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FLOOD INUNDATION MODEL FOR HIGHLY URBANIZED AREA AND ITS APPLICATION TO SIMULATE THE FLOOD INUNDATION IN 2004, KOFU CITY-JAPAN

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The flood inundation model for highly urbanized area is different with general flood inundation due to the increasing of the complexity of nature and internal boundaries. As consequences, the flow is complex and requires a stable numerical model to solve it. In this paper, the flood inundation model for highly urbanized area is presented. The explicit MacCormack scheme was used to solve the flow equations. The artificial viscosity scheme was added to reduce the numerical oscillations. The model was first verified by the benchmark tests. Here, the simulated results were compared with the analytical solutions. The good performance of the model was achieved. The model was applied to simulate and to evaluate the past flood inundation in 2004, Aioi area of Kofu, Yamanashi. Compared with the observed data, the model was satisfied to be applied in highly urbanized area. It could be a useful tool for the water authority and the local government to design the countermeasures, to identify the inundation processes and to determine the potential inundation hazard map.

Key Words: Flood inundation, highly urbanized area, MacCormack, artificial viscosity

1. INTRODUCTION

One of obvious impacts of urban development is the increase in run-off due to the introduction of significant impervious areas and gives larger flows when compare to pre-development condition. As consequences, the inundation occurred in areas where designated overland floodways not adequate to convey large flood flows.

Numerical model for flood inundation have been much developed. In general, the flood inundation model for highly urbanized area is different with other flood inundation model as the increase use of internal boundaries. The dense building, narrow street and solid structures should be taken in the modeling consideration. Because of complexity of the existing conditions, the simplified model such as diffusive waves approach was preferably chosen by many researchers such as in Dutta, D. *et al.*[1)], Bates, P.D, *et al.*[2)], Yu, D. *et al.*[3)] etc. In order to design the appropriate countermeasures and flood advices, the result of that model was not sufficient in giving detail flooding situation.

Recently, some advanced model has been developed. Kawaike *et al.*[4)] developed inundation flow and applied into highly urbanized area in Nagasaki city to identify the dangerous hazardous zones. Ozono *et al.*[5)] and Akiyama *et al.*[6)] applied unstructured grid to analyze the flood induced by Typhoon and dike breaching. Moreover some of models did not include yet the rainfall and infiltration processes in their approaches.

Discussion of flood inundation model in some papers generally refers to the Finite Difference (FD) type of model. The advantage of FD approach is that the computational grids are more readily sampled from the digital topography data and the results fit more easily into raster-based system with little efforts. Zhang *et al.*[7)] applied FD of two-dimensional flood inundation model in Kofu basin. However, In his model the dense building and structures were not considered yet. Neither were the rainfall and infiltration event during inundation processes.

Further urban development is still continuing. More information is being sought on the extend risk of flooding in urban area. Water authority and local government increasingly require digital maps of flood inundation for future planning. The numerical model is an effective tool to meet such kind purposes.

In this paper, a flood inundation model considering the rainfall and infiltration processes is introduced. An explicit MacCormack scheme combined with the artificial viscosity[8, 9] was used to solve the flow equations. The flood inundation at urbanized area of Kofu city was well simulated. The results were verified by the observed data. Finally, the model could be used for assessing the potential inundation hazard and to evaluate the inundation processes in the urbanized area.

2. NUMERICAL MODEL

Two-dimensional flows with consideration of lateral inflow (such as rainfall and infiltration and drainage capacity) can be described by the system of shallow water equations (SWEs). Neglecting the coriolis and wind forces, the matrix form of SWEs can be written in the following terms[10]:

$$U_t + E_x + F_y + S = 0 \tag{1}$$

$$U = \begin{pmatrix} h \\ u \\ v \end{pmatrix} \qquad E = \begin{pmatrix} uh \\ 0.5u^2 + gh \\ uv \end{pmatrix} \tag{2}$$

$$F = \begin{pmatrix} vh \\ uv \\ 0.5v^2 + gh \end{pmatrix} \quad S = \begin{pmatrix} -q_l \\ -g(S_{ox} - S_{fx}) \\ -g(S_{oy} - S_{fy}) \end{pmatrix} \tag{3}$$

$$S_{fx} = \frac{n^2 u\sqrt{u^2 + v^2}}{h^{4/3}} \qquad S_{fy} = \frac{n^2 v\sqrt{u^2 + v^2}}{h^{4/3}} \tag{4}$$

in which indices ***t***, ***x*** and ***y*** shows differentiation with respect to time and flow directions respectively. ***u, v, h*** are flow variables, ***g*** gravity acceleration, ***n*** Manning hydraulic roughness, S_{ox} slope in ***x***-direction, S_{oy} slope in ***y***-direction. q_l represents the net lateral inflow. If rainfall and infiltration are being considered, then net lateral inflow is [***(R(t)-I(x,y,t)***]. ***R(t)*** is rainfall intensity and ***I(x,y,t)*** is infiltration rate.

3. METHODOLOGY

(1) The explicit MacCormack scheme

The MacCormack is explicit, two–step of predictor-corrector scheme. It is second order accurate both in space and time and capable to capture the shocks without isolating them. This scheme has been applied by Fennema and Chaudry and other numerical models[8,9]. There are two-steps in MacCormack scheme, which are:

- ***Predictor step***

$$U_{i,j}^{*} = U_{i,j}^{k} - \frac{\Delta t}{\Delta x}\nabla_x E_{i,j} - \frac{\Delta t}{\Delta x}\nabla_y F_{i,j} - \Delta t S_{i,j} \tag{5}$$

- ***Corrector step***

$$U_{i,j}^{**} = U_{i,j}^{k} - \frac{\Delta t}{\Delta x}\Delta_x E_{i,j}^{*} - \frac{\Delta t}{\Delta x}\Delta_y F_{i,j}^{*} - \Delta t S_{i,j}^{*} \tag{6}$$

where

$$\nabla_x E_{i,j} = E_{i,j} - E_{i-1,j}, \; \nabla_y F_{i,j} = F_{i,j} - F_{i,j-1} \tag{7}$$

$$\Delta_x E_{i,j}^{*} = E_{i+1,j}^{*} - E_{i,j}^{*}, \; \Delta_y F_{i,j}^{*} = F_{i,j+1}^{*} - F_{i,j}^{*} \tag{8}$$

The subscripts ***i*** and ***j*** refer to the grid points in the ***x*** and ***y*** directions respectively. The superscript ***k*** refers to the variable at the known time level, ******* refers to the variables computed at the end of predictor part, and ******** refers to the variables at the end of the corrector part. Finally, ***U*** at the unknown time level ***k+1*** is determined from:

$$U_{i,j}^{k+1} = \frac{1}{2}\left(U_{i,j}^{*} + U_{i,j}^{**}\right)$$

The differencing sequences of $\nabla_x, \nabla_y, \Delta_x$ and Δ_y in (5) and (6) could be alternated each time step to remove directional bias of this scheme.

(2) Artificial viscosity

The MacCormack scheme produces high-frequency oscillations near the steep gradients. These oscillations can be reduced by applying the artificial viscosity to the conserved variables. This approach has been used by Fennema and Chaudry. The diffusion coefficient is computed from a normalized form of gradients of one of the water depth, ***h***. It also depends on the dissipation constant, κ, which is used to regulate the amount of dissipation as suggested in Chaudry[8].

In this procedure, first, determine the following parameters from computed value of ***h*** at the ***k+1*** time level.

$$\nu_{\xi_{i,j}} = \frac{\left|h_{i+1,j} - 2h_{i,j} + h_{i-1,j}\right|}{\left|h_{i+1,j}\right| + \left|2h_{i,j}\right| + \left|h_{i-1,j}\right|} \quad \text{for } x\text{-direction} \tag{9}$$

$$\nu_{\eta_{i,j}} = \frac{\left|h_{i,j+1} - 2h_{i,j} + h_{i,j-1}\right|}{\left|h_{i,j-1}\right| + \left|2h_{i,j}\right| + \left|h_{i,j-1}\right|} \quad \text{for } y\text{-direction} \tag{10}$$

Then, the following equations could be determined.

$$\varepsilon_{\xi_{i+1/2,j}} = \kappa . \max\left(\nu_{\xi_{i+1,j}}, \nu_{\xi_{i,j}}\right)$$

$$\varepsilon_{\xi_{i-1/2,j}} = \kappa . \max\left(\nu_{\xi_{i-1,j}}, \nu_{\xi_{i,j}}\right)$$

$$\varepsilon_{\eta_{i+1/2,j}} = \kappa.\max\left(\nu_{\eta_{i,j}}, \nu_{\eta_{i,j+1}}\right)$$
$$\varepsilon_{\eta_{i-1/2,j}} = \kappa.\max\left(\nu_{\eta_{i,j}}, \nu_{\eta_{i,j-1}}\right) \quad (11)$$

The final values of the variable *U* at the new time step are computed from the following equations:

$$\begin{aligned} U_{i,j}^{k+1} = U_{i,j}^{k+1} &+ \varepsilon_{\xi_{i+1/2,j}}\left(U_{i+1,j}^{k+1} - U_{i,j}^{k+1}\right) \\ &- \varepsilon_{\xi_{i-1/2,j}}\left(U_{i-1,j}^{k+1} - U_{i,j}^{k+1}\right) \\ &+ \varepsilon_{\eta_{i,j+1/2}}\left(U_{i,j+1}^{k+1} - U_{i,j}^{k+1}\right) \\ &- \varepsilon_{\eta_{i,j-1/2}}\left(U_{i,j-1}^{k+1} - U_{i,j}^{k+1}\right) \end{aligned} \quad (12)$$

U refers to *u, v* and *h*. This procedure is equivalent to adding second order dissipative terms to the original governing equations. As can be seen, its influence in the smooth regions is minimal since ν tends to be zero. The value of κ is selected such that it is small as possible and at the same time smoothes the high-frequency oscillations. $\kappa = 0.30$ is recommended as initial trial value[8].

(3) Numerical stability

For the stability reason of the scheme, the Courant-Friedrich-Lewy (*CFL*) number, C_n, is taken less than or equal to 1.

$$C_n = \frac{\textit{actual wave velocity}}{\textit{numerical wave velocity}} \quad (13)$$

Thus, the computational time interval depends upon the spatial grid spacing, flow velocity and celerity which are function of the flow depth.

(4) Adaptive time step algorithm

Since the flow depth and velocity may significantly change during the computations, it is necessary to change the size of computational time interval, Δt, to accelerate the computation. The time interval should be such that C_n is as close to 1 as possible. The time interval is adjusted dynamically according to a fixed maximum CFL number. It is given as:

$$\Delta t \le CFL.\min\left(\frac{\Delta x}{\left\langle |u| + \sqrt{gh}\right\rangle_{max}}, \frac{\Delta y}{\left\langle |v| + \sqrt{gh}\right\rangle_{max}}\right) \quad (14)$$

This condition must be satisfied at each grid point during every computational interval. It is expected that Δt will automatically small when the flow changes rapidly and *vice versa*.

(5) Boundary conditions

There are two types of boundary condition imposed on the model, namely open boundary and wall boundary.

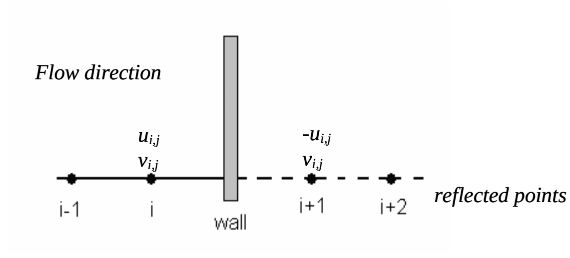

Fig. 1 Wall boundary conditions.

1. *Open boundary.* Open boundary condition is applied at the interface of cells (such as inlet and outlet). It was solved by the characteristics method[8].
2. *Wall boundary.* It is imposed on the internal boundaries such as wall, buildings and other solid structures. It is set as slip condition by reflecting and changing the sign of normal component of velocity as shown in **Fig.1**.

To start the computations, the initial values of *u,v* and *h* at time *t=0* are specified at all grid points.

4. RESULT AND DISCUSSION

(1) Benchmark tests

First, the performance of the model and the stability of algorithm were tested on set of classical test cases. Details are provided in literatures[11, 12, 13].

1-D example problems

Steady transcritical flow in frictionless of 25-m long channel with a bump. Detail geometry was provided by Zhou *et al*[11]. The domain was partitioned with 100 cells and Δx=0.25m. Discharge unit q=0.18m^2/*s* was imposed at the upstream and h=0.33m was specified as the downstream boundary condition.

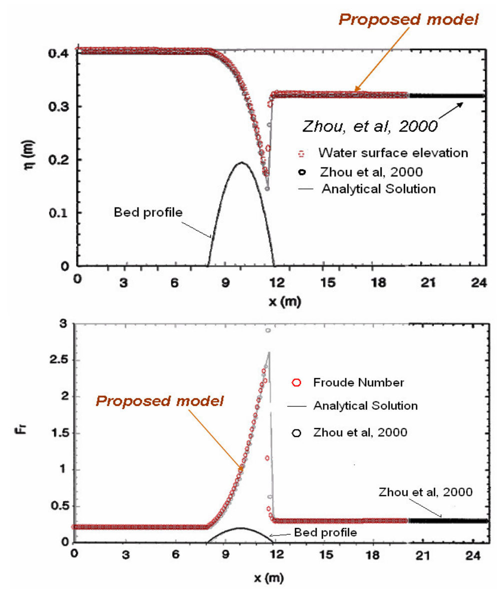

Fig. 2 The comparison results of proposed model (red-circle, o) and result of Zhou *et al.*[11].

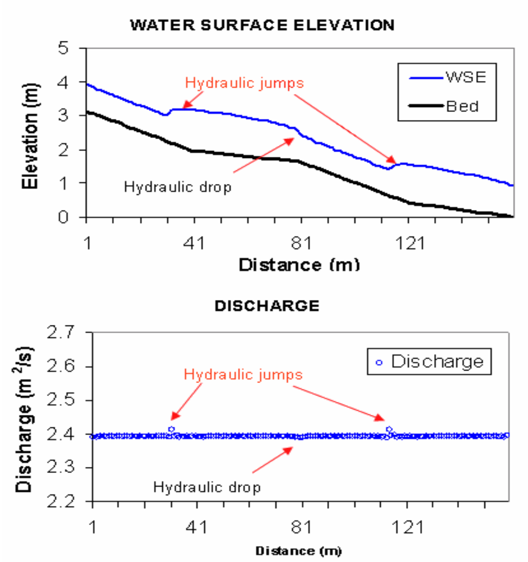

Fig. 3 The simulation results of flow over rough variable topography, according to Tseng *et al.*[12].

The result compares favorably with Zhou *et al.*[11] as shown in **Fig.2**. The model gave smooth water profile and Froude number, along the channel. The ability of the proposed scheme to capture the shock was obviously shown. Another benchmark test was done for a flow over rough variable bed topography provided by Tseng *et al.*[12]. Result of the proposed model was shown in **Fig. 3**. The water surface, the hydraulic jumps and hydraulic drop were solved well without any oscillations. The variation discharge along the channel also could be accurately conserved with excellent mass conservation.

2-D example problem

A two-dimensional asymmetrical dambreak problem has been selected as a benchmark test case for shock capturing numerical model in 2-D flow according to Liang, *et al.*[13]. A square domain was considered, with a side length of 200m and grid size of 5m. The bed was flat and frictionless. A 15m thick dam at x=100m initially separated headwater, with reservoir depth of 10m and the tail water was 5m in depth. A breach located at y=95m–170m occurred suddenly. The water surface and flow velocity at 7.2s after the breach were examined. Also, the result compares favorably with Liang, *et al.*[13].

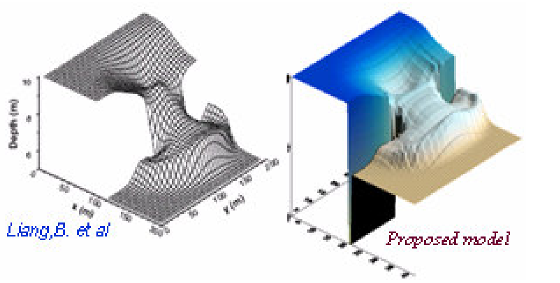

Fig. 4 The comparison results of water surface at 7.2s for 2-D dam-break problem.

In general, the benchmark tests gave acceptable results. Then the model was judged as satisfy enough to be applied into a real situation, especially for highly urbanized area where increasing internal boundaries makes mixed flow condition and occurrence of shocks and other hydraulic phenomena.

(2) Application of model in Aioi area, Kofu city

Kofu is capital city of Yamanashi prefecture in Japan. In the Aioi area, the capacity of drainage channel was not sufficient to discharge storm water during heavy storm event. In August 2004, heavy storm occurred. Channel was overflowed and water flooded to the residence area. Detail location of area study and inundation area was shown in **Fig.5**.

(3) Model structure

The grid mesh was derived from the digital elevation model based on the Laser Data Profiling (LDP) survey within 2-m resolution. The computational domain was drawn in **Fig.6**.

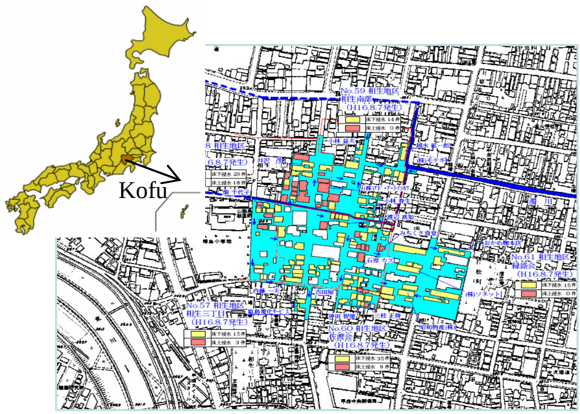

Fig. 5 The map that showed the location of 2004-flood inundation area in Kofu city.

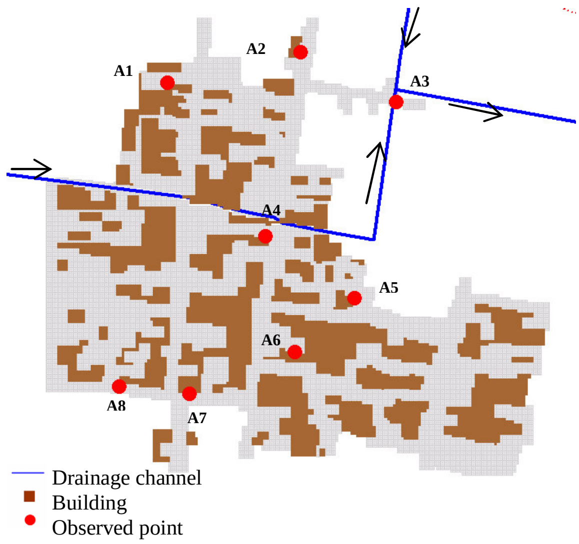

Fig. 6 The computational meshes with 1m x 1m of structured grids were sampled from DEM.

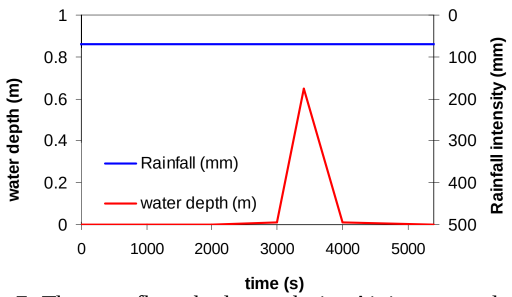

Fig. 7 The overflow hydrograph in Aioi area and rainfall intensity, from Hirabayashi[14].

The structured rectangular grid was imposed to the computational domain of area of study. The building and other solid structures were treated as solid walls in the model. At the outer-edge of boundary area, the transmissive boundary was applied in order to account for the characteristics leaving the domain which allow waves to pass without reflection.

(4) Flood scenario and assumption

In 2004, the rainfall record showed that heavy storm with 78mm/hr of intensity resulted severe inundation in Aioi area. In order to simulate and assess the inundation processes, the reconstructed hydrograph overflow of channel in this area was required as input of the model. **Fig. 7** showed the overflow hydrograph provided by the recent study[14]. A heavy rainfall had occurred since the beginning. The overflow started at 3000*s* and finished at 4000*s*. The hydrology data (hydrograph, rainfall intensity and infiltration rate) was used as input data. The field survey gave the value of hydraulic roughness in this area (*n*) was ranging from 0.011 (concrete) to 0.030 (weedy floodplain). The topography of the area was basically almost plain. Infiltration rate was assumed as 1 mm/hr. The main drainage was considered as open channel flow.

(5) Calibration and verification

The inundation depth of 2004-flood at several locations were investigated by Kofu city office. These investigation results were compared with the simulation results of this model and were used for numerical calibration and results verification.

(6) Inundation Process

The map of inundation at *t*=3500*s* was drawn in **Fig. 8**. The maximum inundation depth was 0.54m. The inundation processes were evaluated by analyzing the inundation hydrographs at observed points. Results showed that the inundation areas could be classified into two-groups. First, the areas which were quickly drained when overflow was finished (A1, A2 and A3).

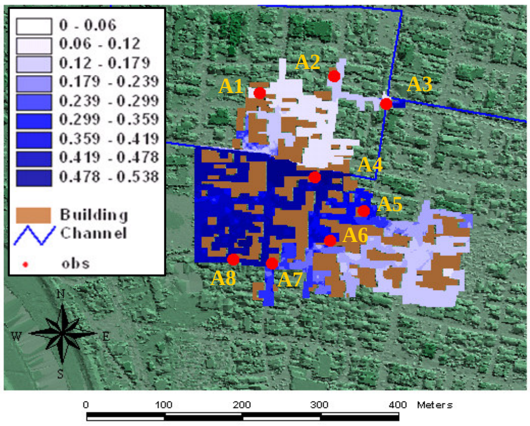

Fig. 8 The map that showed simulation results of inundation depth in Aioi area at *t*=3500*s*.

Second, the areas which were still inundated after overflow was finished (A4, A5, A6, A7 and A8). The identification of inundation processes was necessary and useful for the evacuation planning and the appropriate countermeasures. The inundation hydrographs at observed point were shown in **Fig. 9**. It showed that heavy rainfall occurred since the beginning of 3000*s* gave shallower surface runoff in areas of A3 rather than in A5. When the overflow was finished (t >*4000s*) the area A3 was quickly drained. The area A5 was still inundated and slowly drained. The vector of flow velocity at *t*=3500*s* was also drawn in **Fig. 10** below.

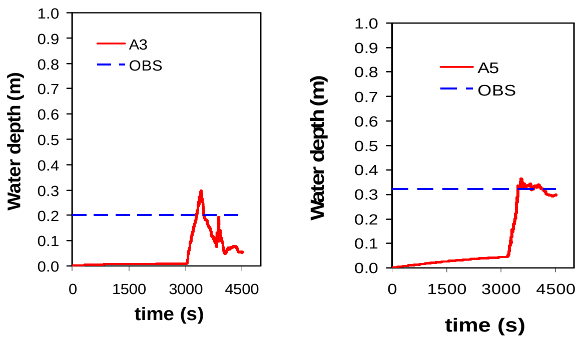

Fig. 9 Hydrograph inundation at point A3 and A5.

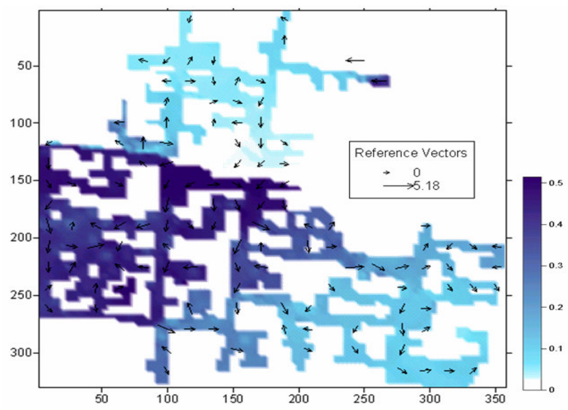

Fig. 10 The simulated flow velocity at *t*=3500*s*.

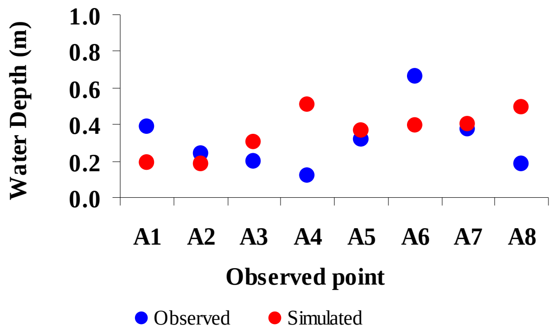

Fig. 11 Comparison of the maximum inundation depth between observed and simulated.

The comparison of the maximum of inundation depth between the observed and the simulation results was drawn in **Fig. 11**. For the maximum of inundation depth at the area A1 and A6, the simulation gave lower values than observed. At the A4 and A8, the maximum of inundation depth were higher than observed. Considering the complex nature of the problems, error of observed data and the uncertainty of overflow hydrograph, the overall results were still acceptable. Finally, the proposed inundation model was able to be applied in highly urbanized area and gave acceptable results.

5. CONCLUSION

A 2-D numerical model of flood inundation for highly urbanized area was successfully developed. The inundation model for urbanized area was different with other flood models due to increasing of internal boundaries. These boundaries produced shocks and flow discontinuity. The explicit MacCormack combined with artificial viscosity scheme had some advantages in calculation of the flow with steep gradient and shocks. In this model, the MacCormack scheme and artificial viscosity were successfully applied to simulate flood flows in urbanized area.

Compared with the investigation data, the overall result of the model could be regarded as acceptable. It was able to reconstruct the past flood and to evaluate the inundation processes. The model was useful for the city flood control to simulate the potential flood in diverse areas. Since the current model simplified the existing sewerage system, it is necessary to incorporate the full drainage systems of the city into the further improvement of the model.

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