農業土木学会論文集
Trans. of JSIDRE
No. 210, pp. 7 ~ 12 (2000. 12)

研究論文

Flood Routing Model for Drainage Analysis in Natural River Watershed

— A Case Study in Ciliwung River, Indonesia —

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Abstract

A flood routing model has been formulated and applied to the natural rivers flowing through the western region of Jakarta, West Jawa, where floods cause severe damages every year. The model consists of the tank model for analyzing the discharge of direct runoff due to torrential rainfall and the hydrodynamic model for routing the behavior of the flow in the river network. The parameters of the tank model were calibrated based on the observed data of actual rainfall and discharge, while the hydrodynamic model was numerically solved by using Preissmann scheme. By utilizing interior boundaries, the geometry of the mountainous river channel having steep slope was approximated by a stepwise channel in order to exclude the supercritical flow. The applicability of the model was recognized with satisfactory results in routing water surface and the model was applied for demonstrating the effectiveness of three drainage projects planned to mitigate flood disasters.

Keywords : Indonesia, mountainous river, drainage project, flood rooting, Preissmann scheme, interior boundary

1. INTRODUCTION

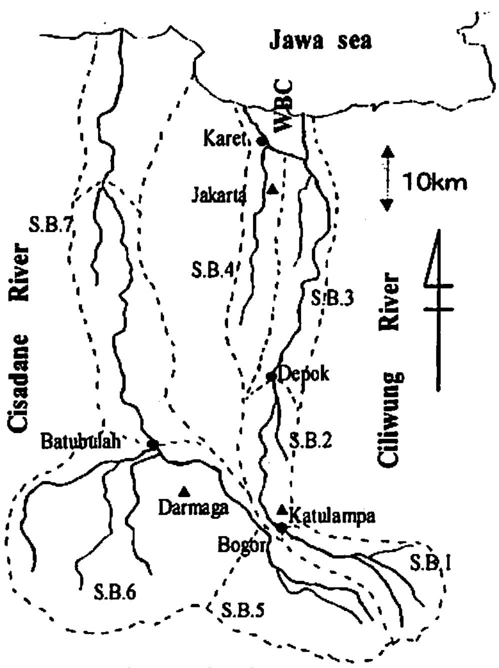
Recently flood prevention projects are designed not only in local inundation area but also in the whole watershed because severe inundation area is usually located in downstream high populated or urbanized area so that river improvement at the area is often difficult to achieve demanded carrying capacity. Jakarta city area, Indonesia is suffering from flood disasters due to torrential rainfall every year. Therefore integrated flood prevention projects were planned in both upstream and downstream areas. The objectives of this study are to develop a flood routing model for wide natural river watershed, and also to apply the model to the evaluation of the project planned for preventing flood disasters.

The model consists of the tank model for analyzing the discharge of direct runoff due to torrential rainfall and the hydrodynamic model for routing the behavior of the flow in the river network. The tank model, which is a conceptual and lumped type one, requires a few input data and has been widely used for both long or short term analysis, and the hydrodynamic model was numerically solved by using Preissmann scheme. The Preissmann's implicit finite difference scheme was employed in this study, because numerical time step Δt and distance Δx can be set freely so that it is good for long term analysis, combining with hydrological model and direct utilizing of topographic data which were usually observed at irregular intervals. Various models based on the Preissmann scheme have been applied as the practical method to the one dimensional flood routing modeling in the field of hydraulic engineering and presented in several papers or textbooks (Abbott 1979; Chaudhry 1993), however it is great practical importance to address its limitations for applying to natural rivers. The Preissmann scheme is invalid for transcritical flow which was characterized by the existence of both supercritical and subcritical flows within the considered domain. Meselhe (1997) showed that the origin of this peculiar problem was the mismatch in the number of equations and the number of unknowns. It becomes serious problem in mountainous rivers. In many cases, kinematic model or explicit schemes are employed for calculating unsteady flow at the steep channel where there are possibilities of occurring transcritical flows. However those schemes have limitation of very short time step Δt by Courant-Friedrichs condition. It is main purpose to simulate unsteady flows with same algorithm and long time step in the all domain. Therefore, in this study many combined interior boundaries were used in 40 km length along mountainous river part to eliminate supercritical flow. Although that approximation of riverbed slope can't express local transcritical flow accurately, it can yield more advantages in long term runoff modeling of wide range watershed.

2. STUDY AREA

Floods caused severe damages in the western region of Jakarta, West Jawa, in Indonesia every year especially in 1996. The region is classified tropical zone influenced by two seasonal monsoons, and annual average rainfall is about 1,800 mm in the northern plain area around Jakarta and more than 4,000 mm in the southern mountainous area around Bogor city. Both elevation and amount of rainfall increase as going to south, and the rainfall peak is usually recorded in January or February.

The main rivers flowing through the region are the Ciliwung and the Cisadane rivers as shown in **Fig.1**. The catchment areas of two rivers are 421 km^2 and 1,411 km^2, and their lengths are 110 km and 140 km, respectively. Each river consists of 4 and 3 sub-basins. The Ciliwung river flows through the central part of Jakarta and often causes floods in downstream plain area. Therefore, the Western Banjir release Canal (WBC) was constructed to reduce a flood discharge at the downstream of the Ciliwung river. However the central Jakarta is still suffering from flood damages until now. The widening of the WBC to improve it's discharge capacity was planned, but it was not implemented because of the highly populated area.



▲ rain gauged station

● water level gauged station

S.B sub-basin

Fig.1 The Western Region of Jakarta

The rainfall and runoff patterns in the region showed the torrential rainfall at the upper basin caused flood disaster in it's downstream. Therefore, a floodway was planned to divert a substantial amount of water from the upstream Ciliwung river to the adjacent Cisadane river at a suitable site in Bogor City.

3. MODELS of ANALYSIS

3.1 Rainfall-Runoff Model

Fig.2 shows a series of tanks used for the rainfall-runoff model. The tank model, which is a conceptual and lumped type one, requires a few input data and has been widely used for the long or short term analysis. In addition to the simple structure of the model, it can also express the non-linear runoff process by adjusting the positions of the outlet holes such as $h1 \sim h5$. Generally, the top tank gives the surface runoff, the second gives the infiltration and surface layer runoff, and the third and fourth give the ground water runoff.

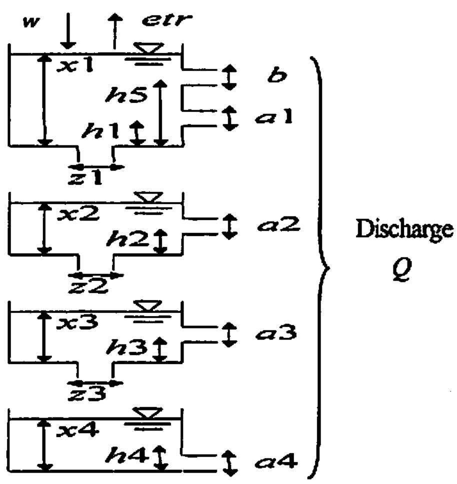


Fig.2 Tank Model

The basic equation for the top tank storage (i =1)is ;

$$-\frac{\Delta X(i)}{\Delta t} = a(i)\{X(i)-h(i)\} + z(i)X(i) + b\{X(i)-h(i+4)\} - w + etr \qquad (1)$$

and for other tank storage ($i = 2 \sim 4$, $z4 = 0$) ;

$$-\frac{\Delta X(i)}{\Delta t} = a(i)\{X(i)-h(i)\} + z(i)X(i) - z(i-1)\cdot X(i-1) \qquad (2)$$

where ; X = depth of storage, a,b = coefficient of outlet hole, h = height of outlet hole, z = coefficient of infiltration hole, etr = evapotranspiration rate, w = rainfall depth, Δt = time step.

And river runoff discharge Q is calculated as follows ;

$$Q = b\cdot(X1 - h5) + \sum_{i=1}^{4} a(i)\cdot\{X(i)-h(i)\} \qquad (3)$$

3.2 Hydrodynamic Model

A gradually varied unsteady flow in an open channel is mathematically described by the St.Venant equations. The governing continuity and movement equations are as follows ;

・continuity equation

$$\frac{\partial A}{\partial t}+\frac{\partial Au}{\partial x}=0 \tag{4}$$

・movement equation

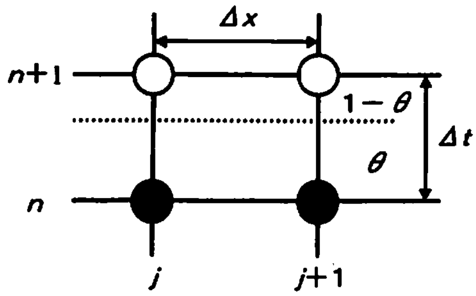
$$\frac{\partial u}{\partial t}+\frac{\partial}{\partial x}\left(\frac{u^2}{2}+gh\right)=g\left(S_0-S_f\right)$$

$$S_f=\frac{n^2|u|u}{R^{4/3}} \tag{5}$$

where ; A = wetted cross-sectional area, g = gravitational acceleration, S_f= friction slope, S_0= bottom slope, R = hydraulic radius, n = Manning roughness coefficient, t = time, x = distance along the channel, h = water depth, u = mean velocity

3.2.1 Preissmann Scheme

Fig.3 shows the structure of the Preissmann scheme. The value of 0.55 was chosen for the weight factor θ based on Fread's research (1973), which must be within the range of $0.5 \leqq \theta \leqq 1.0$ for the unconditional stability.



O:unknown ●:known

j : node number, n : time level

Δt : time step Δx : node distance

Fig.3 Preissmann Scheme

In order to solve the discretized equations, the Newton-Raphson method was employed, where nonlinear discretized equations were expanded around the provisional solutions and approximated by linear equations as follows;

・continuity equation

$$a\cdot\Delta h_{j+1}+b\cdot\Delta h_j+c\cdot\Delta u_{j+1}+d\cdot\Delta u_j=e \tag{6}$$

・momentum equation

$$p\cdot\Delta h_{j+1}+q\cdot\Delta h_j+r\cdot\Delta u_{j+1}+s\cdot\Delta u_j=y \tag{7}$$

where $a, b, c, d, e, p, q, r, s, y$ = coefficients resulting from the linearization, j = node number and Δ denotes a correction to a provisional solution. Eqs.(6) and (7) are written for every reach connecting two nodes in the computational domain. The provisional solutions are improved by solving resultant linear equations, and this process is repeated until a desirable accuracy is achieved. These linealized equations usually form a banded matrix, so the double sweep method (Cunge et al 1980) can be applied to the objective linear equation system.

3.2.2 Interior Boundary

As the Preissmann scheme is valid only for the pure subcritical or supercritical flow, it is invalid for transcritical flow. Many researches had been done to apply the Preissmann scheme to transcritical flow. Reducing or totally dropping the convective terms from the momentum equation is a common practice used when the Preissmann scheme is applied to transcritical flow (Abbott et al 1991). Some other researchers solved the mass and a reduced Bernoulli equation instead of the standard St.Venant equation to simulate transcritical flows using the Preissmann scheme (Kutija 1993). However, very little attention was devoted to analyzing the origin of the invalidity. In this study, the interior boundaries, distinguished from the exterior boundaries like upstream or downstream ones, were used to represent special places or hydraulic structures such as junction, gate, or weir, and they were also used to eliminate supercritical flow (Liggett and Cunge 1975). Three typical hydraulic structures having three or two interior boundaries are shown in Fig.4 (a)-(c). Compatible equations, which usually consist of continuity and energy equations, connect those interior boundaries (Kubo and Nakase 1994). By using several interior boundaries representing small weirs, steep river bed was approximated by a stepwise channel to exclude the supercritical flows from simulated flows (Fig.5).

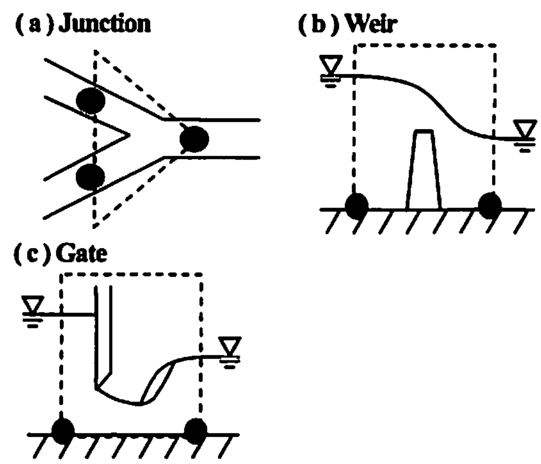


Fig.4 Examples of Interior Boundary

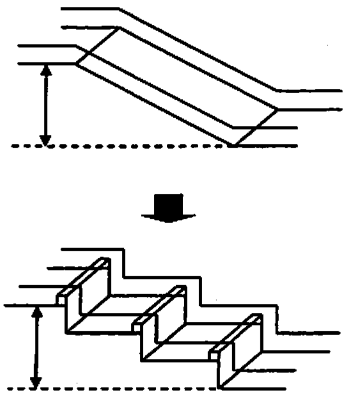
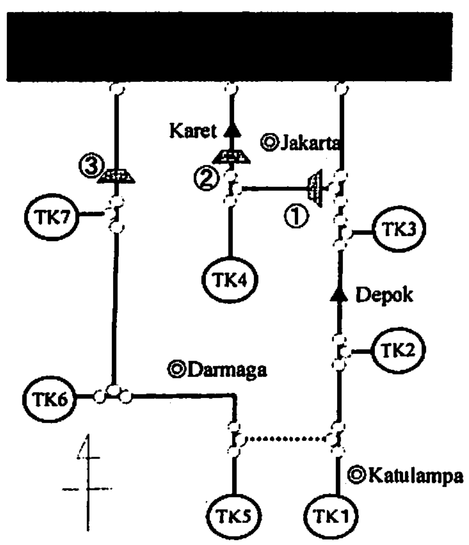


Fig.5 Alternation of Steep Slope Channel

4. APPLICATION

4.1 Modeling of Study Area

To apply the proposed flood routing model, the western region of Jakarta was schematized in **Fig.6** showing the sub-basins and river network. In **Fig.6**, solid lines and broken line show river channels and release canal where flows were analyzed by hydrodynamic model and Tk is sub-basin tank where direct runoff were calculated by the tank model. River cross-sections were approximated by rectangular ones along the main courses based on 94 and 105 available cross-sectional data for the Ciliwung and the Cisadane rivers, respectively. The exterior boundaries for the dynamic model were runoff discharges simulated by tank models and tide levels observed at the Jawa sea, while the interior boundaries were applied to 3 control gates located downstream of each rivers, and also to mountainous river having steep bed slope in order to prevent the occurrence of supercritical flows.



TK : sub-basin tank, ◎: rainfall station

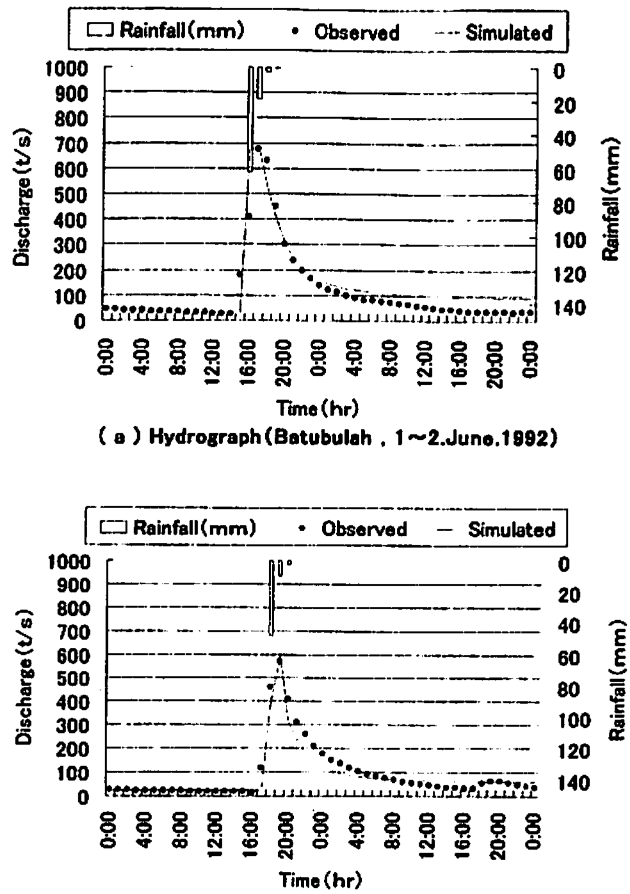
O: channel junction

▲: stream gauging station , ①-③ : gate

Fig.6 Schematized Study Area

4.2 Results of Runoff Analysis

To each of the 7 sub-basins, tank model was applied and it's parameters were calibrated based on observed floods in June and December 1992, which were the latest hourly discharge data. The simulated runoff hydrographs at Batubulah station are shown in **Fig.7(a)** and **7(b)**. The simulated and observed results are in good agreement for both magnitude and timing of peak discharge.



(a) Hydrograph(Batubulah , 1~2.June.1992)

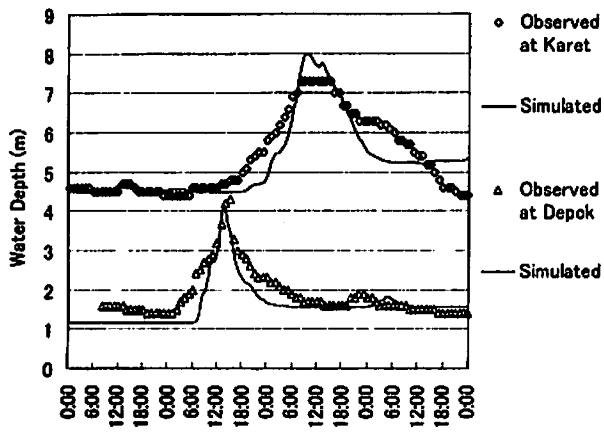
(b) Hydrograph(Batubulah , 20~21.Dec.1992)

Fig.7 Simulated Hydrographs of Tank Model

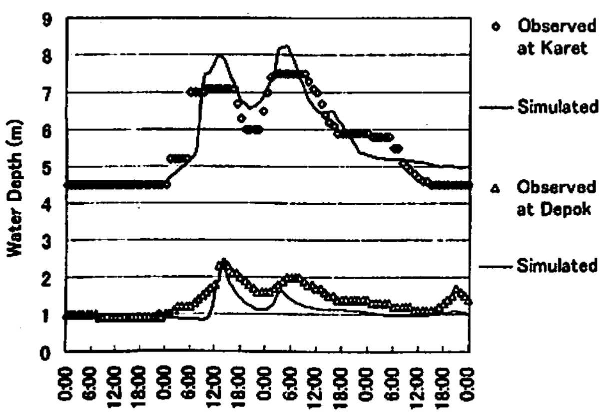
4.3 Results of Water Surface Routing

With the tank model, unsteady flows were simulated by hydrodynamic model using flood data in January and February 1996. The flood pattern in January was due to 50 years' return period rainfall at the upstream region, and that in February was due to 100 years' return period rainfall at downstream region. Computational time step Δt was set to 1200 s for both cases.

For the flow simulation in the river network, the coefficient of energy loss is the key parameter for the model calibration. The observed data of water depth from the gauged station at Depok in January were used to calibrate the value of Manning's coefficient n because water depths at Depok station did not exceed the embankment. The value of the Manning's n was determined to be 0.059 depending on relative error between simulated and observed results, and it was within an adequate range for the meandering natural river having vegetated irregular bank. Then the model was verified based on the observed data in February. The results of calibration and verification at Depok and Karet stations are given in **Fig.8(a)** and **8(b)**. The simulation results are in good agreement with the observed ones for both the magnitude and timing of peak water depth excepting the peak depth of at Karet station. Rather large differences at the raising and reducing periods of the peaks were attributed to utilizing of the lumped type runoff model and rectangular approximation of the river cross section. The water depths observed at Karet station both in January and February showed flat at every peaks due to embankment overflow. Actually the height of embankment at Karet was 7.1m. In this model simulation, the embankment overflow was not considered.



(a) Calibration (5-8 January 1996)



(b) Verification (9-12 February 1996)

Fig.8 Calibration and Verification Results

4.4 Case Study for Flood Prevention

In the previous analysis, the applicability of the proposed model to water surface simulation was confirmed with satisfactory accuracy. Then the model was used to evaluate the effectiveness of three projects planned for mitigating the flood disasters by simulating the flood in January.

The planned projects are shown as follows ;

Case① :

The channel widening by 10 m along the Western Banjir Canal to increase it's carrying capacity

Case② :

The flood peak cut by connecting the upstream Ciliwung river to the upstream Cisadane river with a rectangular release tunnel having 8 m wide and 1 km length

Case③ :

The integrated project of Case① and ②

The demonstrated water depth at Karet station located in the inundated area were shown in **Fig.9**. In Case.1 about 10 % mitigation effect was expected for the peak depth. And in Case.2 as well as in Case.3, about 20 % and 26 % mitigation effects were estimated, respectively. From these results and rainfall patterns in the study area, the flood diversion project in upstream area was concluded to be effective one for flood mitigation in downstream area.

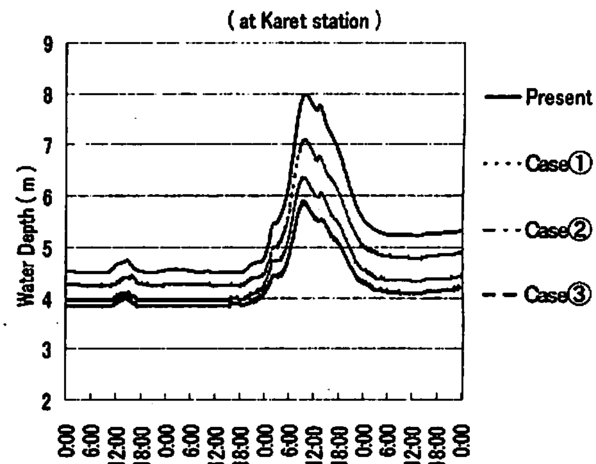


Fig.9 The Effect Prediction of three Project Cases

5. CONCLUSIONS

The flood routing model was developed by combining tank model and hydrodynamic model, and it's applicability was demonstrated through it's application to the natural rivers flowing through Jakarta. The interior boundaries, which can express hydraulic structures or etc., were utilized to exclude supercritical parts from numerically calculated flows and the simulation results were in good agreement with the observed ones. Then flood prevention project planned in Jakarta was evaluated with the proposed model. However the model still needs further improvement for practical applications. First, it should be developed to deal with the compound channel, and second, the inundation phenomena also should be modeled.

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(Received Feb. 3, 2000, Accepted Sep. 27, 2000)
(Questions and/or discussions on this paper for public debate will be accepted before Jun. 24, 2001)

自然河川流域における排水解析を目的とした洪水追跡モデル

インドネシア国チリウン川を対象として

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要旨

現在インドネシア国首都ジャカルタでは毎年の河川氾濫による被害軽減のため、下流氾濫域とその洪水の原因となる上流域において総合的な排水事業を計画している。本研究では集水域から河川への流出をタンクモデルにより、河川ネットワークにおける水移動をプライスマン型非定常モデルにより解析を行った。上流の渓流河川においては複合内部境界条件を用いて河床を階段状に近似し、同一スキームでの非定常計算が可能なモデルを構築した。構築したモデルによる実洪水の再現性は良好であり、計画されている事業効果についてシミュレーションにより検討した。

キーワード：インドネシア、渓流河川、排水事業、洪水追跡、プライスマンスキーム、内部境界条件