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INUNDATION FLOW ANALYSIS IN THE ISAHAYA LOW-LYING AREA AND ITS APPLICATION TO FLOOD MITIGATION PLAN

By

K. Kawaike
Faculty of Engineering, Nagasaki University, Nagasaki, Japan

H. Maruyama
Graduate School of Science and Technology, Nagasaki University, Nagasaki, Japan

S. Yoshimoto
Sanki Construction Company, Fukuoka, Japan

and

M. Noguchi
Faculty of Engineering, Nagasaki University, Nagasaki, Japan

SYNOPSIS

In this study, a comprehensive inundation flow model, which is comprises of a one-dimensional unsteady flow model, a two-dimensional inundation flow model and a runoff model, is developed and applied to the Isahaya low-lying area, in Nagasaki Prefecture. The validity of this model is investigated by comparing it with the actual records of the inundated area and water level of the river network. Then, as an application example of this model to flood mitigation plan, the effects of the pump capacity improvement on the inundated area and water level of the river channel are discussed.

INTRODUCTION

Recently in Japan, flood disasters due to heavy rainfall occur frequently in highly urbanized areas, which result in severe damage over a large area. As countermeasures against these kinds of inundation disasters, not only structural countermeasures but also non-structural ones have been adopted such as publishing "hazard maps" for flood disasters by many local governments in Japan, which include both potential hazardous areas for flood disasters by using numerical simulations and evacuation information such as shelters and evacuation routes. Therefore, accurate simulation models for inundation flow analysis have become more and more necessary as one of the countermeasures against flood disasters.

In this study, a numerical model, which can simulate inundation flows due to heavy rainfall by considering the effects of land use, streets, small channels and hillside areas, is proposed. This model is then applied to the Isahaya low-lying area in Nagasaki Prefecture, Japan, which has been suffering from frequent flood disasters due to heavy rainfalls. As a practical application example of this model, the effect of a hypothetical pump capacity on the inundated area and the water level of the river channel is discussed.

ISAHAYA LOW-LYING AREA

Isahaya City is located in the western part of Japan as shown in Fig.1. This city is located in a low-lying area facing Isahaya Bay, so it has problems with rainwater drainage and has sustained frequent inundation damage due to heavy rainfall.

In 1957, the Hommyo River, which runs through the central part of the Isahaya City, overflowed due to heavy rainfall and a large amount of driftwood, and caused a severe flood. Most of the low-lying area was inundated and more than 500 people were killed in this disaster. Thereafter, the manager of the Hommyo River was changed from the local government to the ministry of construction, and there has not been any floods due to overflowing from the Hommyo River since then.

However, the Isahaya low-lying area began to sustain frequent inundation damage due to heavy rainfall recently. In 1999, heavy rainfall hit the Isahaya City. The temporal change of

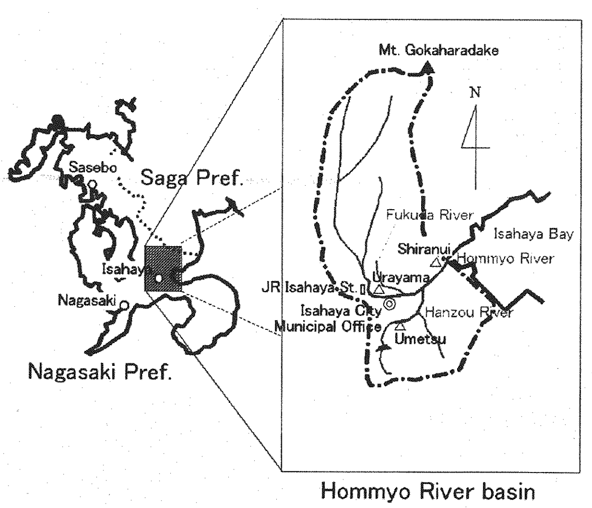


Fig.1 Location of Isahaya City

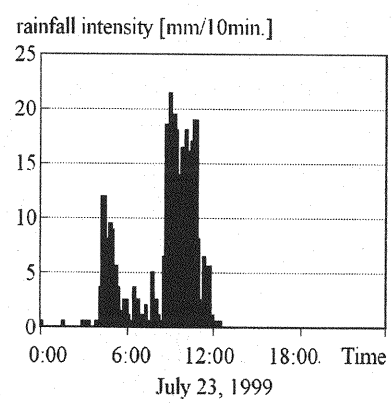


Fig.2 Rainfall intensity observed at Isahaya City

rainfall intensity observed at Isahaya City every 10 minutes is shown in Fig.2. The maximum rainfall intensity was 95mm per hour, and the total rainfall amounted to 347mm. This heavy rainfall caused inundation damage and a large part of the low-lying area was inundated as shown in Fig.3. The cause of this disaster was not due to floodwater from the Hommyo River, but due to heavy rainfall and insufficient capacity of drainage system.

Now, as countermeasures against inundation disasters, various kinds of facilities have been planned or constructed in the Isahaya City. Furthermore, to prepare for cases where flood control facilities have no effect for some unexpected reasons, "hazard maps" with information about inundation water depth and evacuation system were distributed to citizens. Fig.4 is a "hazard map" for flood disasters of the Hommyo River published from the Isahaya City.

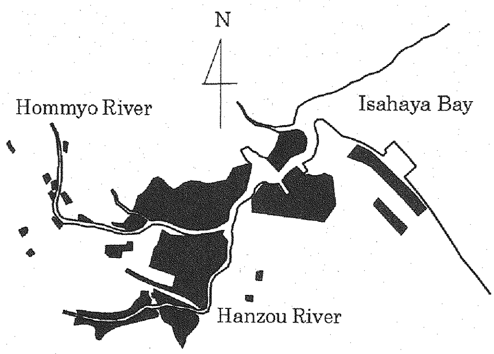


Fig.3 Inundated area observed in 1999

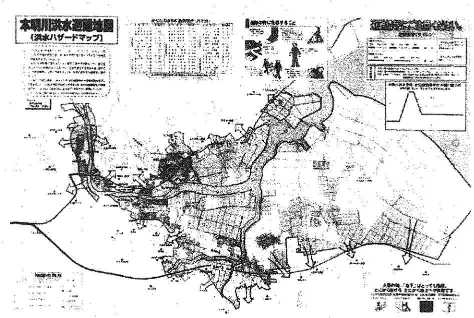


Fig.4 Hazard map published from the Isahaya City

INUNDATION FLOW ANALYSIS IN ISAHAYA LOW-LYING AREA

Governing Equations

In this study, the computational area is divided into three parts: the river channel, the flood-prone area and the hillside area, as shown in Fig.5.

In the river channel, a one-dimensional unsteady flow analysis using the characteristics method is applied following Inoue (2000b). The following continuity and St. Venant equations are used here:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{1}{g}\frac{\partial u}{\partial t} + \frac{u}{g}\frac{\partial u}{\partial x} + \frac{\partial h}{\partial x} = s_0 - s_f \tag{2}$$

where A is the cross sectional area of flow, Q is the discharge, q is the lateral inflow from unit length of x-direction, $u = Q/A$ is the velocity averaged over cross-section, $s_0 = \sin\theta$ is the river bed slope, $s_f = n^2 u|u|/R^{4/3}$ is the friction slope, R is the hydraulic radius and g is the gravitational acceleration.

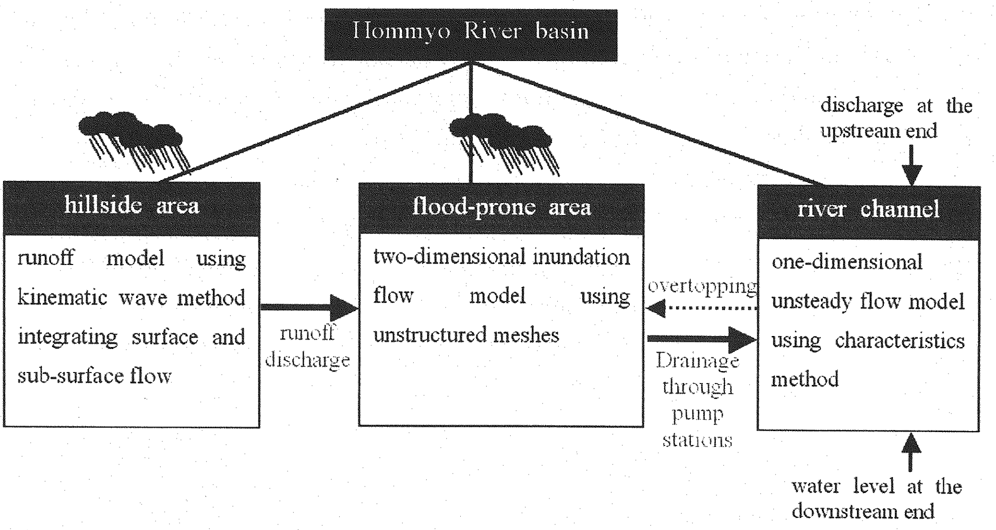


Fig.5 Framework of the model

In the flood-prone area, a two-dimensional inundation flow analysis, based on irregularly-shaped meshes called as "the unstructured mesh model" (Kawaike, 2000), was conducted. The governing equations used here are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=r \tag{3}$$

$$\frac{\partial M}{\partial t}+\frac{\partial (uM)}{\partial x}+\frac{\partial (vM)}{\partial y}=-gh\frac{\partial H}{\partial x}-\frac{gn^2M\sqrt{u^2+v^2}}{h^{4/3}} \tag{4}$$

$$\frac{\partial N}{\partial t}+\frac{\partial (uN)}{\partial x}+\frac{\partial (vN)}{\partial y}=-gh\frac{\partial H}{\partial y}-\frac{gn^2N\sqrt{u^2+v^2}}{h^{4/3}} \tag{5}$$

where h is the water depth, M and N are x and y-directional discharge per unit width, respectively, u and v are x and y-directional flow velocity, respectively, r is the rainfall intensity, n is the Manning's roughness coefficient, and H is the water level ($= h + z_b$, z_b is ground elevation). The reason for using unstructured meshes is that they are easy to express the boundary of river channels, streets and paddy fields etc. and that the effects of those factors on the behavior of inundation water can be expressed in a relatively simple way (Inoue, 2000a). The rainwater given to the flood-prone area is drained through pump stations and the drained water is given to the river channel as the lateral inflow.

In the hillside area with steep slopes, a runoff analysis using the kinematic wave method integrating surface and subsurface flows (Tachikawa, 1997) was applied. The governing equations used here are as follows:

$$\frac{\partial h}{\partial t} + \frac{1}{b}\frac{\partial (q'b)}{\partial x} = r\cos\theta_s \tag{6}$$

$$\begin{cases} q' = \dfrac{k\sin\theta_s}{\gamma}h & (0 < h < \gamma D) \\ q' = \dfrac{\sqrt{\sin\theta_s}}{n}(h-\gamma D)^m + \dfrac{k\sin\theta_s}{\gamma}h & (h \geq \gamma D) \end{cases} \tag{7}$$

where h is the substantial water depth on the slope, q' is the discharge per unit width on the slope, b is the slope width, θ_s is the slope gradient, k is the hydraulic conductivity, γ is the effective porosity, D is the superficial A-layer depth and m is the constant value of 5/3. The obtained runoff discharge at the downstream end of each slope is given to the flood-prone area as the boundary condition.

Application to the Isahaya Low-Lying Area

The computational reach of the Hommyo River is from Urayama (6.0km from the river mouth) to Shiranui (0.8km from the river mouth), and that of the Hanzou River is from Umetsu to the confluence with the Hommyo River. The spatial interval of dicretization Δx is 200m, and the values of roughness coefficient for the Hommyo River and the Hanzou River are determined based on a comparison with observed data by trial and error.

The steep slopes used in the hillside area are adjacent areas to the flood-prone area as shown in Fig.6, and the number of them is 567. The numerical model for the flood-prone area can only be applied to a flat area, so the border between the steep slope area and the flood-prone area should be judged from the density of the coutour lines on the map. The values of the parameters used here are: k is 0.002 [m/s], γ is 0.15, n is 0.3 [$m^{-1/3}s$] and D is 0.5 [m] (Ichikawa, 1999).

The number of the computational meshes used in the flood-prone area (shown in Fig.6) is 5,429 and these computational meshes were divided into four categories depending on their land use: urban areas, channels, streets and cultivated areas, as shown in Fig.7. The values of roughness coefficient of these four categories are 0.067, 0.020, 0.043 and 0.025 (Xanthopoulos, 1976), respectively. And on the basis of our field survey, the elevation of channel meshes was assumed to be 3-meters lower than that of their adjacent meshes.

The rainwater in the Isahaya City flows into drainage channels and is usually drained through sluice gates to the Hommyo River. However, during the time of the flood of the Hommyo River, all the sluice gates are supposed to be closed and the rainwater is drained through pump stations. In this study, it is assumed that all the sluice gates were closed and the rainwater drainage through 19 pump stations is investigated.

As the simulation conditions, the discharge at Urayama and Umetsu, and the water level at Shiranui observed at the time of the disaster of 1999, shown in Fig.8, are given to the river channel. The temporal change of rainfall intensity per 10 minutes observed at Isahaya City

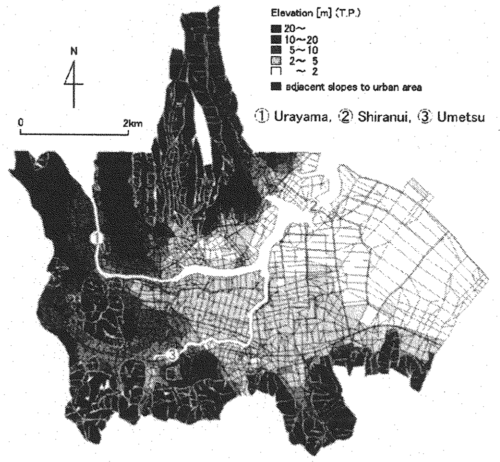


Fig.6 Slopes and computational meshes

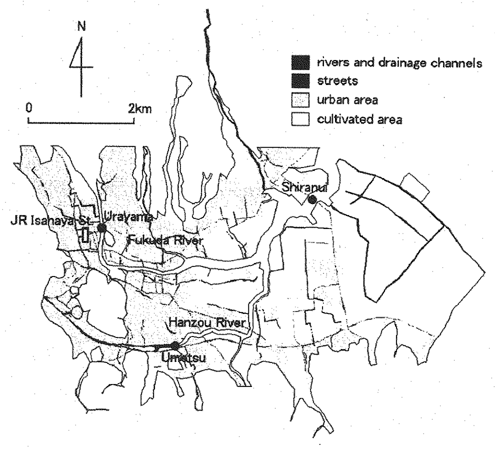


Fig.7 Mesh categories of four types

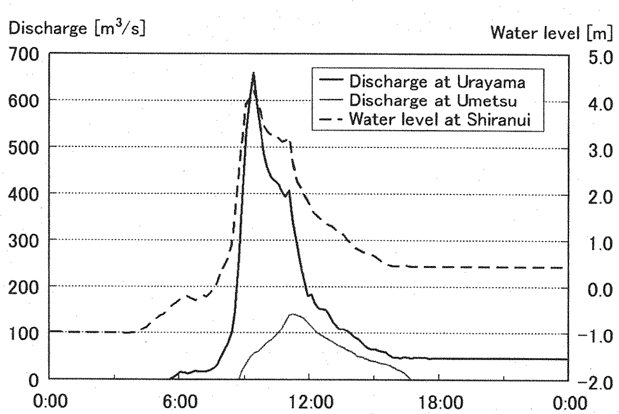


Fig.8 Boundary conditions of the Hommyo River channel

in 1999, as shown in Fig.2, is uniformly given to the whole hillside and flood-prone areas. The computational time step Δt is set to be 0.05s for the river channel, the hillside and the flood-prone areas.

Reproduction of the Inundated Area at the Disaster of 1999

Fig.9 shows the comparison between the actual inundated area and the simulation results. The actual inundated area is observed at the time of disaster of 1999 shown in Fig.3. The simulation result demonstrates the inundated area with more than 0.1m water depth obtained from 24-hour simulation. It can be seen from this figure that the central part of the computational area has a good agreement between the actual inundated area and the simulation result because streets and channels in these areas are considered in detail. But the inundated areas

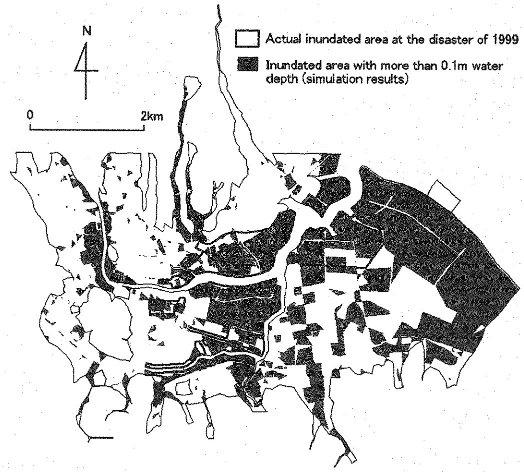


Fig.9 Comparison between the actual inundated area and the simulation result

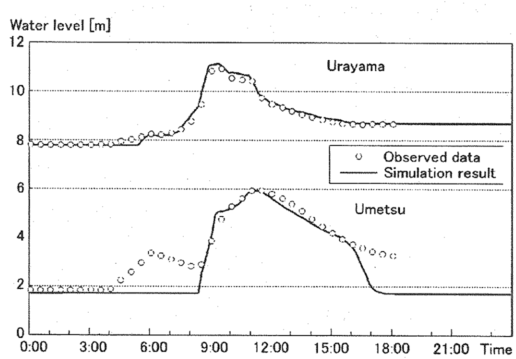


Fig.10 Temporal change of the water level of the Hommyo River

of the western and eastern part of the computational area are not well expressed by the simulation. The reasons for these disagreements are perhaps be due to the assumptions that the rainfall spatial distribution is inappropriate, that drainage system by the sewerage is not fully considered or that the storage of inundation water due to more detailed water channels or paddy fields are not considered in this simulation.

Fig.10 shows the comparison between observed data and simulation results about the temporal change of water level at Urayama and Umetsu when the roughness coefficients are 0.030 and 0.045 for the Hommyo River and the Hanzou River, respectively. This is a case where the difference between the observed and computed water levels are smallest. From this figure, the simulation result of Urayama indicate a good agreement with the observed data. On the other hand, the water level at Umetsu is not well expressed around the small peak of 6 o'clock. The reason for this disagreement is that either the boundary discharge or the observed water level at this point is incorrect. Consequently, it is found that good results of water level of the Hommyo River and inundated area around the central part of the computational area can be obtained, if an appropriate spatial distribution of rainfall is given to the computational area.

STRATEGIES REDUCING FLOOD DAMAGE

Effects of Additional Pump Capacity on Inundated Area

As the countermeasures against inundation disasters, plans were made to construct some pump stations in the Isahaya low-lying area. In this section, using the numerical simulation proposed in this paper, the effect of additional pump capacity is estimated.

From the simulation results of the previous section, three zones of A, B and C are determined as shown in Fig.11 because these zones reveal a good agreement between the simulation results and the actual inundated area observed in 1999. A hypothetical construction of new pump stations shown in Fig.11 and the extension of existing pump capacity is assumed here. The relationship between this additional pump capacity and inundated areas of A, B and C zones with more than 0.1m water depth are individually computed. This relationship is shown in Fig.12 (a), (b) and (c), respectively. The vertical axis denotes the inundated area of each zone, and the horizontal one denotes the total additional pump capacity from the existing one.

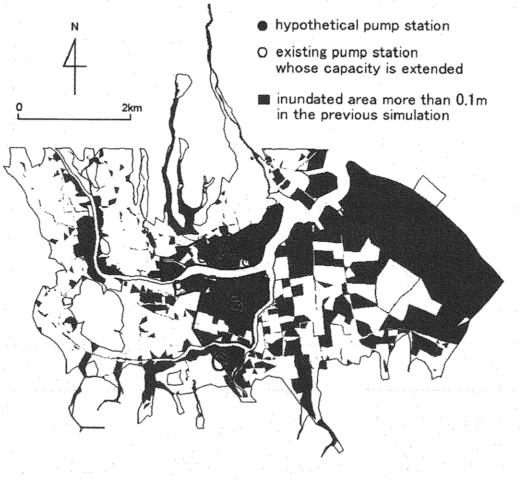
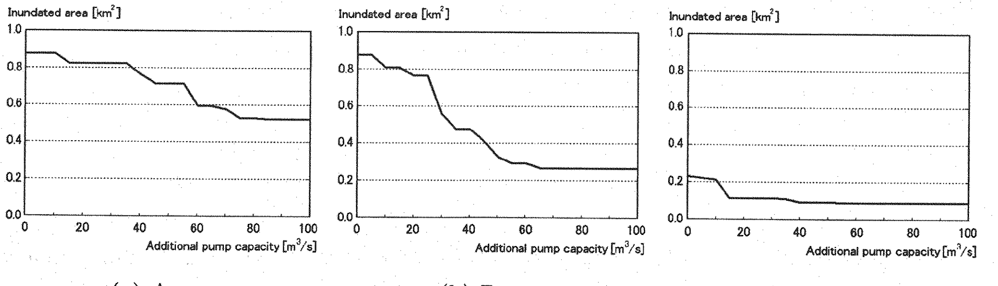


Fig.11 Assumed pump stations



(a) A zone (b) B zone (c) C zone

Fig.12 Relationship between additional pump capacity and inundated area

As for the A zone, about 20% of the total area is urbanized. Even if the pump capacity of $100m^3/s$ is added to this zone, $0.5km^2$ of the inundated area with more than 0.1m-depth still remains. Therefore, additional countermeasures for urban areas were found to be necessary in this zone.

Most of the B zone is flat, so the inundated area is spreading shallowly and widely, and is decreasing discontinuously depending on the additional pump capacity. Extention of pump capacity or embankment could protect the urbanized area (about 10% of this area) from inundation.

The C zone is one of the most frequently damaged areas due to heavy rainfall in the Isahaya City. If a pump capacity of $100m^3/s$ is added to this zone, the inundated area decreases from $0.24km^2$ to $0.12km^2$. Since the urban area is about 10% of the C zone and is located in a relatively higher area, even a pump capacity with less than $100m^3/s$ can be expected to result in good effects.

In any zone, additional pump capacity of $100m^3/s$ reduces the inundated area by half. But even additional pump capacity of more than $100m^3/s$ does not make a significant difference. It goes without saying that the more the pump capacity is increased, the more it costs. In this way, useful information to determine a flood mitigation plan is available from these simulation results.

Effects of Additional Pump Capacity on Water Level of River Channel

It is obvious that the water level of the Hommyo River channel rises if the pump capacity is extended. Fig.13 shows the comparison of the maximum water level of the Hommyo River before and after adding the pump capacity of $100m^3/s$ to each of the A, B and C zones. From this figure, it can be seen that the water level of the Hommyo River rises at most 0.2m. However, the water level is quite close to the dike level around the downstream end, so overtopping flow from the Hommyo River might occur when more dangerous conditions exist.

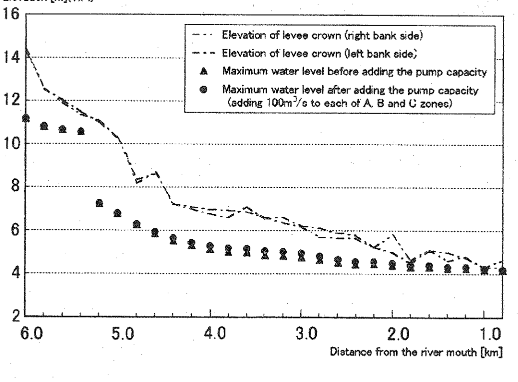


Fig.13 Comparison of the maximum water level before and after adding pump capacity

CONCLUSIONS

In this study, a comprehensive simulation method for inundation flow of the Isahaya low-lying area is proposed. By means of this simulation model, the dangerous areas for heavy rainfall can be designated, and the effects of newly planned flood-control facilities on the inundated area and water level of the Hommyo River can be estimated. Furthermore, this model can be applied to estimate the effects of sewerage systems, storage facilities in the upper areas, and to determine the operation rules of pump stations.

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APPENDIX - NOTATION

The following symbols are used in this paper:

A	=	cross sectional area of flow;
b	=	slope width;
D	=	superficial A − layer depth;
g	=	gravitational acceleration;
H	=	water level;
h	=	flow depth;
k	=	hydraulic conductivity;
m	=	numerical constant of the kinematic wave model;
M, N	=	respective discharge per unit width in x and y directions;
n	=	Manning's roughness coefficient;
Q	=	flow discharge;
q	=	lateral inflow from unit length of x−direction;
q'	=	discharge per unit width on the slope;
R	=	hydraulic radius;
r	=	rainfall intensity;
s_0	=	river bed slope;
s_f	=	friction slope;
t	=	time;
u, v	=	respective flow velocity in the x and y directions;
x, y	=	coordinates of the flow;
z_b	=	ground elevation;
γ	=	effective porosity;
Δt	=	computational time step;
θ	=	river bed slope; and
θ_s	=	slope gradient.

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