, expanding the flood plain on both sides of the main rivers. Simulated water levels were compared with observed hydrographs at five points and maximum flood extents. The calculated water levels were a little bit lower than the observed ones (Figures 6 and 7).

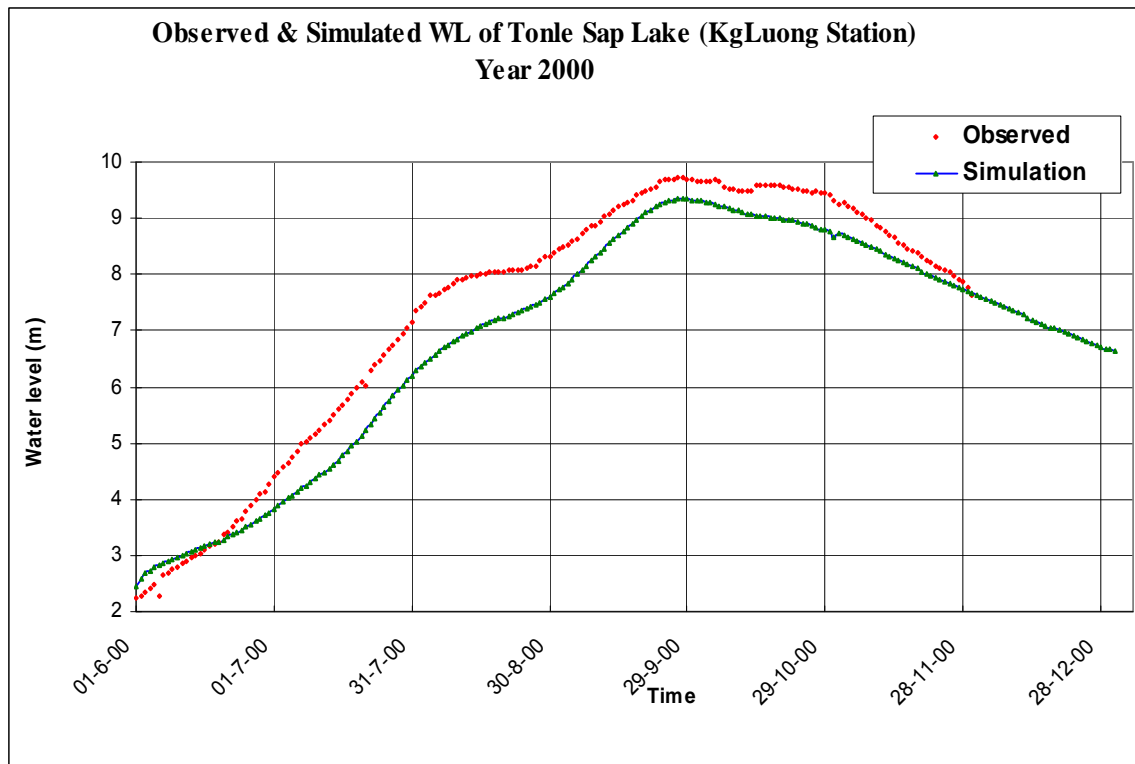


Figure 6: Observed and Simulated water levels of Tonle Slap Lake in 2000.

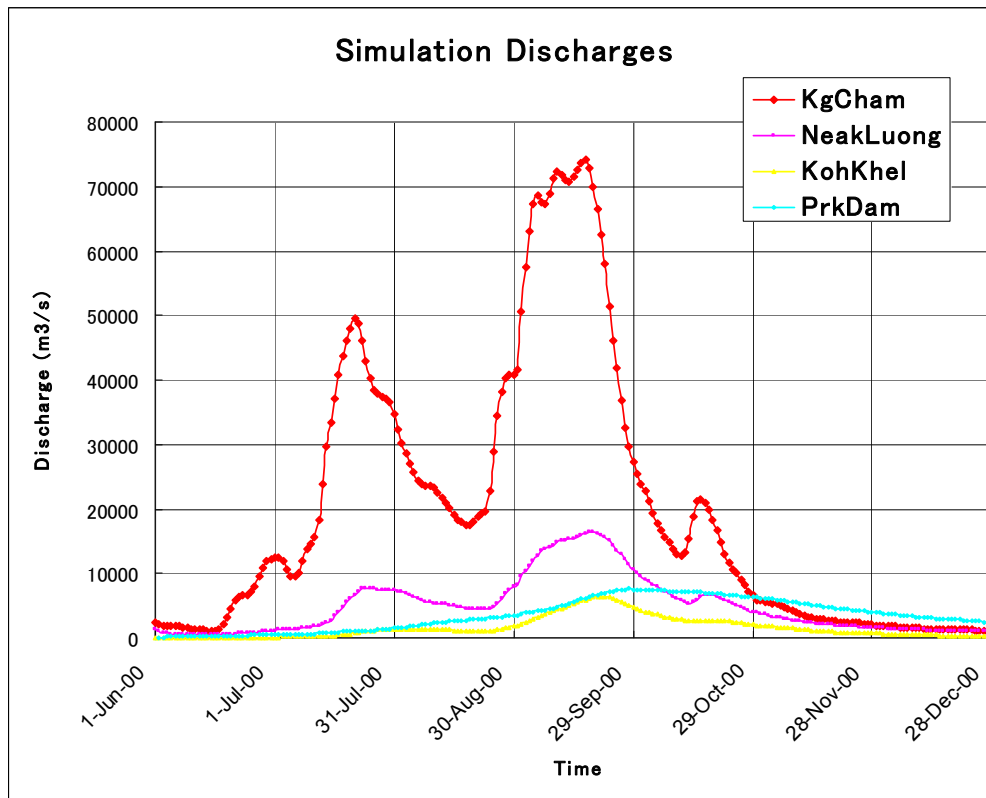


Figure 7: Simulated Discharge at 5 Key Points of the Study Area.

Simulated Results and Comparison

The computed water level in previous simulation results showed lower than observed at 5 locations. To simulate inundation process, the rainfall and evaporation data were not considered in the model. In this concern, it is to be expected that the simulation results could be improved considering with rainfall and evaporation in the simulation process. At first, the daily rainfall and evaporation data was interpolated and the net amount of water depth was computed. Then, it was added into the main model for the new simulation. The programs are written to run at two conditions namely Initial condition and Hot condition. If the simulation is stopped somehow then the program for Hot condition will be used for continuing the simulation process. This condition uses inputs initial and boundary condition from previously simulated results.

New simulated results considering with rainfall and evaporation were plotted to compare with observed and previous (without considering rainfall and evaporation) simulated water levels at 5 locations namely Kompong Cham, Kompong Luong, Prek Kdam, Neak Luong and Koh Khen as shown in Figure 8. Due to unavailability of the observed discharge data, new simulated discharges were plotted with previous simulated results which were shown in Figure 9. In

the new simulation, the direct rainfall amount on the water body and evaporation significantly affect simulation results.

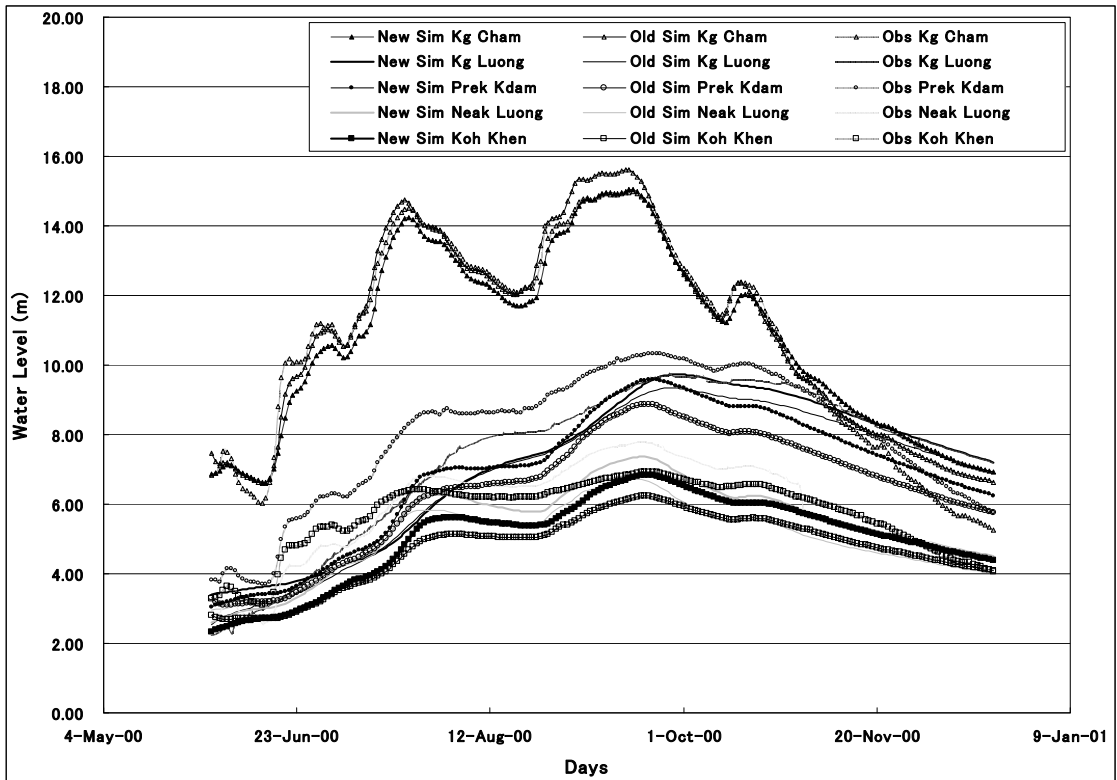


Figure 8: Simulated Water Levels Compared with Observed and Previous Simulated Water Levels for Year 2000

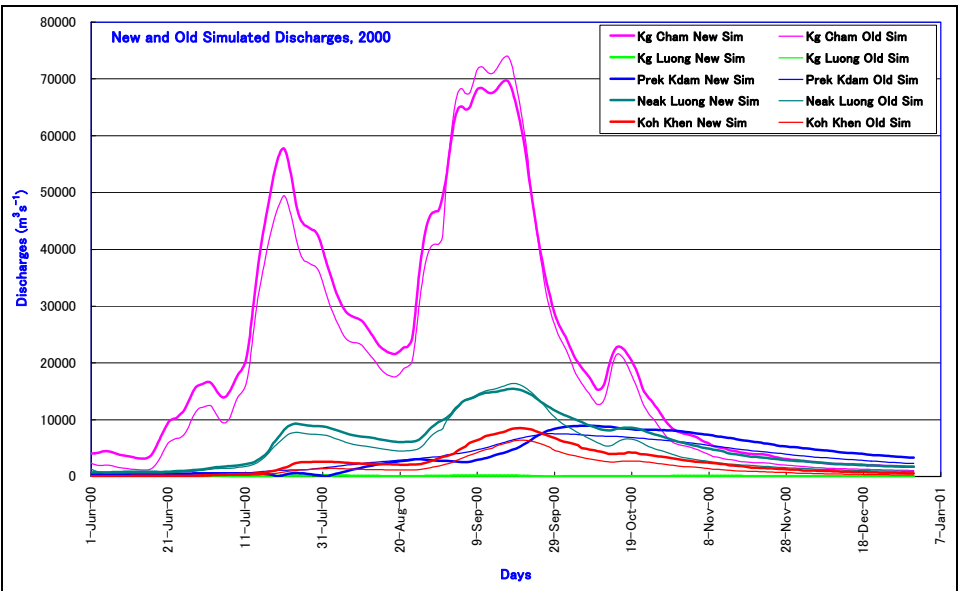


Figure 9: New and Previous Simulated Discharges at 5 Locations for Year 2000

7.0 Estimation of Inundation Volume on Paddies

Agricultural land use in and around Tonle Sap Lake is classified roughly as paddies and dry fields. Figure 6 shows land use in Cambodia with the simple classifications of forest, dry fields, and paddies. The grid size of the digital map is 1 km. In order to evaluate the role of agricultural lands in flood protection and agricultural water use, we estimated the volume of flooded water on paddies. The estimation was carried out by summing up the height of floods (Figure 4, for example) in accordance with all meshes of paddies and dry fields (Figure 10). Figure 4 is the results of maximum inundated area and water depth, on 28 September 2000 and on 9 October 2003, respectively. The years 2000 and 2003 are the representatives of the recent largest flood and drought years.

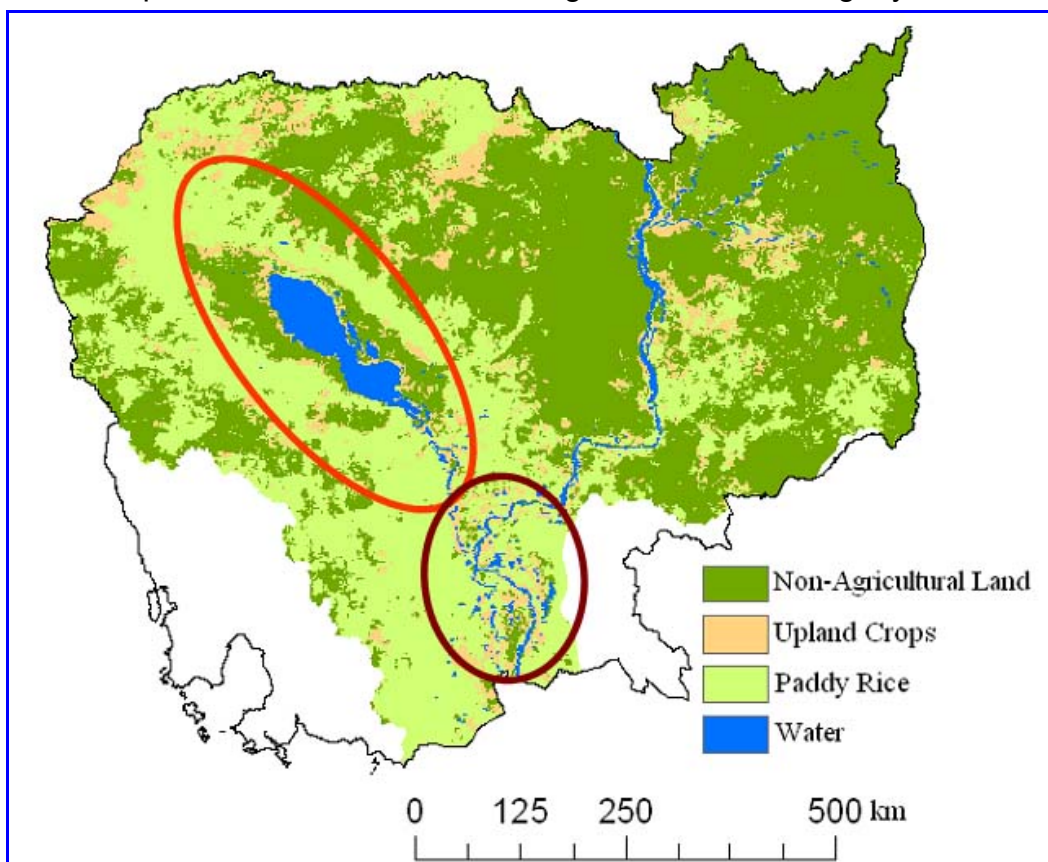


Figure 10: Land Use in and Around Tonle Sap Lake (Source: USGS).

Table 1 shows the calculated results for the flooded area of paddies, the flooded volume in the paddies, and the ratio of the flooded volume in the paddies to the total flooded volume. Take an example of the year 2000 flood for instance, about 42% ($12,249 \text{ km}^2 / 29,280 \text{ km}^2$) of paddies in Cambodia were affected, and it was estimated that paddies apparently stored 22.4% of the whole flooded volume in and around the Tonle Sap and its environs. Even for the recent smallest flood in 2003, the ratio of the flooded volume on the paddies accounts

for 15.1% of the total storage (apparent value at the peak). In total, the ratio of flooded areas to the total paddy area in Cambodia varied from 30% (2003) to 42% (2000).

Table 1: Estimated Inundation Area and Volume for Floods in 2000 and 2003.

Year	Flooded area of paddies (km ²)	Flooded volume in paddies (10 ⁹ m ³)	Ratio of flooded volume in paddies to the total (%)
2000 as a recent largest flood year	12,249	21.914	22.4
2003 as a recent drought year	5,527	8.171	15.1

The ratio of the flooded volume on paddies to the total flood was about 19%. Hence, we can say that roughly one-fifth of the total flood volume was stored on paddies in and around Tonle Sap Lake and its environs. In addition to the estimation of flooded volumes on paddies, flooding areas and the volume on dry fields were also calculated. The results of the estimation show that dry fields in and around Tonle Sap Lake were also flooded at the same or greater volume as paddies, while the size of the flooded areas/volumes on dry fields was not large compared with that of paddies in the colmatage area.

Conclusions and Discussions

A 2D-FEM model fitted well to geometric complexity of topography and boundaries of the study area. The model was successfully used to investigate the flood inundation process in the Tonle Sap lake area and its environs of the Mekong River Basin using the FEM (Finite Element Method) technique with 2-D shallow water equations. The model is based on an explicit two-step, finite element method that is capable of predicting water depth, mean velocities in the vertical direction, and the positions of wet and dry areas during water flow propagation. The model was applied to the water flows over the years 1996 through 2003. The model simulations showed real inundation processes of the study area. The model was applied to the inundation processes in the floodplains of Tonle Sap Lake and its environs, where hydro-meteorological data had been missing for a long time due to the civil war in the area. The simulated results on this area produced a lot of hydrologic information to us. As the demonstrated

analysis of the years 2000 and 2003, some excess water can be stored in the form of floods in many places, and stored floods can be released gradually, which enables farmers downstream to utilize the water. Furthermore, it can be conveniently applied to other river basins. This information can be used to assist agencies in developing emergency and evacuation plans and analyzing risk potential in the event of flooding.

Acknowledgments

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