

## DISTRIBUTED HYDROLOGIC MODEL FOR FLOOD INUNDATION SIMULATION

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### SYNOPSIS

There were several research studies carried out in the last few years to develop mathematical models for flood inundation simulation. However, such models considered only overland and river flows components of hydrologic cycle and were designed to simulate floods in local scale only, not in basin scale. In real situation, infiltration and base flow to river have significant impacts on the occurrence or non-occurrence of floods due to a particular rainfall event. Therefore, flows in unsaturated and saturated zones too should be considered for proper flood inundation simulation. In this study, a physically based distributed hydrologic model is developed for flood inundation simulation by combining a newly developed overland flow and river flow simulation models with unsaturated zone and groundwater models. The overland flow and river flow models are validated individually with test data and then, coupled with other models. The model is applied in a river catchment in Japan to simulate a flood event of 1996. Output of the model shows satisfactory agreement with surveyed flood inundation and thus, shows that the model is suitable for basin scale flood inundation simulation.

### INTRODUCTION

Many studies have been done in the past to develop flood inundation simulation models (1-5). However, such models consider only surface and river flows. Unsaturated and groundwater components of hydrologic cycle are neglected. In real situation, infiltration and base flow to river have significant impacts on the occurrence or non-occurrence of floods due to rainfall. Also, these models are applicable in local scale, not in basin scale. In this study, a physically based distributed hydrologic model is developed for flood inundation simulation by combining newly developed overland flow and river flow models with unsaturated zone and groundwater modules of Institute of Industrial Science Distributed Hydrologic Model (IISDHM) (6). The overland flow and river flow models are initially validated individually with test data and then, coupled with other modules. The coupled distributed model is applied in a river basin in Japan to simulate a flood event of 1996. GIS is used to perform the pre- and post-processing of large amount of spatial input data and output results efficiently.

## Distributed hydrologic model and its components

Distributed hydrologic model is a mathematical representation of all the components of hydrologic cycle based on their physical governing equations that can be used to simulate movement of water in different components of hydrologic cycle in a river basin. There are five major components of a distributed hydrologic model such as, i) Interception and Evapotranspiration, ii) Overland flow, iii) River flow, iv) Subsurface flow and v) Ground water flow. Figure 1 shows a schematic diagram of a distributed hydrologic model. There are already several distributed hydrologic models available, which are developed by various researchers or research organizations for different purposes such as Systeme Hydrologique Europeen (SHE) model (7), TOPMODEL (8), WATFLOOD (9) (<http://www.hydomodel.com/duan/hydrology>), IISDHM, etc. However, none of these models can simulate flood inundation process properly, mainly due to the limitations in overland and river flow components and their coupling to consider outflow from or inflow to river from overland, which are the most important components in flood inundation simulation. In this study, a coupled mathematical model is developed for overland flow and open channel network flow simulation and it is integrated with the evapotranspiration, unsaturated zone and saturated zone components of IISDHM, a distributed hydrologic model developed in the authors' laboratory. IISDHM solves the evapotranspiration component using Kristensen and Jensen model, unsaturated zone by three-dimensional Richard's equation and groundwater flow by two-dimensional (2D) non-linear Boussinesq's equation. The development process of one-dimensional (1D) open channel flow simulation model and 2D overland flow simulation and their coupling method are described in the next section.

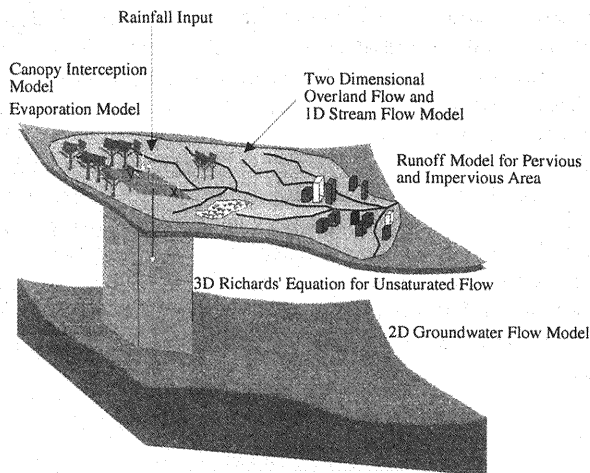


Fig. 1: Schematic diagram of a distributed hydrologic model

## MODEL DEVELOPMENT

There are several existing solution schemes for open channel and overland flow simulation using complete hydrodynamic equations. However, all these solutions schemes are tested in laboratory or, in small areas with very mild slopes. In real situation, a microtopography, surface roughness, and soil hydraulic properties vary over distances of centimeters to meters, and they strongly influence runoff characteristics along the hillslope, and hillslope hydrographs. To incorporate these heterogeneity of physical characteristics of a river basin, it is often required to take many assumptions for solving governing equation of flow. Diffusive wave approximation of Saint Venant's equations is good enough to represent surface and open channel flow in a river basin and with this approximation, numerical instability of mathematical model can be avoided in basin scale flood inundation

simulation. In this study, both 1D open channel flow simulation and 2D overland flow simulation models are derived using diffusive wave approximation of St. Venant's equations. The basic concept of channel network flow simulation model is taken from Y-channel solution scheme presented by Akan and Yen (10), which is modified for large channel networks with any number of connecting channels in converging or diverging junctions in this study. Details of the model development processes are described in this section.

### 1D Open Channel Flow Simulation Model

#### a) Governing equations

Gradually varied unsteady flow in open channels can be expressed mathematically by the conservation of mass and momentum equations. These two governing equations for unsteady 1D open channel flows are well known as St. Venant's equations.

Mass conservation equation (continuity equation);

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (1)$$

And the momentum equation;

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{A} \right) + g \left( \frac{\partial z}{\partial x} + S_f \right) = 0 \quad (2)$$

where  $t$  = time;  $x$  = distance along the longitudinal axis of the watercourse;  $A$  = cross-sectional area;  $Q$  = discharge through  $A$ ;  $q$  = lateral inflow or outflow distributed along the  $x$ -axis of the watercourse;  $g$  = gravity acceleration constant;  $z$  = water surface level with reference to datum; and  $S_f$  = friction slope.

The friction slope  $S_f$  for turbulent flow can be estimated by Manning's formula as follows;

$$S_f = \frac{n^2 Q |Q|}{A^2 R^{4/3}} \quad (3)$$

where  $n$  = Manning's roughness coefficient;  $R$  = hydraulic radius.

#### b) Diffusive wave equations approximation

In the diffusive wave approximation of the St. Venant's equations, the local and convective acceleration terms in the momentum equation (i.e. the first two terms in the Eq. 2) are neglected. Thus, Eq. 2 is simplified as,

$$S_f = -\frac{\partial z}{\partial x} \quad (4)$$

Combining Eqs. 3 and 4 yields,

$$Q = \frac{1}{n} A R^{2/3} \frac{-\frac{\partial z}{\partial x}}{\left| \frac{\partial z}{\partial x} \right|^{1/2}} \quad (5)$$

#### c) Finite difference equations

Fully implicit finite difference scheme is used to solve these non-linear partial differential equations. Using forward-difference scheme, Eqs. 1 and 5 can be expressed as,

$$\frac{A_i^{i+1} - A_i'}{\Delta t} + \frac{Q_{i+1}^{i+1} - Q_i^{i+1}}{\Delta x} = \frac{q_i^{i+1} + q_i'}{2} \quad (6)$$

$$Q_i^{i+1} = \frac{1}{n_i} A_i^{i+1} (R_i^{i+1})^{2/3} \frac{\frac{z_{i+1}^{i+1} - z_i^{i+1}}{\Delta x}}{\left| \frac{z_{i+1}^{i+1} - z_i^{i+1}}{\Delta x} \right|^{1/2}} \quad (7)$$

Since the flow cross-sectional area  $A$  and hydraulic radius are known functions of water surface elevation  $z$ , substituting Eq. 7 in Eq. 6, yields a equation with three unknowns in the following form (11).

$$f(z_{i-1}^{i+1}, z_i^{i+1}, z_{i+1}^{i+1}) = 0 \quad (8)$$

For a single channel with  $n$  points, a set of  $N-2$  equations with  $N$  unknowns can be written. These can be solved with another two equations obtained from upstream and downstream boundary conditions. The solution techniques are explained in the latter sections.

#### d) Channel network equations

For channel networks, the most important point is the appropriate considerations of hydraulic conditions in converging and diverging channel junctions. Hydraulic conditions at a converging channel junction may be described by the continuity equation as,

$$\sum Q_k = Q_o + \frac{ds}{dt} \quad (9)$$

where  $s$  = the storage within the junction. The subscript  $k$  stands for any one of the in-flowing channels and  $o$  represents the out-flowing channel. Junctions have small storage volumes in most open-channel networks for which the term  $ds/dt$  in Eq. 9 is negligible. Thus, it can be written as,

$$\sum Q_k = Q_o \quad (10)$$

Similarly, the above condition can be derived for diverging channel junctions as follows,

$$Q_i = \sum Q_r \quad (11)$$

where subscript  $i$  represents the in-flowing channel and  $r$  stands for anyone of the out-flowing channels.

Using the above condition and upstream and downstream boundary conditions, sufficient numbers of equations can be obtained in channel network for obtaining solution as, in connecting converging or diverging junctions, head is same for all the connecting points of the joining branches.

#### e) Network solution algorithm

Simultaneous equations resulting from the finite difference approximation of channel networks can be written in matrix notation as  $[A]\{X\}=\{B\}$ , where  $[A]$  is coefficient matrix,  $\{X\}$  is vector of unknown variable  $z$  and  $\{B\}$  is vector of intercept values. The Newton-Raphson iteration method is employed for the solution of the simultaneous non-linear finite difference equations.

### 2D Overland flow simulation model

#### a) Governing equations

Governing equations for 2D gradually varied unsteady flow can be derived from conservation of mass and momentum equations. Overland flow equations are the 2D expansion of 1D open channel flow St. Venant's equations, which are written as:

Mass conservation equation (continuity equation):

$$\frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} + \frac{\partial h}{\partial t} = q \quad (12)$$

Momentum Equations;

In  $X$ -direction:

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \left( \frac{\partial Z}{\partial x} + S_{fx} \right) = 0 \quad (13)$$

In  $Y$ -direction:

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \left( \frac{\partial Z}{\partial y} + S_{fy} \right) = 0 \quad (14)$$

where  $u$  and  $v$  are velocities of flow and  $S_{fx}$  and  $S_{fy}$  are friction slopes in  $X$ - and  $Y$ -directions.

Friction slope can be evaluated using a uniform, steady-flow empirical resistance equation such as Chezy's or Manning's. Using Manning's equation,

$$S_{fx} = \frac{n_x^2 u^2}{h^{4/3}} \quad (15)$$

and,

$$S_{fy} = \frac{n_y^2 v^2}{h^{4/3}} \quad (16)$$

where  $n_x$  and  $n_y$  are Manning's roughness coefficients in  $X$ - and  $Y$ -directions.

#### b) Diffusive wave approximation

Neglecting the local convective acceleration terms in the  $X$  and  $Y$  momentum equations (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> terms in Eqs. 13 and 14), the momentum equations can be written in the diffusive wave form as follows;

$$\frac{\partial h}{\partial x} = S_{ox} - S_{fx} \quad \text{in } X\text{-direction} \quad (17)$$

$$\frac{\partial h}{\partial y} = S_{oy} - S_{fy} \quad \text{in } Y\text{-direction} \quad (18)$$

Combining Eq. 15 with Eq. 17 and Eq. 16 with Eq. 18, yields

$$uh = \frac{1}{n_x} \left( S_{ox} - \frac{\partial h}{\partial x} \right)^{1/2} h^{5/3} \quad (19)$$

$$vh = \frac{1}{n_y} \left( S_{oy} - \frac{\partial h}{\partial y} \right)^{1/2} h^{5/3} \quad (20)$$

Replacing the above two relations in Mass balance equation of 2D surface flow, we obtain

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{1}{n_x} \left( S_{ox} - \frac{\partial h}{\partial x} \right)^{1/2} h^{2/3} h \right] + \frac{\partial}{\partial y} \left[ \frac{1}{n_y} \left( S_{oy} - \frac{\partial h}{\partial y} \right)^{1/2} h^{2/3} h \right] = q \quad (21)$$

#### c) Solution scheme

An implicit finite difference scheme is used to solve the diffusive wave non-linear overland flow (Eq. 21) with the following assumptions (11).

1. First, the non-linear terms  $h^{2/3}$ ,  $(S_{fx})^{0.5}$  and  $(S_{fy})^{0.5}$  are considered explicitly, in the implicit solution of linear terms with Gauss-Seidal iteration using successive over relaxation (SOR) method,
2. Then, non-linear terms are updated with the new head and then, iteration is done again to solve the whole equation implicitly to obtain final  $h$  for the next time step.

#### Coupling of Channel and Overland Flow Models

The exchange of flow between the channel network and flood plains is simulated using the

floodplain compartment concept (12). The floodplain compartments are surface grids along the river channels, which are considered as boundary conditions in overland flow routing. Flow transfer between floodplain compartment and river is assumed to occur along  $\Delta x$  reaches which adjoin the river and floodplain compartments; this flow is assumed to be broad-crested weir with submergence correction. Flow can be either away from the river or into the river, depending on the relative water surface elevations of the river and the floodplain compartment (Fig. 2). The river elevations are computed using 1D diffusive wave model solution for channel network and the floodplain elevations are computed by 2D diffusive wave model for overland flow as described before. The exchange of flow between flood compartment and river reach in time step  $\Delta t$  is computed by a simple storage routing relation, i.e.,

$$V_l^{t+1} = V_l^t + (I^{t+1} - O^{t+1})\Delta t$$

where  $V_l$  = volume of water in the floodplain compartment at time  $t+1$  or  $t$  depending on the water elevation,  $I$  = inflow from the river grids to adjacent floodplain compartments, and  $O$  = outflow from the floodplain compartments to adjacent river grids. The broad-crested weir flow into or out of a single compartment is determined according to the following;

$$I = c_f s_b (h_r - h_w)^{3/2} \Delta L \quad \text{if } h_r > h_w \text{ and } h_r > h_{fp}$$

$$O = c_f s_b (h_{fp} - h_w)^{3/2} \Delta L \quad \text{if } h_{fp} > h_w \text{ and } h_{fp} > h_r$$

where  $c_f$  = a specified discharge coefficient,  $h_r$  = the river elevation,  $h_{fp}$  = water surface elevation of the floodplain,  $h_w$  = crest elevation of levee,  $\Delta L$  = length of river reach, and  $s_b$  = submergence correction factor, i.e.,

$$S_b = 1.0 - 27.8(H_r - 0.67)^3 \quad \text{if } H_r > 0.67, \quad \text{else} \quad S_b = 1.0$$

$$H_r = (h_r - h_w)/(h_{fp} - h_w) \quad \text{if } h_r > h_w \text{ and } h_r > h_{fp}$$

$$H_r = (h_{fp} - h_w)/(h_r - h_w) \quad \text{if } h_{fp} > h_w \text{ and } h_{fp} > h_r$$

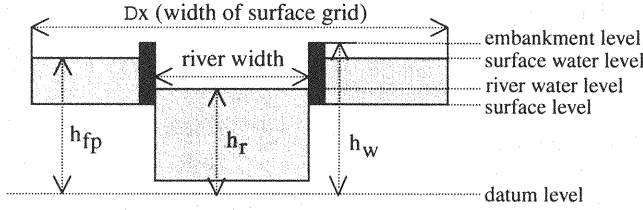


Fig 2: Concept of flow exchange between river and surface grids considering embankment heights

## Coupling of Channel Network and Overland Flow Simulation Models with Other Components

The newly developed combined channel network and overland flow simulation model is combined with other components of IISDHM such as 1) evapotranspiration, 2) unsaturated zone, and 3) saturated zone modules, to develop the complete distributed hydrologic model for flood simulation. The flow chart of Fig. 3 shows the concept of coupling. Commons blocks in Fortran code are used to formulate the algorithm for coupling the different flow simulation modules at a specified time interval.

## MODEL APPLICATION

### Study Area

The study area selected for the model application is Ichinomiya river basin, a moderate basin in size with an area of 220 sq. km, located in the Chiba prefecture, Japan between longitude 35°18' N to 35°30' N and latitude 140°10' E to 140°25' E (Fig. 4). The topography of the basin varies from hilly areas in the western part with maximum elevation of about 155 m to lowland flat areas in the eastern

part with minimum elevation of about 1 m from mean sea level. The mean annual rainfall is approximately 1,700 mm and rainfall distribution is uniform in the entire basin.

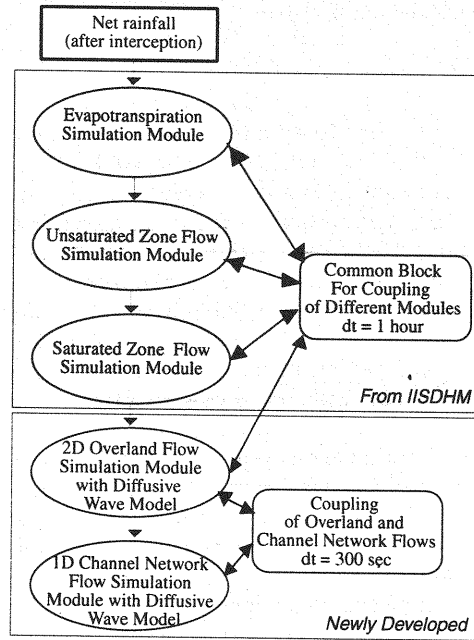


Fig. 3: Flow chart showing coupling process of distributed model

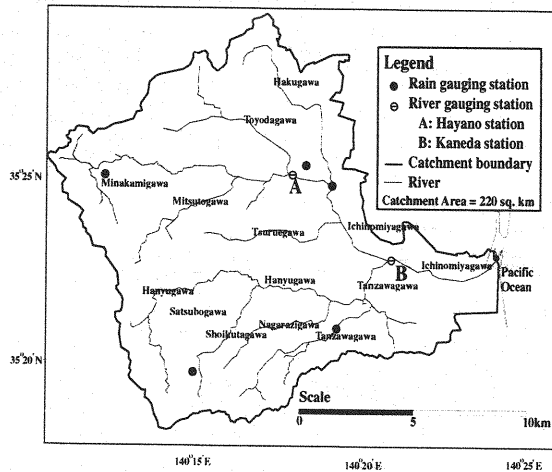


Fig. 4: Ichinomiya river basin

#### Data Preparation

DEM of study area was generated from 50 m grid elevation data that was obtained from Japan Map Center. As the generated river system was not following actual river path, the original DEM was modified with additional 1m interval contour data from 1:2,500 scale map for the lower flat area and river network is generated again. There are total six major landcover classes such as forest, paddy, light grass, vegetable, water body and urban, within the study area as classified from SPOT satellite

data of 20 m pixel. Hourly rainfall data from 5 rainfall gauging stations are available. Daily pan evaporation of one station was known. Soil map was obtained from Mitsui Consultant Company of Tokyo, which has six major soil classes and soil parameters were measured from the soil field test data conducted in different areas within the basin.

### Flood Inundation Simulation

During September 22- 25, 1996, the basin suffered from a big flood disaster due to the heavy rainfall caused by Typhoon 17. Within 24 hours during September 21-22, the whole basin received about 360 mm rainfall. The distributed hydrologic model was used to simulate this flood event. The model was run for a total 4 days starting from September 20, one day before the typhoon passed through the basin. As the input rainfall data was with hourly resolution, coupling time for different modules of the model was selected as one hour except for surface and river modules. Coupling time between surface and river modules was taken as 300 sec. to avoid any numerical instability in the simulation.

Figure 5 shows the simulated flood inundation with floodwater depths and the boundaries of surveyed flooded areas. The simulated extent is the maximum flooded area with above 1 m height of water. By comparing the simulated results with the survey flood, in general it can be said that simulated result is close to the actual situation. From the simulated results, floodwater can be seen in some surface areas along the upstream channel networks. One of the possible reasons of this may be the averaged topography data, due to which estimated slopes may be different from the actual situation in upstream flooded areas. In this study, obtained topography data for the upper part of the basin is averaged data for 50 m gridsize. A high resolution and accurate topography data is essential for getting high accuracy in simulated flood inundation output. Also, due to lack of detailed information about hydrogeological properties of different soil types in the basin, several assumptions are made in estimation of soil characteristics. This may be another possible reason of less precise output. Also, it can be noticed that there is some shifting of simulated flood inundation from the surveyed one. This is due to the difference between actual channel network and that generated from the DEM, which is used for simulation. It can be seen from the Fig. 5 that generated river network is not matching well with the actual flow paths in the lower part of the basin. As most of the flooded areas are along the rivers, simulated flooded areas are also shifting from the original locations along with the river network. Also, simulated flood extension is larger than the observed flooded areas. This may be due to road networks that worked as embankments in many areas preventing the movement of flood water from river sides, but the road networks are yet to be separately considered in the model.

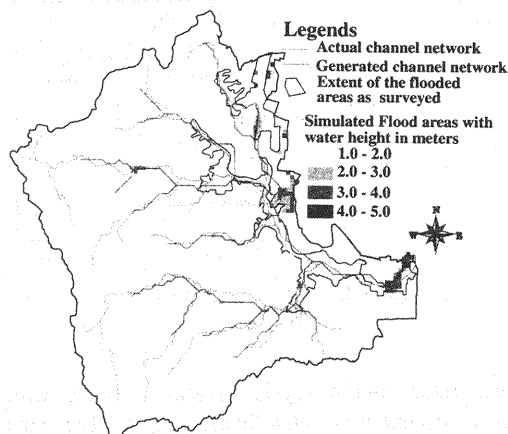


Fig. 5: Simulated flood inundation and the flooded areas as surveyed

Figure 6 shows the comparison of simulated flood hydrograph with observed hydrograph at the gauging station A (Hayano station, refer to Fig. 4). Except the peak, simulated flood hydrograph is matching quite well with the observed one.

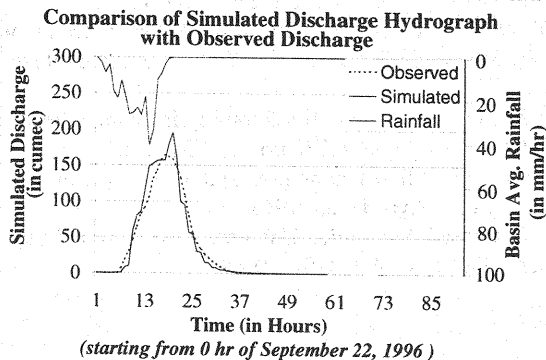


Fig. 6: Simulated and observed flood hydrographs at Hayano station

### CONCLUSIONS

An integrated distributed model is developed in this study by combining a newly developed coupled overland and channel network flow simulation model with other components of IISDHM. The model was applied to simulate a flood event in a Japanese river basin to verify its applicability in basin scale flood simulation. Although, the results are not perfectly matching with observed data, they are very close to actual trends. It is possible to improve the model outcome with the improvement of input spatial parameters and some further modifications such as incorporation of road network, etc.

From this study, it can be concluded that physically based distributed hydrologic models with detailed catchment information can be used for flood inundation simulations at basin scale.

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