FLOOD FLOW MODEL IN URBAN AREAS

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Abstract

This paper describes a two-dimensional numerical model of flooding in urban areas with trees, buildings, roads, and other such obstructions to flow caused by the overbank flow of a river. At first, the model was applied to an artificial city in order to test the model and then it was applied to the city of Sapporo. The overbank flow was calculated along the road network and around buildings. Several problems became clear during the course of this study including difficulty in treating the boundary conditions and the fact that highly detailed data of elevations, building density, and other geometric factors in urban areas are needed in order to correctly model urban floods.

1. Introduction

Recently, because of the construction of river improvement structures, the possibility and frequency of flooding in urban areas has been greatly reduced. However, some river mprovement works are still under construction and some rivers may still have floods which exceed the capacity for which the river was designed. Especially in urban areas, a flood could have disastrous effects due to the high density of population and capital investments. Present urban emergency plans inlude various coordinated emergency plans in the case of fires or earthquakes but do not include plans for the case of a flood. Urban emergency plans include places to go in the case of emergencies, but since these evacuation or shelter places have not been designed for the case of a flood, they may become inundated by flood waters. Therefore, the location, depth and velocity of urban flood waters becomes very important for the design of city emergency plans. Many studies have been conducted on overbank flows, but they have been almost entirely in rural areas without the need for a detailed model of roads, buildings and other such urban structures. Thus, because these previous models did not need fine details, the calculations could be conducted with large numerical grid cells. Therefore, the goal of this study is to eventually create a precise numerical model with a fine grid scale which can be used for urban planning. In this paper, a model is used to simulate flooding in Sapporo, and in doing so, several problems, which must be studied further, have been illuminated.

2. Overbank Flow Analysis

2.1 Basic Equations

The overbank flow is treated as a two dimensional plane flow, and the following basic equations are used.

The continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{1}$$

Momentum equation in the x-direction:

$$\frac{\partial M}{\partial t} + \frac{\partial (uM)}{\partial x} + \frac{\partial (vM)}{\partial y} = -gh\frac{\partial H}{\partial x} - \frac{\tau_x}{\rho} + \frac{\partial}{\partial x}\left(\varepsilon\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial M}{\partial y}\right) \tag{2}$$

Momentum equation in the y-direction:

$$\frac{\partial N}{\partial t} + \frac{\partial (uN)}{\partial x} + \frac{\partial (vN)}{\partial y} = -gh\frac{\partial H}{\partial y} - \frac{\tau_y}{\rho} + \frac{\partial}{\partial x}\left(\varepsilon\frac{\partial N}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon\frac{\partial N}{\partial y}\right) \tag{3}$$

Here, x, y = horizontal Cartesian coordinates; u, v = flow velocities in the x-, y-directions: h = depth; H = elevation of the water surface; ρ = density of flowing fluid; ε = eddy viscosity coefficient: g = acceleration of gravity;τ_x, τ_y = bottom shear stresses in the x-, y-directions; t = time: M, N = discharge per unit width in the x-, y- directions; and M=uh, N=vh.

2.2 Method of the Numerical Calculation

The preceeding equations were solved by the finite difference method. The calculation grid is shown in Figure 1. In order to reduce the instability of the numerical calculation, a staggered grid was used. For the time grid, delta t, the C.F.L. condition was used as follows:

$$\Delta t \leq \frac{\Delta x}{\sqrt{gh} + \mid u \mid} \tag{4}$$

$$\Delta t \leq \frac{\Delta y}{\sqrt{gh} + \mid v \mid} \tag{5}$$

In which Δx and Δy are the unit grid lengths in the numerical plane. Therefore, delta t was chosen to satisfy Equations (4) and (5) at the same time.

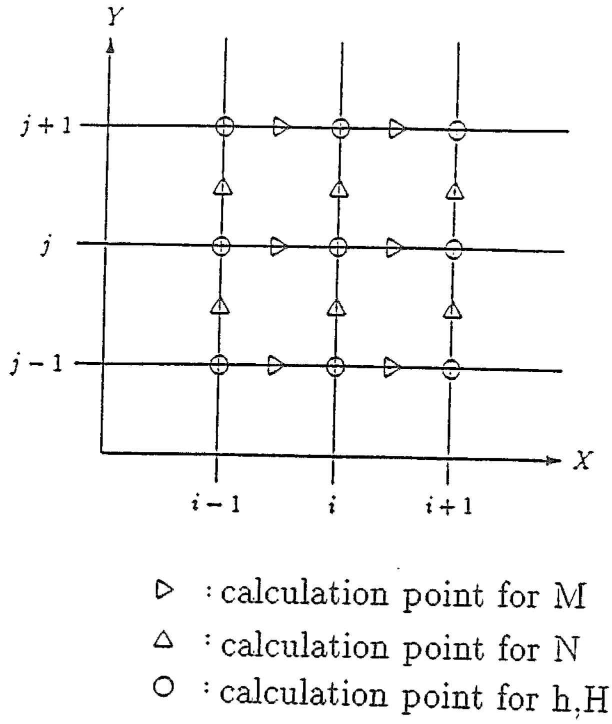

Figure-1 Calculation lattice and calculation points

2.3 Treatment of the Boundary Conditions

The boundary condition at the front of a spreading flood is determined by two adjacent latice points. Here, the spreading in the x-direction is discussed, using the water depth h(i-1,j), h(i,j) as the basis for the discussion.

The boundary conditions can be classified into three groups as follows: (1) both grid points are submerged (wet); (2) only one of the two points is submerged and the other is emergent (dry); and (3) both points are emergent. Conddition,(1) is the case of a fully submerged flow, and condition (3) is the case of dry land which has yet to be flooded. Condition (2) is the case of the spreading front of the flood. In condition (2) both the depth of water and land elevation must be considered. Assuming that the point (i,j) as in Figure 2 has a finite water depth h(i,j) and point (i-1,j) is dry, h(i-1,j)=0, if the water surface elevation H(i-1,j) is greater than H(i,j), the DHDX term in Equation 2 will be nonzero and a flux from (i-1,j) to (i,j) would result.

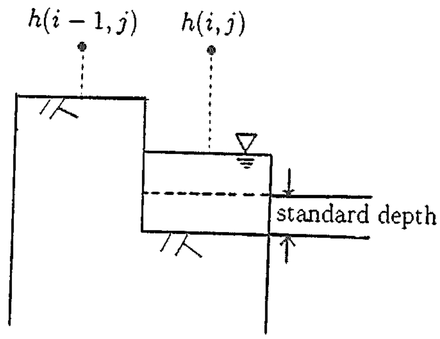

Figure-2 Boundary condition at the front

Thus, the numericalcode was constructed to prevent a flux from a dry node to a wet node, and the flux, M, in this case is set to equal zero. However, in the case where h(i-1,j) is zero and the surface elevation H(i,j) is greater than H(i-1,j), a flux should result in the (i-1,j) direction. For these reasons both the elevation and water depth must be considered at the same time.

3. Calculation of the Overland Flow in Urban Areas

3.1 Calculations in an Artificial City

In order to test the characteristics of the model, an artificial city was constructed as shown in Figure 3. The vertical and horzontal lines of diamonds in Figure 3 represent 2 highways built on pylons, such that water can pass under them. The squares represent buildings with roads runnig alongside them, and the oval shaped object represents a park with a pond. The river flows along the x-axis. The break point of the bank faces the buildings. The roughness of the bed is given as 0.8 in the city, and the road and the pond is 0.02. The parks are flat, and the buidings and roads are 5 meters higher than the surrounding land. The calculated velocity vectors are shown in Figure 4. It can be seen that the water moves along the streets in this case.

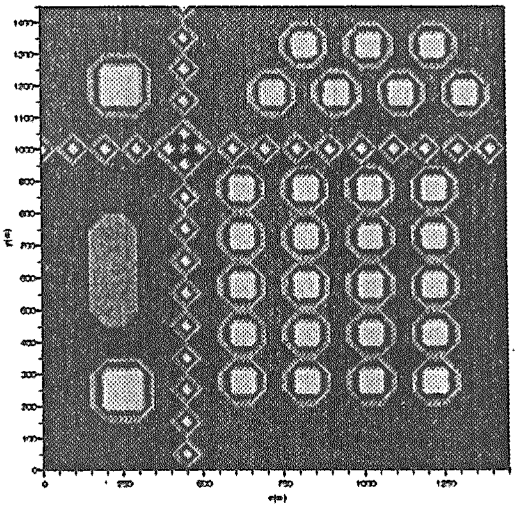

Figure-3 Artificial City

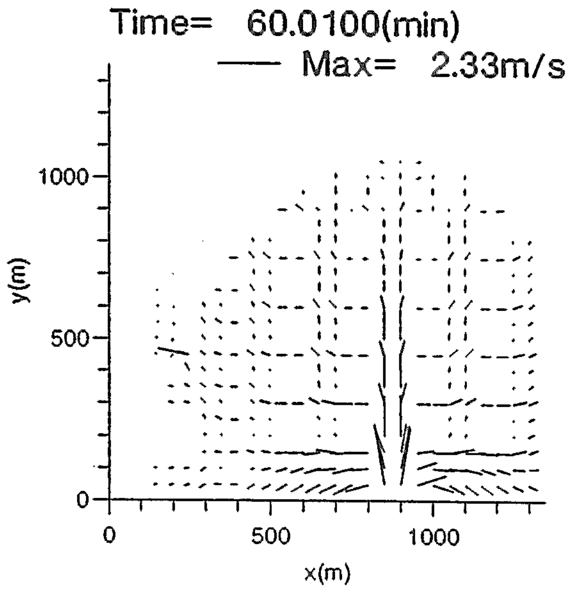

Figure-4 Calculation

In Figure 5, the highway parallel to the x-axis has been replaced by a ditch able to carry water. The slope of the ditch is 1/1000, and has a discharge capacity of 10.0m3/s. The other conditions in Figure 5 are exactly the same as Figure 4. Figure 6 shows the depth versus time in the ditch, which increases as the flood proceeds.

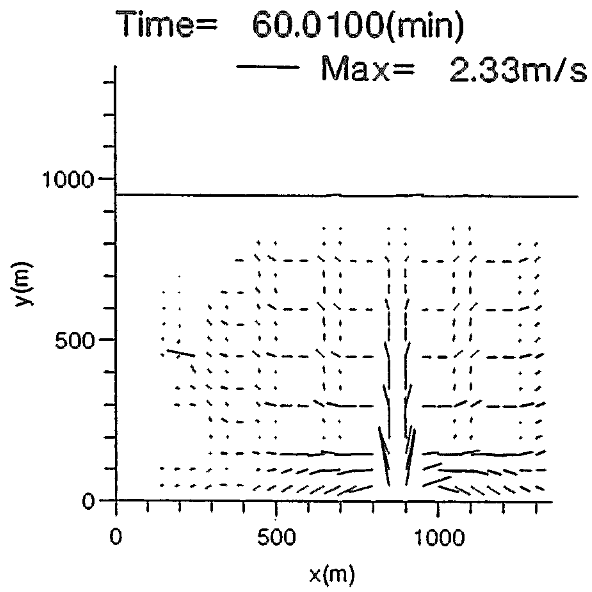

Figure-5 Calculation

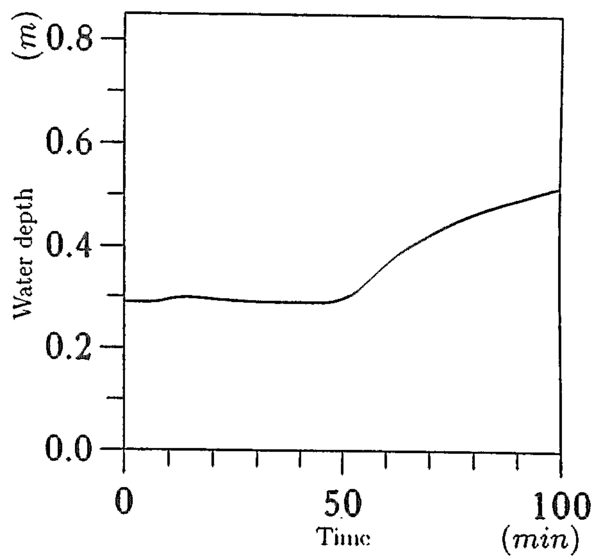

Figure-6 Water depth in the ditch

3.2 Application of the Model to the City of Sapporo

A simulation of an urban flood using the preceeding model was conducted on the city of Sapporo assuming a flood of the Toyohira River. The left bank of the Toyohira River near the Toyohira Bridge was assumed to be the point where the embankment is breached, because the river channel here is narrow. Also, if the river is breached at this point, the damage to the urban area is assumed to be great. The assumed breach is shown in Figure 7, and a breach length of 150m is assumed.

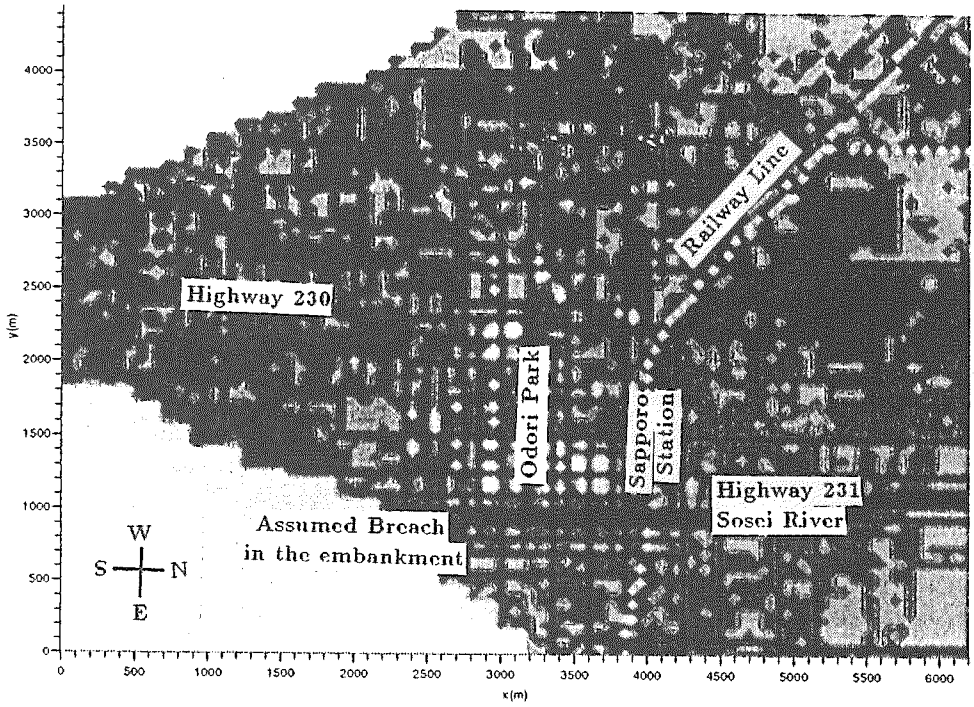

Figure-7 Roughness coefficients

The roughnessesused in this calculation are shown in Table 1 according to the study of Fukuoka et al.2). The density of structures and other factors needed for the determination of the roughness coefficients were obtained from a 1:25,000 map. Figure 7 indicates the distribution of the coefficient of roughness. The dark lines are streets and the lighter colored areas correspond to buildings, where the lighter the color is the more dense the buildings are. The boundary conditions were set so that no water was flowing into or out of the Toyohira River except at the breach point, and no water could pass the boundary of Mt. Moiwa. These areas are shown in white on the lower and uper right hand side of Figure 7. The elevation was taken from a National Digital Informationmap (ks-124-1). A grid spacing of 50 meters was used for the calculations.

Table-1

Density of structures and coefficient of roughness

density of structures	coefficient of roughness
vacant areas	0.02
streets	0.01
building density 20%	0.03
building density 50%	0.05
building density 80%	0.10
building density over 80%	0.80
rivers, ponds	0.01

For this calculation the design maximum flood was simulated. The Toyohira River is designed to have a capacity of 2000m3/sec. However, until the time that upstream dams and other improvement structures are completed, floods of 2300m3/sec are still possible. Thus, an overbank flow of 300m3/sec was used for the calculation. Figure 8 shows the hydrograph of the simulated flood. The numerical calculation results are shown in Figure 9. This figure is 200 minutes after the beginning of the flood, which is when the overbank flow was stopped. Figure 9 shows that flood water flowed along the street network. Examples of the depth and velocity are as follows. 0.11m, 0.27m/sec to the west at West 8 Odori Park; 0.13m, 0.04m/sec to the west at the Sapporo Station; 0.17m, 0.02m/sec to the west at the Clock Tower; and 0.07m, 0.25m/sec to the norh at Highway 213 near North 7 jo.

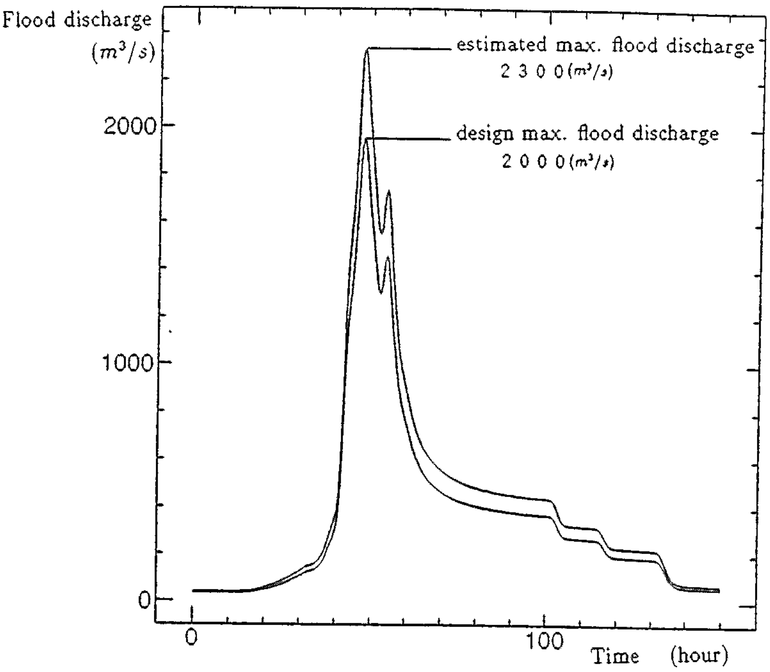

Figure-8 Hydrograph

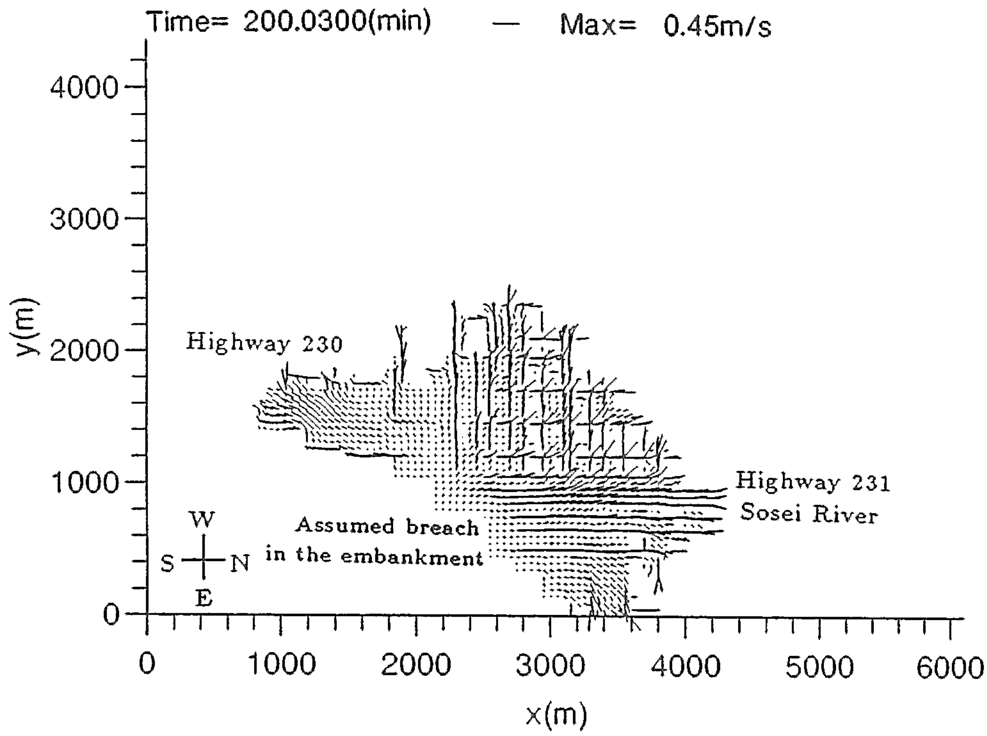

Figure-9 Calculation

4. Issues Related to Topographic Data

The data used in this calculation was (1) the density of buildings used for the roughness, (2) land elevation, (3) the flood hydrograph. In this paper, the point of overflow from the Toyohira River was chosen with some justification, but it is not known exactly where this breach would take place. The building density was taken from a 1:25,000 map. The 50 meter grid spacing of the calculation corresponds to 2mm on the map. Thus, it was very difficult to extract the amount of information needed from this map, and since there is no automated procedure, the process of collecting this information takes a lot of time. It is therefore very difficult to extract the needed information from this map even though it is the most detailed map available.

Because taking the needed information from a map is dificult, research about the application of aerial and satellite photography to this problem is needed. The relationship between the building density and roughness is not very well known and should be studied further. The land elevation data was taken from the National Digital Information map (ks-124-1), but this data is for a 250 meter grid and had to be interpolated to a 50 meter grid. Therefore, data at a finer scale is needed. Second order mesh data is available. However, the higher the latitude is, the worse the accuracy of this data is.

5. Conclusion

The calculation of overbank flows into areas which were previously dry is very unstable and accurate simulation is difficult. For example, when poiuring water onto the ground, water flows from high to low, but it is difficult to accurately predict how the water will spread.

In this paper, we did a simulation of overbank flow into an urban area and some problems were cleared. Physical experiments are necessary in order to clear up many of the problems that still exist in predicting floods in urban areas.

6. References

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