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A mathematical model for flood loss estimation

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Abstract

This paper introduces an integrated model for flood loss estimation in a river basin. The model is the combination of a physically based distributed hydrologic model and a distributed flood loss estimation model. The hydrologic model considers major processes of the water cycle through physically based governing equations, which are solved to simulate the propagation of water in each of these processes. It is designed to consider the man-made flood control structures, such as river embankments, retarding basins, etc. which affect flooding characteristics. The loss estimation model is formulated based on stage-damage relationships between different flood inundation parameters and landuse features. It calculates the economic loss to different landuse features based on the simulated flood parameters obtained from the hydrologic model for any flood event.

A case study illustrates the real world application of the integrated model to a medium size river basin in Japan, which is frequently affected by floods. The simulated river discharge and surface inundation by the flood model show good agreement with the observations. Urban flood loss simulated by the loss estimation model with the simulated flood parameters agrees with the estimated damage using post flood surveyed parameters.

Keywords: Distributed hydrologic model; Flood inundation modeling; Flood loss estimation; Stage-damage functions

1. Introduction

Rapid estimation of economic loss caused by floods in an urban catchment is very important for flood disaster mitigation measures. A flood loss estimation model is essential for this purpose. Such a model has a wide range of application in various flood disaster mitigation aspects ranging from structural measures such as, improvement of river training works for flood control, etc. to non-structural measures such as, flood warning, flood insurance policy development, real-time flood mitigation measures, etc. A quick estimate of economic loss after a disaster can be very useful in allocating resources for recovery and reconstruction. Similarly, estimation of potential flood damage is needed in long-term flood control planning, emergency management and useful for land use planning and management (Burby, 1998; NAP, 1999; Mileti, 1999). While the potential flood hazard reduces with improved flood mitigation scheme, flood damage potential increases with the accumulation of wealth and urban

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expansion. A prior estimate of flood damage potential helps in crisis management after a large-scale urban flood disaster.

There are two basic approaches for estimating flood impacts: the first approach employs unit loss models and the second employs models, which estimate the linkage effects, or inter-sectoral relationships, of floods within economy (Parker, 1992; Islam, 2000). The unit loss model was originally developed by American researchers (White, 1964; Kates, 1965) and later adopted by British and then Australian researchers (Parker and Penning-Rowsell, 1972; Smith and Greenaway, 1988). Although the general concept of unit model approach, which is based on a property-by-property assessment of potential damage, is the basis for loss estimation in many countries, there are wide variations in the existing methodologies for flood loss estimation around the world and only a handful of countries have adopted standardized methodologies for flood loss estimation (Penning-Rowsell et al., 1987; Tang et al., 1992). Some countries like UK, Australia have established detailed methodologies for estimation of tangible losses (Penning-Rowsell and Chatterton, 1979; Smith, 1981; UNSW, 1981). However, in case of USA, Japan, etc. detailed damage estimation methodology is limited to urban damage only (USACE, 1988a; MOC, 1996a). It can be noted that these countries have adopted similar approach in damage estimation i.e. unit loss approach (Parker et al., 1987; Smith, 1994; NTIS, 1996; Parker, 2000). From the various available reports, it is found that countrywide standard methodologies of flood damage assessment are available in Japan and UK, i.e. for assessment of damage caused by floods in any part of the country same standard methodologies are used (Parker et al., 1987; Penning-Rowsell, 1992; MOC, 1996b). USA is in the process of developing a standardized methodology for the whole country. However, in Australia and many other countries, damage assessment methodologies vary in different regions within the country according to individual studies (Thompson and Handmer, 1996).

Establishment of an adequate flood loss estimation model involves many issues due to the nature of damage caused by floods. Some of the most important issues in flood loss estimation are obtaining detailed flood parameters such as flow velocity, depth and duration at any given location; proper classification of damage categories considering nature of damage; and establishment of relationships between flood parameters and damage for different damage categories. Stage-damage functions define the relationship between flood parameters and possible damage, which are derived based on historical flood damage information, questionnaire survey, laboratory experiences, etc. (Krzysztofowicz and Davis, 1983; Smith, 1994). This is the conventional way of damage estimation in different countries around the world. Only a handful of models are available for flood damage assessment at present. Out of that, three well-known models are FDAP (Flood Damage Analysis Package), ANUFLOOD and ESTDAM. FDAP was developed at the Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers at Davis, California to compute flood losses (USACE, 1988b, 1994). Series of HEC programs including HEC-1, HEC-2 and HEC-3, which are a comprehensive set of computerized programs for hydrologic analysis, are included in FDAP (USACE, 1973, 1977, 1979). FDAP utilizes the ‘frequency method’ for calculation of the expected annual damage (Carl and Davis, 1989). The model calculates damage potential for specific flood magnitudes and then weighs the damage values with the probability of exceedence. ANUFLOOD is an Australian model developed by the Center for Resource and Environmental Studies (CRES) of the Australian National University for flood damage assessment based on synthetic stage damage curves for residential and commercial property (Greenaway and Smith, 1981; Taylor et al., 1983; Smith et al., 1983; Smith and Greenaway, 1988). It is available as an interactive computer package and aimed for the users involved with planning and management of flood-prone urban areas for estimation of potential flood damage in residential and commercial sectors. ESTDAM is a standardized flood loss estimation model developed at the Middlesex Polytechnic for UK (Chatterton and Penning-Rowsell, 1981). All these models are useful as a tool for flood plain management as they can estimate potential damage for different scenarios based on historical data of flood parameters. However, none of these models can be used for real-time flood loss estimation or forecasting as there is no well established mechanism available in these models for simulating flood parameters of an actual flood event based on the physical characteristics of the flooded area. FDAP is principally designed for floodplain management, which can provide annual damage values.

A few research works have been conducted on real-time loss estimation modeling so far. One of such modeling approaches was based on GIS and remote sensing technology. In this approach, GIS and remote sensing technology were used for delineation of flood inundated areas for loss estimation (Yamagata and Akiyama, 1988; Shaw, 1994; Consuegra et al., 1995; Lanza and Siccardi, 1995; Tinkeke and Matthijs, 1996). However, the limitation of GIS and remote sensing technology in adequate estimation of flood inundation parameters severely restricts the practical application of these techniques. In 1996, the Delft Hydraulic Institute developed a flood hazard assessment model integrating GIS and hydraulic model in an attempt of real-time damage estimation modeling (Jonge et al., 1996). For a series of discharges, the model calculates the flooding depth in the flood plains and the damage is estimated based on the calculated flood depths. The model focuses on the socio-economic impacts of flooding. The flood model considered in this methodology is a 1D hydraulic model. For a given discharge curve at the upstream boundary, the flood model calculates water levels at discrete points in the river for each defined time step. The maximum simulated water level in each river node is used as input for flood inundation simulation. However, it does not have a physically based model for the flood inundation simulation, instead GIS is used for spreading of floodwater based on river model simulation.

Although there has been a great need for a real-time loss estimation model for flood disaster mitigation, it is realized from the review of previous research works on this subject that only a handful of researchers or research organizations have undertaken such damage estimation modeling. The main difficulty associated with such modeling approach is obtaining adequate flood inundation parameters, which are the most important inputs in loss estimation modeling. There is a need for an integrated modeling approach, which combines a flood inundation simulation model and a generalized loss estimation model such that the simulated flood inundation parameters can be used in the loss estimation model for real-time flood loss estimation as well as for flood disaster reduction planning such as cost-benefit analysis of any proposed flood control plan in a river basin, flood hazard mapping, etc.

The model introduced in this paper is an integrated model, which has two major components: a physically based distributed hydrologic model and a grid-based distributed loss estimation model. The physically based hydrologic model consists of major hydrologic processes and the governing equations for flow propagation in these processes are solved using finite difference schemes. The loss estimation model consists of three kinds of primary tangible flood damage: urban, rural and infrastructure damage. The loss estimation model is based on the unit loss approach. It is formulated as a grid based model with a similar grid network to that used in the distributed hydrological model. In the application process, the distributed hydrologic model simulates flood inundation parameters for each grid and these are used in the loss estimation model to simulate flood damage for each grid cell. Fig. 1 shows a schematic diagram of the integrated model.

2. Modeling of flood inundation and damage

2.1. Physically based distributed hydrologic model

The physically based distributed hydrologic model considers five major processes of hydrologic cycle: interception and evapotranspiration, river flow, overland flow, unsaturated zone flow and saturated zone flow. Interception is modeled using the concept of BATS model (Dickinson et al., 1993). Evapotranspiration process is solved using the concept presented by Kristensen and Jensen (1975). For all other processes, water movement is simulated using the physically based governing equations. The governing equations are solved by finite difference schemes. Table 1 shows the governing equations used for each process. For river flow, diffusive approximation of the 1D St-Venant's equation is considered (Akan and Yen, 1981). An implicit finite difference scheme is used to solve the governing equations of flow for river network. Similarly, for overland flow diffusive approximation of the 2D St-Venant's momentum equations is considered and the governing equations are solved using an implicit finite difference scheme. For the unsaturated zone flow, 3D Richard's equation

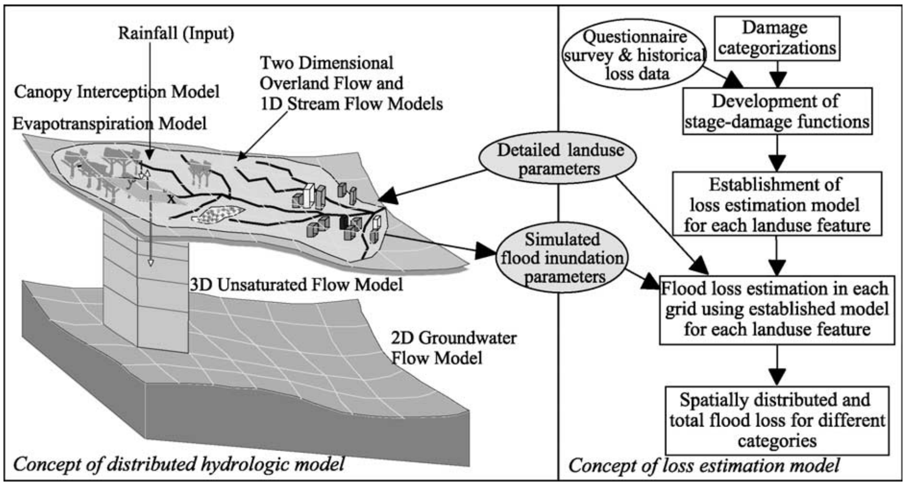

Fig. 1. A schematic diagram of the integrated flood loss estimation model.

of unsaturated zone is solved implicitly (Marsily, 1986). 2D Bossinesq's equation of saturated zone flow is solved implicitly (Thomas, 1973; Bear and Verruijt, 1987). A uniform network of square grids is employed to solve the governing equations with finite different schemes.

Within each process, governing equations are first solved individually and then coupled in each time-step of solution for exchange of parameters. The coupling time can be varied depending on the simulation requirement and resolution of input temporal datasets. The flowchart of solution schemes, shown in Fig. 2, illustrates the coupling procedure. For the present application of the model, the coupling time step is considered as 1 h for all the processes except for overland and river flow. For accurate representation of the dynamic exchange of flow between surface and river, the coupling time between these two processes are considered as 300 s. A flood compartment concept is used to couple overland and river flow processes in which existing embankment heights along the rivers can be incorporated and exchange of flow between surface and river is calculated using a storage routing relation with the assumption of broad-crested weir flow with sub-mergence correction (Fread, 1988). Flow can be either away from the river or into the river, depending on the relative water depths in adjacent river and surface grids. With this process, flood inundation can be simulated for both inland and river overflow flooding. The details of the model formulation, solution scheme of the governing equations of different components and their coupling procedure are described elsewhere and are not elaborated here (Herath, 1987; Herath et al., 1992; Jha et al., 1997; Dutta et al., 2000).

2.2. Flood loss estimation model

In general, flood damage can be broadly classified into two categories: tangible and intangible damages. Tangible flood damages, which can be expressed in monetary value, are of two types: direct and indirect damages, which can be further subdivided into primary and secondary damages as shown in Table 2 (Green et al., 1983; Parker, 1992; Smith, 1994). Direct tangible flood damages are those caused by direct contact of floodwater. In this study, losses are restricted to primary tangible damages for each of the major categories. This is due to the complexity involved in modeling secondary tangible and intangible flood damage. Based on the landuse patterns and nature of damage, flood damages are categorized into three main groups: (i) urban, (ii) rural and (iii) infrastructure. These three categories are divided into several sub-categories based on flood damage characteristics as shown in Table 3. Business interruption loss caused by damage to non-residential structures is not incorporated in the present model.

Table 1
Governing equations used in distributed hydrologic model for different components

Components	Governing equations
Interception (BATS concepts), Evapotranspiration (Kristensen and Jensen equations)	Canopy interception : $I = C \times \text{LAI}$ Actual transpiration : $E_{\text{at}} = f_1(\text{LAI}) f_2(\theta) \text{RDF} E_p$ Actual evaporation : $E_s = E_p f_3(\theta) + \{E_p - E_{\text{at}} - E_p f_3(\theta)\} f_4(\theta) \{1 - f_1(\text{LAI})\}$ where I is intercepted rainfall depth; LAI, leaf area index; C, parameter dependent on vegetation type; RDF, root distribution depth; f_1, function of LAI; f_2, function of soil moisture content at root depth level; and f_3 and f_4, functions of soil moisture at top soil layer
River flow (1D St-Venant's equations)	Mass conservation equation (continuity equation): $\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$ and the momentum equation: $\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\left(\frac{\partial z}{\partial x} + S_f\right) = 0$ where t is time; x, distance along the longitudinal axis of watercourse; A, cross-sectional area; Q, discharge through A; q, lateral inflow/outflow; g, gravity acceleration constant; z, water surface level with reference to datum; and S_f, friction slope
Overland flow (2D St-Venant's equations)	Mass conservation equation (continuity equation): $\frac{\partial uh}{\partial x} + \frac{\partial vh}{\partial y} + \frac{\partial h}{\partial t} = q$ Momentum equations: In X-direction $\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\left(\frac{\partial z}{\partial x} + S_{fx}\right) = 0$ In Y-direction $\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\left(\frac{\partial z}{\partial y} + S_{fy}\right) = 0$ where u is flow velocity in X-direction; v, flow velocity in Y-direction; z, water head elevation from datum level; S_{fx}, friction slope in X-direction; and S_{fy}, is friction slope in Y-direction
Unsaturated zone (3D Richard's equation)	$C(\psi)\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left[k(\psi)\frac{\partial \psi}{\partial z} + k(\psi)\right] + \frac{\partial}{\partial x}\left[k(\psi)\frac{\partial \psi}{\partial x}\right] + \frac{\partial}{\partial y}\left[k(\psi)\frac{\partial \psi}{\partial y}\right] - S_z$ where ψ is pressure in soil; C, soil water capacity function; $K(\psi)$, unsaturated hydraulic conductivity; and S_z is source or sink term

Table 1 (*continued*)

Components	Governing equations
Saturated zone (2D Boussinesq's equation)	$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial x}+Q_w-Q_{\text{vert}}\pm Q_{\text{riv}}-Q_{\text{leakout}}+Q_{\text{leakin}}$$ where T is aquifer transmissivity; h, head; t, time; S, aquifer storage coefficient; Q_w, rate of pumping per unit area; Q_{vert}, water entering from unsaturated zone; Q_{riv}, water inflow from or outflow to river; Q_{leakout}, rate of leakage going out of layer; and Q_{leakin} is rate of leakage coming to the layer

2.2.1. Formulation of mathematical model for flood loss estimation

In this study, the unit loss model concept was adopted in the formulation of a mathematical model for the different categories of flood losses. Considering the need of dynamic linking of the loss estimation model with the inundation simulation model, the loss estimation model is formulated as grid based model with uniform network of square grids, which is same as hydrologic model. In the model, stage-damage functions are used to calculate unit damage percentage to any object for a given condition of flood. The mathematical sub-models for different damage categories are described later.

Mathematical models for urban damage. Urban flood damage includes the direct damage to residential and non-residential buildings, which are of mainly four types: (i) damage to building structure/property, (ii) damage to building contents/stock, (iii) damage to outside property, and (iv) emergency and clean up costs. Generic mathematical models are designed for estimation of damage for these four categories, these use flood depth as the governing flood parameter. The mathematical models adopted for grid based urban damage estimation are shown in Table 4, the procedures for structure and content damage are based on the existing methodology of Japanese Ministry of Construction (MOC, 1996a).

Mathematical models for rural damage. Rural damage covers damage to the agriculture sector, which can be considered as economic opportunity lost due to flood. Taking agriculture farm infrastructures into account, three damage categories are considered in this model development. These are: (i) damage to crops and vegetables, (ii) damage to farm houses, and (iii) damage to farmland and infrastructure. Average

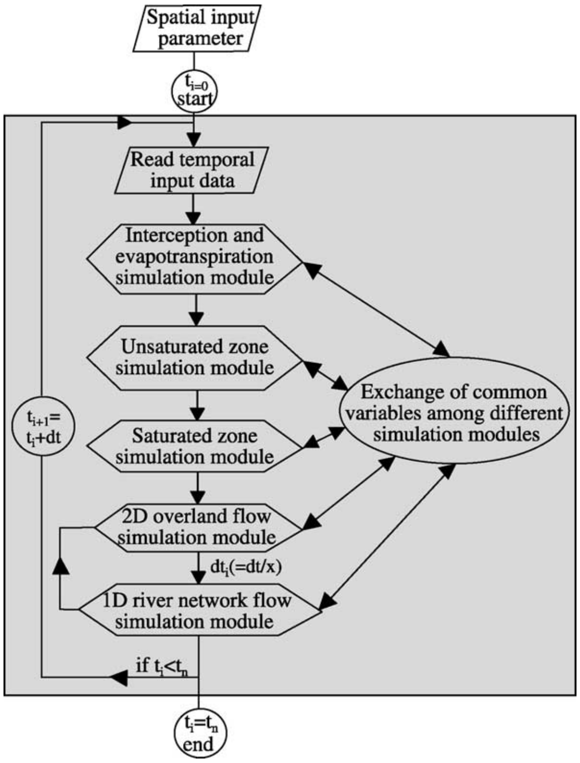

Fig. 2. Flowchart of coupling of different modules of distributed hydrologic model.

Table 2
Flood damage categories and loss examples

Category	Tangible				Intangible
	Direct		Indirect		
	Primary	Secondary	Primary	Secondary	
Examples	Structures, contents and agriculture	Land and environment recovery	Business interruptions	Impact on regional and national economy	Health, psychological damage

damage to agriculture products (crops and vegetable) in any grid (i,j) is estimated as follows,

$$\mathrm{AD}(i,j) = \sum_{k=1}^{n} [D_m(i,j,k)\mathrm{CRP}_a(i,j,k)mn(k)]$$

and

$$D_m = \mathrm{CP}_k Y_k DC_k(i,j)$$

where AD is total agriculture damage; and n total number of crops.

For any type of crop k at any grid $(i,j) : D_m$ is damage to crop per unit area (damage as a proportion of flood-free gross returns); CRP_a is total area of cultivation of crop type k; mn is loss factor for crop type k depending on the time period in a year; CP_k estimated cost per unit weight of crop type k; Y_k is normal year yield of crop type k per unit area; and DC_k is stage-damage function for crop type k.

Property and stock damage to farm houses are estimated using similar models used for non-residential buildings. Damage to farmland infrastructure can be estimated using the following model.

$$D_{fl}(i,j) = \mathrm{TA}(i,j)\mathrm{EC}_{fl}(i,j)C_{fl}(i,j)$$

where in any grid (i,j), D_{fl} is total damage to infrastructure; TA, total farm area; EC_{fl}, estimated cost of complete replacement of farm infrastructure; and C_{fl}, stage-damage function.

Mathematical model for infrastructure damage. Flood associated damage to any infrastructure is governed by many local factors in addition to the flood parameters and because that uncertainties are very high in estimating damage to infrastructure. At present, there is no well-established methodology available for loss estimation to infrastructure. The methodology adopted in this model development is based on the existing methods for estimation of damage to lifeline facilities due to an earthquake (NIBS, 1997). It states that system damage (SD) to any component x of a lifeline system;

$$\mathrm{SD}_x = \sum_{i=1}^{nc} [\mathrm{DR}_c\mathrm{TC}]$$

Table 3
Detailed categories of damage considered in flood loss estimation modeling

Primary tangible flood damage				
Urban damage		Rural damage	Damage to infrastructure	
Damage to residential and non-residential buildings	Structure/property damage	Damage to agriculture products	Water supply	System damage
	Content (stock) damage	Damage to farm houses	Sewerage and drainage	System interruption loss
	Outside property damage Emergency and clean up costs	Damage to farm infrastructure	Gas supply Power supply	
			Telecommunication Transportation	

Table 4
Mathematical models for urban flood damage estimation

Damage to residential buildings	Damage to non-residential buildings
Structure damage $D_{sr}(i,j) = \sum_{k=1}^{rt} \{NR(i,j,k)FA(i,j,k)EC_{sr}(i,j,k)C_{sr}(i,j,k)\}$	Property damage $D_{pnr}(i,j) = \sum_{n=1}^{NI} \{NW(i,j,n)EC_{pnr}(i,j,n)C_{pnr}(i,j,n)\}$
Content damage $D_{cr}(i,j) = NF(i,j)EC_{cr}(i,j)C_{cr}(i,j)$	Stock damage $D_{snr}(i,j) = \sum_{n=1}^{NI} \{NW(i,j,n)EC_{snr}(i,j,n)C_{snr}(i,j,n)\}$
Outside property damage $D_{opr}(i,j) = NEC_{opr}(i,j)C_{opr}(i,j)$	Outside property damage $D_{opnr}(i,j) = \sum_{n=1}^{NI} \{NW(i,j,n)EC_{opnr}(i,j,n)C_{opnr}(i,j,n)\}$
Emergency and clean up costs $D_{er}(i,j) = NEC_{er}(i,j)C_{er}(i,j)$	Emergency and clean up costs $D_{enr}(i,j) = \sum_{n=1}^{NI} \{NW(i,j,n)EC_{enr}(i,j,n)C_{enr}(i,j,n)\}$

Where for any grid (i,j), rt is number of types of residential buildings (based on building materials); NR(k), number of residential building of type k; FA(k), unit residential floor area for building type k; NF, number of households; N, number of total residential buildings; EC, unit price for respective category in present condition; C, depth-damage function for respective category; NI, total number of industry types; and NW(n), number of workers for industry type n

$$DR_c = \sum_{i=1}^{n} [DR_i P(ds_i)]$$

and, service disruption loss (SL) of any lifeline system due to damage of any component x;

$$SL_x = \sum_{i=1}^{nc} [RF_c SC]$$

$$RF_c = \sum_{i=1}^{n} [RF_i P(ds_i)]$$

where nc is total numbers of lifeline component x; TC, replacement costs of component x; DR_c, total damage ratio in percentage; $P(ds_i)$, probability of being in damage state i; DR_i, damage ratio for damage state i; n, total number of damage states; SC, service loss per day due to disruption; RF_c, total restoration function; and RF_i, Restoration function for damage state i.

For both system damage and interruption losses, damage may vary with type of objects and according to the classification made by users.

Traffic interruption loss due to a flood event is the total of marginal costs and opportunity costs. The two important factors in traffic interruption loss estimation are duration of closer of any particular road due to floods and diversion routes and reallocation of traffic. In this study, using network model with origin and destination (OD) information, possible diversion routes are estimated for given condition of flooding of a particular route. The marginal cost (MC) and delay cost (DC) can be estimated as follows.

$$MC=\sum_{i=1}^{n}\left[\sum_{j=1}^{m}[E_l(i)\{a(j)+\frac{b(j)}{v(i,j)}+c(j)v(i,j)^2\}T_v(i,j)td]\right]$$

$$DC=\sum_{i=1}^{n}\left[\sum_{j=1}^{m}[E_l(i)v(i,j)D_c(i)T_v(i,j)td]\right]$$

where n is number of roads flooded; m, mode of transport in any road i; $E_l(i)$, extra length to be covered due to floodwater in road i; $a(j)$, $b(j)$, $c(j)$, fuel consumption related constants for mode of transport j;

$v(i,j)$, average speed of model of transport j at road i; T_v, total volume of traffic for mode of transport j in road i per hour; t, total duration of flood in hours; d, factor to consider the variation of traffic volume in weekdays and weekends; and D_c is delay cost per unit time for road i.

2.2.2. Establishment of stage-damage functions

Stage-damage functions are essential components of flood damage estimation model, which relate flood damage to flood inundation parameters for different classes of objects (Krzysztofowicz and Davis, 1983; Smith, 1994). The flood inundation parameters considered for stage-damage functions are flood depth, duration and velocity, which govern the damage characteristics. The stage-damage functions are usually derived two ways: one way is based on damage data of past floods, and other way is from hypothetical analysis based on land cover and land use patterns, type of objects, information of questionnaire survey, etc. known as synthetic stage-damage functions. For the application of the loss estimation model in Japan, in this study stage-damage functions for different objects are derived from the averaged and normalized data published by the Japanese Ministry of Construction which are based on the site survey data accumulated since 1954 (MOC, 1996b). These

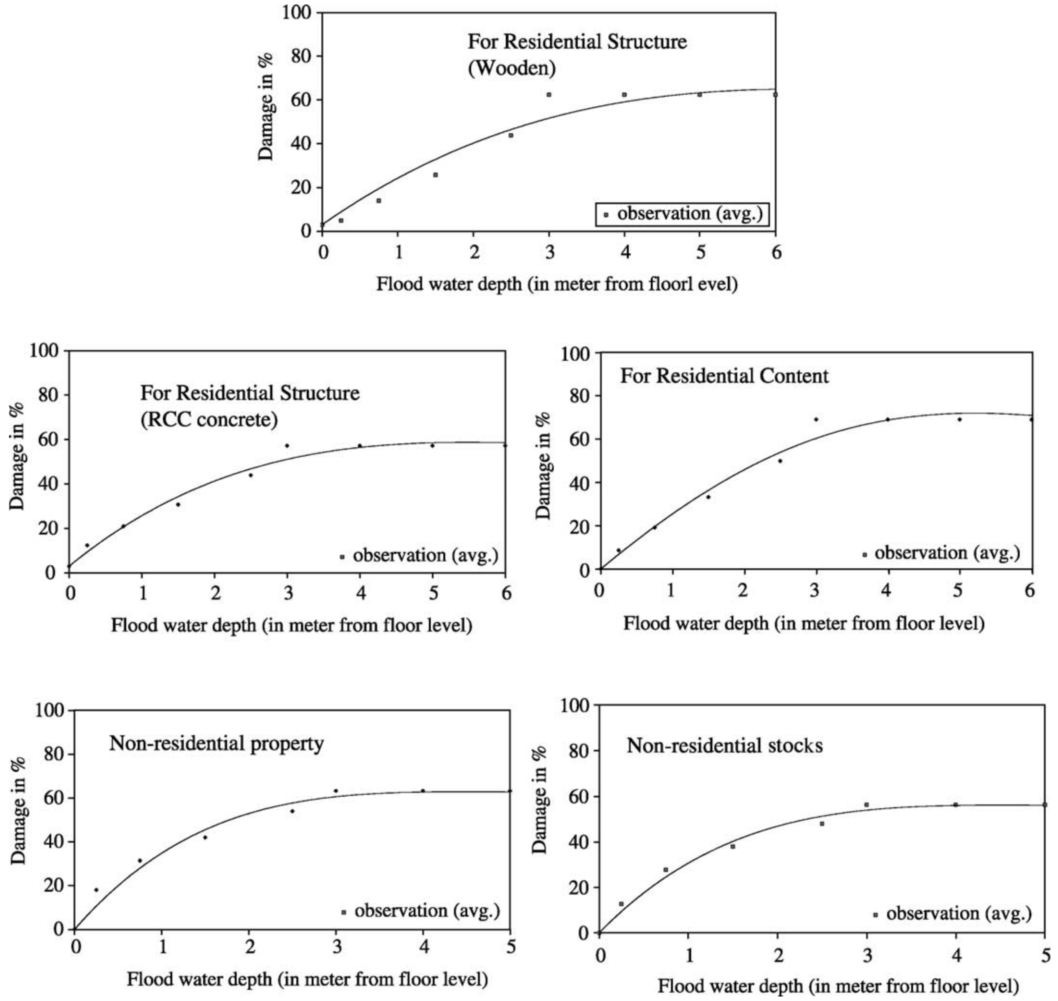

Fig. 3. Depth-damage curves formulated for urban damage estimation.

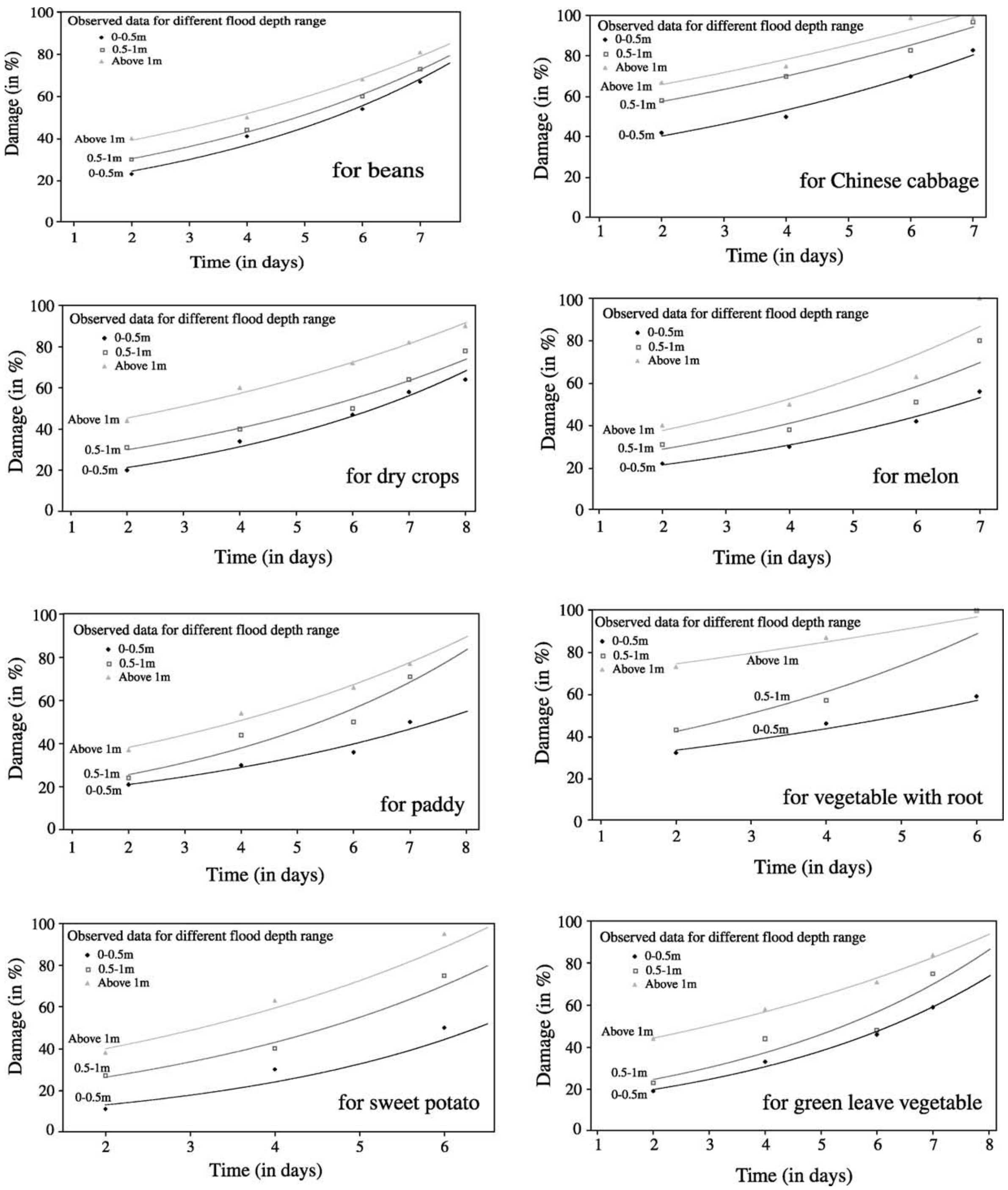

Fig. 4. Stage-damage curves formulated for agriculture product damage estimation.

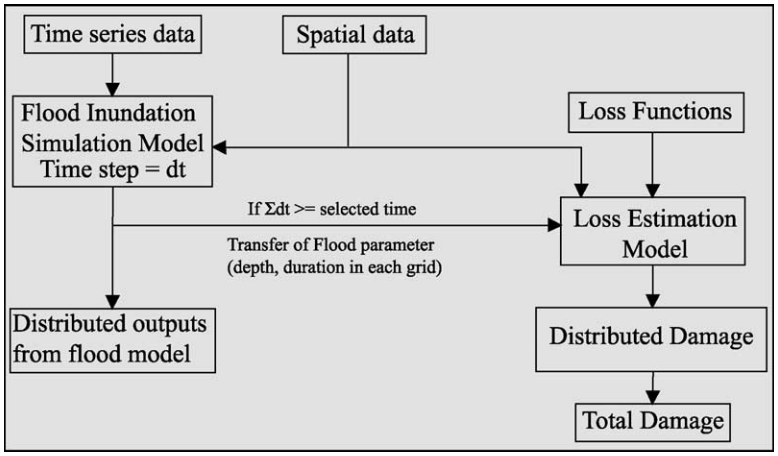

Fig. 5. Concept of integration of flood inundation simulation and loss estimation models.

normalized data are used by the Ministry for design and planning purposes.

As depth of floodwater is the governing flooding parameter for damage to urban buildings, in construction of stage-damage functions for urban damage, only flood depth is considered in this study. Based on the availability of information, five categories of stage-damage functions are used to describe urban flood damage as follows;

- depth-damage functions for residential structure (wooden)

Table 5
Input datasets for setting up of distributed hydrologic model

Model component	Input data requirement	
	Temporal data	Spatial data
Interception and evapotranspiration	Rainfall Potential evaporation Leaf area index Root distribution function	Landcover Surface roughness
River flow	U/s and d/s boundary conditions Water level/discharge	River network Branch cross-sections, bed profile River training works Flood control structure
Overland flow	Rainfall	Topography Rain gauge locations Detention storage Surface roughness coefficient
Unsaturated zone		Soil type distribution Hydrogeological properties of soil Initial soil-moisture
Saturated zone	Groundwater withdrawal	Aquifer and aquitard layers Hydrogeological properties of aquifer and aquitard layers Locations of pumping wells Initial groundwater table

- depth-damage functions for residential structure (RCC concrete)
- depth-damage functions for residential content
- depth-damage functions for non-residential property
- depth-damage functions for non-residential stock

In this case, residential building structures are considered as two types: wooden structure and concrete structure, which are main types of residential building structures in Japan. Due to limitation of historical data, for non-residential property and stock, single depth-damage functions are considered as representative of all types of non-residential buildings. However, the unit property and stock value are different for different categories of non-residential buildings, which are grouped into ten categories. These categories are as follows: (i) mining, (ii) construction,

Table 6
Input spatial parameters required for establishing loss estimation model

Damage category		Input data required
Urban damage	Residential building	Total floor area Type of structures Value of any structure per unit floor area Building height Household distribution Content and outside property value per household
	Non-residential building	Total floor area Type of non-residential buildings Number of non-residential building per type Property, stock and outside property values of non-residential building per worker per type Total workers of non-residential building per type
Rural damage	Farm house	Total number of farm houses Farmhouse property, stock and outside property value per farmer Total number of farmers per farm house
	Crop and vegetables	Type of crops/vegetable cultivated Area of cultivation per crops Cultivation season for each crop Yield per crop per unit area Market value of each type of crop per unit weight
	Farm infrastructure	Distribution of farm house infrastructure Replacement costs of different infrastructure
Infrastructure damage	System	Type of lifeline systems Number of components in each type of lifeline system Replacement cost
	Service interruption	Loss per day for disruption of any component
	Transportation interruption	Road network Total mode of transport Traffic volume in each road in temporal scale Average velocity of each mode in each road Maximum traffic capacity in each road Running cost parameters Delay cost per unit time

(iii) production, (iv) electricity/gas/water supply, (v) transportation, (vi) wholesale and retailed sale, (vii) finance and insurance, (viii) real estate, (ix) service and (x) government. Fig. 3 shows the stage-damage curves constructed for urban damage for Japan.

In formulating stage-damage functions for agriculture damage, both depth and duration of floods are taken into account. Based on the nature of damage due to floods, agricultural products are categorized into eight categories in Japan by MOC and Fig. 4 shows the stage-damage curves fitted to these data and used in the present study.

2.3. Integration of distributed hydrological model and loss estimation model

Integration of the flood inundation simulation model and loss estimation model has been done for dynamic exchange of simulated parameters. As illustrated in Fig. 5, in each time step of simulation, or, in any selected time step, the flood inundation model simulates inundation using input spatial and temporal parameters, and the simulated flood inundation parameters in each grid are transferred to the damage estimation model. Using grid based mathematical models and stage-damage functions, losses are simulated by the model. The damage can be obtained two-ways: first is temporal variation of damage with time step and secondly, for total damage up to the simulated time step in each grid. Finally, total damage is estimated from each grid data for each time step or, total damage up to the required time step.

2.4. Input model parameters

The integrated flood loss estimation model requires a large amount of spatial and temporal input parameters. Temporal data are only required for the flood inundation simulation model, however, spatial input datasets are required for both the models. Tables 5 and 6 list the temporal and spatial datasets required for setting up the integrated model for application.

3. Model application

3.1. Study area

For the preliminary application of the integrated model, a medium size and frequently flood affected Japanese river basin has been selected. This is the Ichinomiya river basin, 220 km^2 in size, located in the Chiba prefecture between longitude 35°18′N to 35°30′N and latitude 140°10′E to 140°25′E (Fig. 6). There are seven major land cover classes, namely: dense forest, light forest, grassland, paddy, vegetables, water body and urban land use. Urban areas

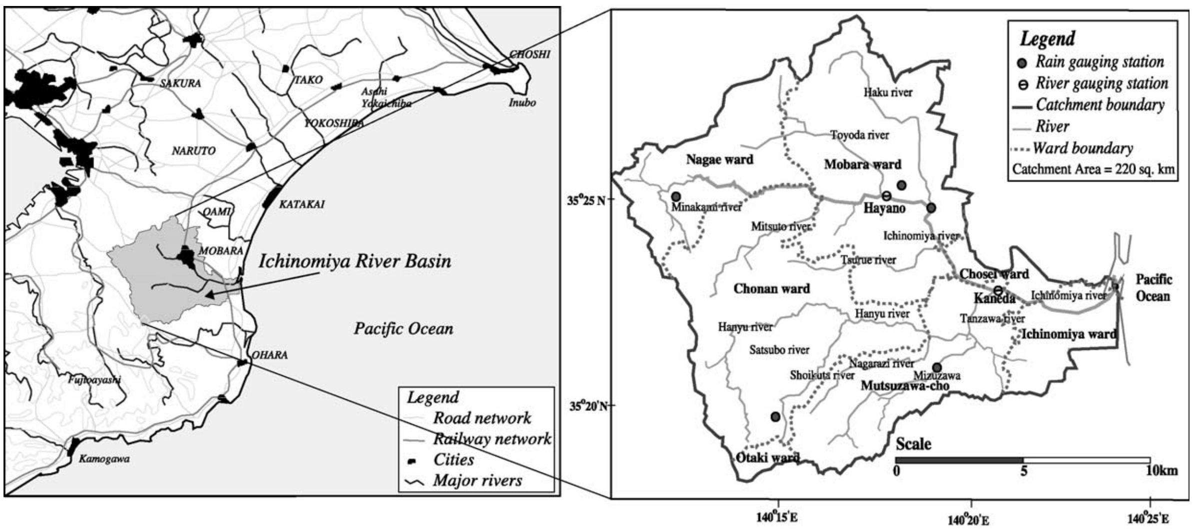

Fig. 6. Location map of the study area selected for preliminary model application.

Table 7
Ward level population statistics in the study area (for 1995)

Population statistics	Ward located in the study area					
	Ichinomiya	Mutsuzawa	Chonan	Nagae	Mobara	Chosei
Population	11,302	8250	11,339	8848	91,670	12,679
Household	3432	2238	2988	2355	29,805	3576

are located in the lower part of the basin with flat topography and are the most vulnerable to floods. Severe damage has occurred to the urban areas many times in the past. For the model application, a major flood event of 1996 was selected.

3.2. Data preparation

Accuracy of simulated outputs of the model greatly depends on the accuracy of the input temporal and spatial datasets. It is not possible to obtain measured input parameters in each simulation grid for the model and data interpolation is required with several assumptions to generate all the parameters from available limited measured parameters. In this section, the procedures and assumption made for preparation of input temporal and spatial datasets for flood inundation and loss estimation models are summarized.

3.2.1. Data for flood inundation model

A digital elevation model (DEM) of 50 m resolution for the study area was obtained from Japan Map Center. It was improved in the flat areas by adding contour data of 1:2500 scale contour maps to enhance the generated river system from the DEM to match the actual river paths. River cross-section data in each branch, bed profiles, embankment heights along the main river and rating curves were obtained from the local city office. Land cover information was derived from SPOT satellite images. Soil map was obtained from Mitsui Consultant Co. Ltd, Japan, which has six major soil classes and soil parameters were measured from the field test data conducted in different areas within the basin. Groundwater information was limited and assumptions were made in setting up the model based on the available literature. Hourly rainfall data were obtained from five gauging stations. Daily pan evaporation data was available for one station. Leaf area index and root distribution functions for different land cover types were taken from available literature (Dutta, 1999).

3.2.2. Data for loss estimation model

Urban damage. In the study area, residential and non-residential building information, including average building heights, number of households and workers, were available at ward level (Tables 7–9). Although, the information of residential

Table 8
Housing data of Mobara Ward and Chiba Prefecture (from 1993 Housing Survey (MCA, 1993))

Housing details			Mobara	Chiba
Type of buildings	Detached	Total	21,380	1,057,100
		Single storey	6810	260,200
		Two stories or more	14,580	796,900
	Tenement-house	Total	1230	51,300
		Single storey	540	11,900
		Two stories or more	690	39,400
	Apartments	Total	4500	707,400
		Single storey	–	300
		Two stories	2080	256,700
		3–5 stories	1300	319,300
		Six stories or more	1120	131,100
Construction materials	Detached	Wooden	23,070	1,018,700
		Concrete	4110	26,900
	Tenement-house	Wooden	590	34,800
		Concrete	640	14,800
	Apartments	Wooden	1710	177,300
		Concrete	2790	504,500

Table 9
Ward level statistics of non-residential buildings in the study area (year 1995)

Industrial statistics		Ward located in the study area					
Type	Number	Ichinomiya	Mutsuzawa	Chonan	Nagae	Mobara	Chosei
Mining	Office	0	1	0	0	2	0
	Employee	0	7	0	0	235	0
Construction	Office	55	56	77	67	391	52
	Employee	389	254	343	446	3327	368
Production	Office	49	32	50	54	248	41
	Employee	653	815	1962	1153	12,428	1388
Electricity/Gas/Water	Office	0	0	1	2	4	0
	Employee	0	0	14	28	197	0
Transportation	Office	10	6	15	11	73	10
	Employee	121	46	115	137	1895	81
Wholesale and retail sale	Office	281	81	158	102	1908	290
	Employee	1344	354	546	292	10,753	1987
Finance and insurance	Office	5	0	1	0	71	2
	Employee	49	0	13	0	1151	27
Real estate	Office	30	3	1	8	110	2
	Employee	96	11	5	50	477	8
Service	Office	206	70	105	77	871	87
	Employee	1395	743	766	907	7182	754
Government	Office	11	7	10	7	27	8
	Employee	195	75	137	85	865	82

and non-residential buildings were available in ward level, their geographical distribution details within the ward were not available. Grid level distribution of these information are approximated based on the detailed urban land use map derived from LANDSAT imagery (Fig. 7) (Herath et al., 1999). Residential and non-residential floor areas in each simulation grid were derived from land use classification map as follows

$$\mathrm{FA}(i,j) = \text{grid area}(i,j) N_l(i,j) \mathrm{AF}(i,j) \times \sum_{k=1}^{n} [X(i,j,k) F(i,j,k)]$$

where N_l is type of land cover (if urban land use, $=1$, else, $=0$), AF, area fraction of urban land use within the grid, n, total urban land use types; X, building ratio for urban land use type k; and F is floor area fraction for urban land use type k.

Floor area fraction and building ratios for residential and non-residential buildings in different urban land use types were estimated from aerial photographs and detailed base map available in ward level for housing distribution. Table 10 shows the average unit property values for the study for both residential and non-residential buildings.

Rural damage. Various agriculture data for the study area were derived from the averaged prefectural datasets obtained from the census report of Ministry of Agriculture, Forestry and Fisheries of the Government of Japan (MAFF). For grid level spatial distribution of these datasets, the following assumptions were made:

1. Within the study area, agriculture parameters were assumed to be distributed within the agriculture land cover areas obtained from classified LANDSAT image;

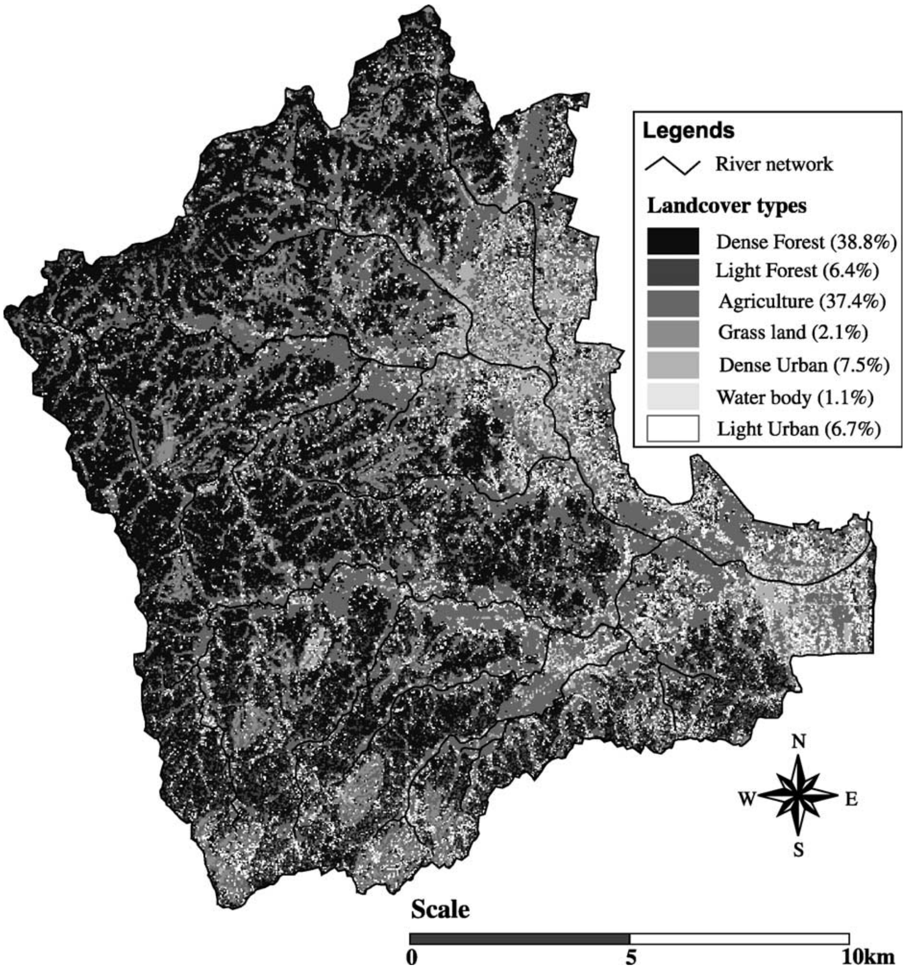

Fig. 7. Land cover map derived from LANDSAT TM image.

2. Farm area proportion and upland and low land crop information were used to decide the area fraction for different crops and vegetables in the different wards within the study area.

Infrastructure damage. In this application of the model, estimation of infrastructure damage was limited to traffic interruption loss due to limitation of existing input datasets and stage-damage functions. Traffic data including OD information were collected from Traffic Census Report prepared by the Ministry of Transportation, Japan. Fig. 8 shows the road network in and surrounding the study area. Traffic volume data in daily and hourly level, running cost parameters and the economic value of time were available for different modes of transportation for each road shown in the road network map.

3.3. Simulation results

3.3.1. Flood inundation simulation

During September 22–25, 1996, the basin experienced a major flood disaster due to the heavy rainfall caused by Typhoon 17. Within 24 h the whole basin received about 360 mm rainfall. The distributed flood inundation model was used to simulate this flood event. The model was run for a total of 4 days starting from September 20, 1 day before the typhoon passed through the basin.

Table 10
Unit economic values of different urban objects in the study area

Category			Value in Million Yen
Residential building		Structure value per unit area	0.169
		Content value per unit area	5.40
Non-residential Building	Mining	Property value per employee	8.16
		Stock value per employee	1.91
	Construction	Property value per employee	1.98
		Stock value per employee	6.61
	Production	Property value per employee	5.18
		Stock value per employee	3.69
	Electricity /gas/water	Property value per employee	129.87
		Stock value per employee	1.87
	Wholesale and retail sale	Property value per employee	2.45
		Stock value per employee	2.90
	Finance and insurance	Property value per employee	5.72
		Stock value per employee	0.64
	Real estate	Property value per employee	26.05
		Stock value per employee	34.54
	Service	Property value per employee	5.72
		Stock value per employee	0.64
	Government	Property value per employee	5.72
		Stock value per employee	0.64

The detailed results of the flood inundation simulation and verification of simulated hydrographs with observation are not discussed in this paper as those results were presented elsewhere (Dutta et al., 2000). Fig. 9 shows the comparison of simulated flood hydrographs with observed hydrographs at the Hayano and Kaneda gauging stations (Fig. 6). Except for the peak, simulated flood hydrographs agree well with the observed hydrographs. Fig. 10 shows the simulated flood inundation with floodwater depths and the boundaries of surveyed flooded areas. By comparing the simulated results with the survey flood, in general it can be said that the simulated results are 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, topography data used for the upper part of the basin is averaged data for 50 m gridsize. High resolution and accurate topography data are essential for high accuracy in simulated flood inundation outputs. In addition, due to lack of detailed information about the 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 precised output. The shifting of the simulated inundated areas from the actually inundated areas along the main river in the flat region of the basin can be attributed to the shift of generated river networks from the actual channels in these areas. In addition, 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 floodwater from river sides, but the road networks are yet to be separately considered in the model.

Fig. 11 shows four snapshots of the simulated flood inundation areas along with input rainfall at four

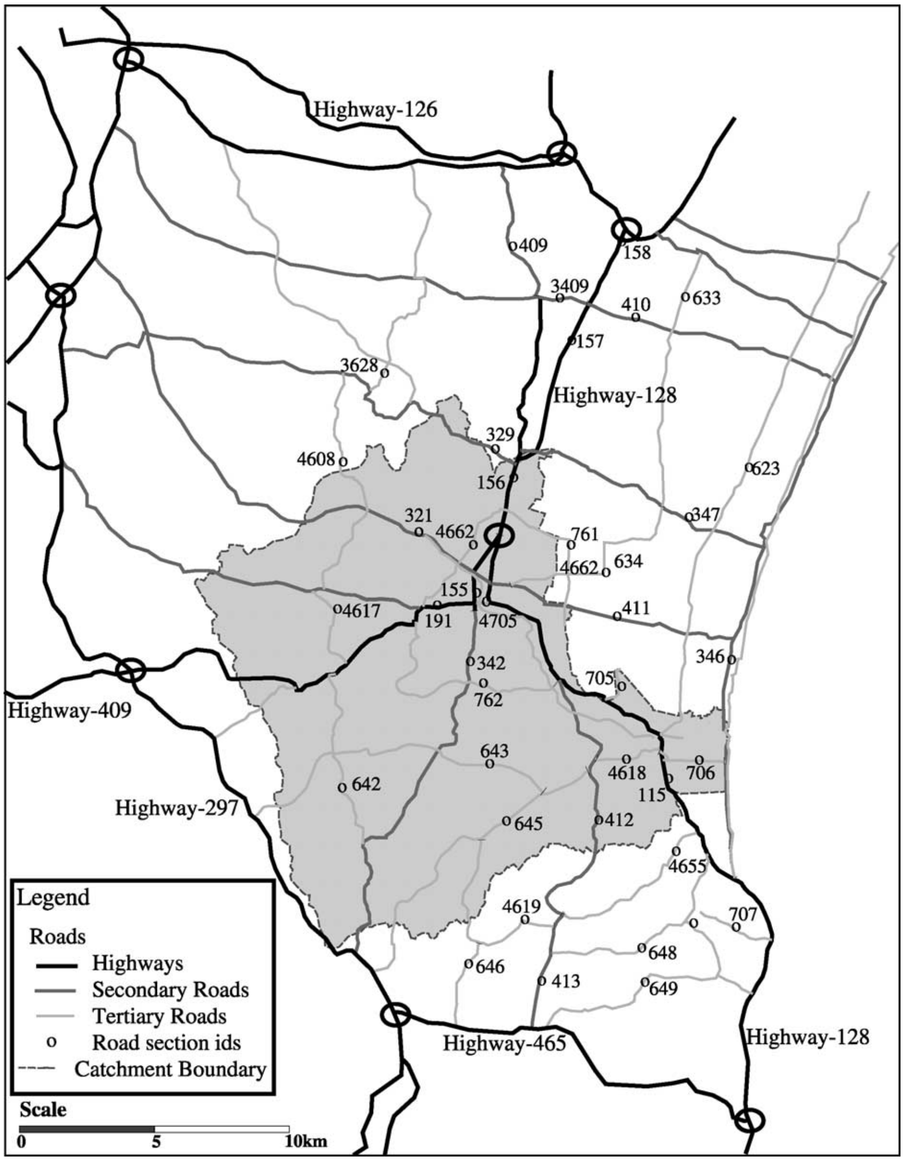

Fig. 8. Road network distribution in and surrounding the study area.

different time steps, which explains the capability of the model to capture the temporal and spatial gridwise information of flood inundation, which are required as input parameters for the loss estimation model.

3.3.2. Flood loss estimation

Flood damage estimation was undertaken for all the three categories; urban, rural and infrastructure. However, verification of the results with actual surveyed data could be done only for urban damage due to non-availability of surveyed data for other two categories.

Estimates of the different categories of urban damage for the surveyed and simulated flood inundation parameters of 1996 floods are shown in Fig. 12. It can be observed from this figure that estimated urban damage from simulated flood inundation is higher than the estimated damage from surveyed flood inundation

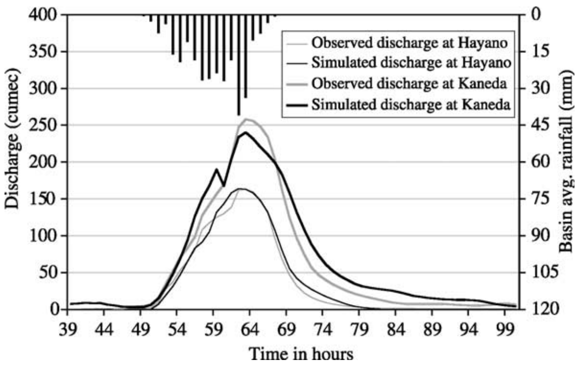

Fig. 9. Simulated and observed hydrographs at the gauging stations.

parameters. Simulated losses for residential buildings are higher by about 40% and non-residential buildings by 30% than the estimated damage based on surveyed flood parameters. One of the main reasons of this large difference between simulated and estimated losses was the difference between simulated and surveyed flood extents. As can be seen from Fig. 10, the simulated flood extent was larger than the surveyed flood extent and it deviated from the actual flooded locations in several places. These discrepancies in the simulated flood inundation extents were mainly due to two reasons: one was the less vertical accuracy of the input DEM and another was the non-consideration of the locally elevated highways, which modified the movements of floodwater. Due to larger simulated floods extents, which mainly covered the urban areas, the flooded residential and non-residential areas simulated by the model were larger than the actual and that resulted in larger simulated damage for residential and non-residential buildings.

Fig. 13 shows spatial distribution of simulated damage to residential contents and non-residential properties in the flood affected areas of the basin. It demonstrates that the integrated model is capable of providing the spatial distribution of various categories of damage in the flood affected areas. From this figure,

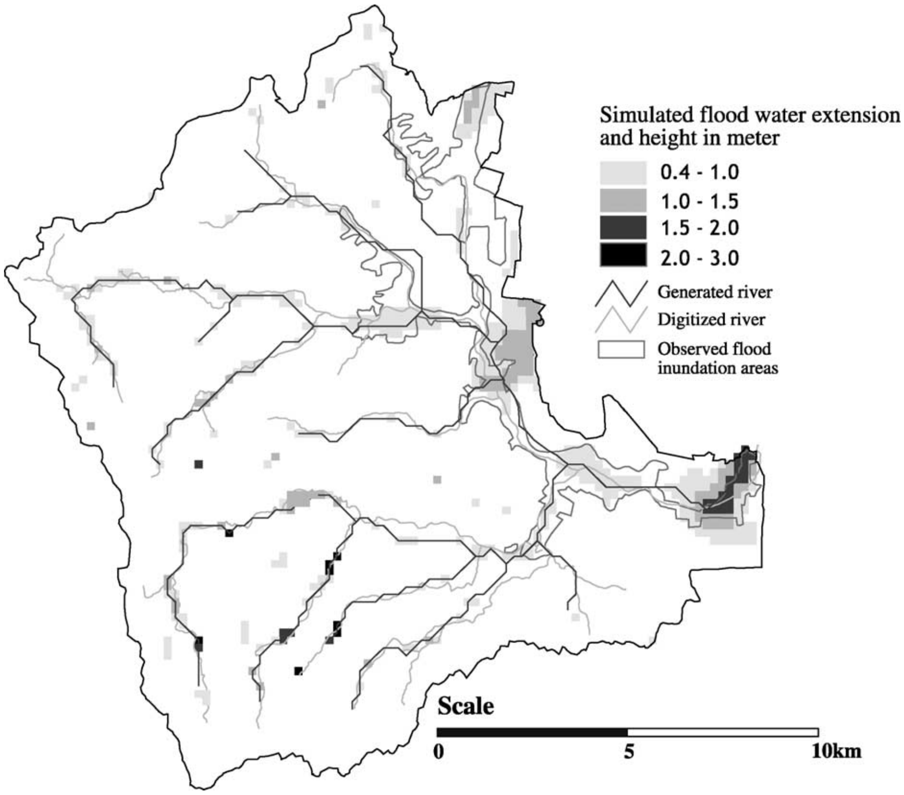

Fig. 10. Simulated maximum flood inundation areas.

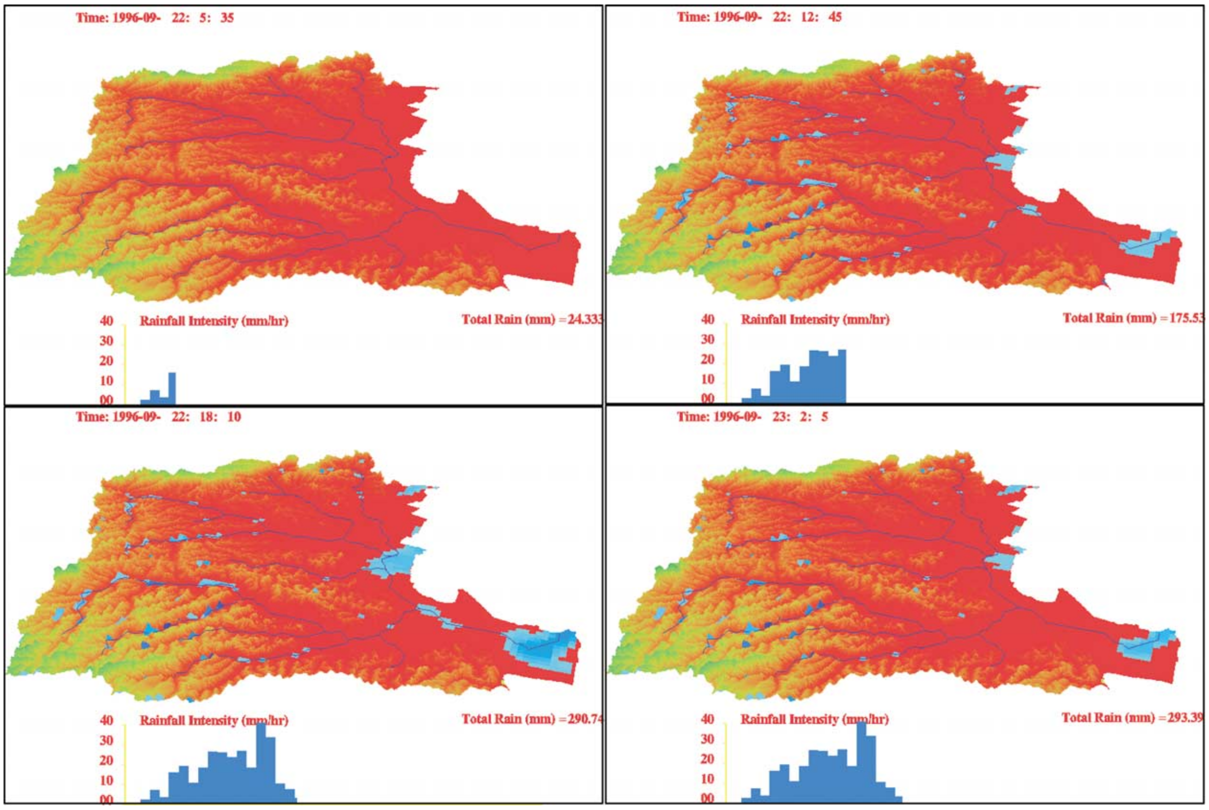

Fig. 11. Simulated flood inundation maps at four different time steps.

it can be observed that total amounts of all categories of urban damage are high in the areas along the Ichinomiya river in Mobara and Ichinomiya wards. From Fig. 7 it can be seen that these are densely populated and that resulted in higher damage in these wards. Based on careful analysis of such spatially distributed damage results, risk maps can be derived for the study area for floods of different magnitudes.

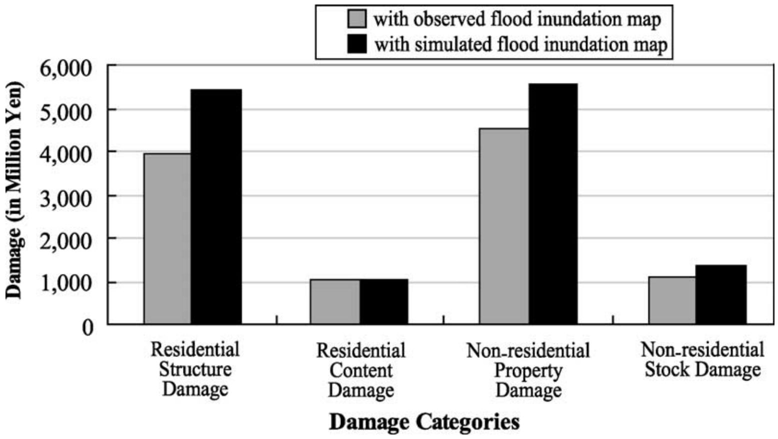

Fig. 12. Simulated urban flood damage.

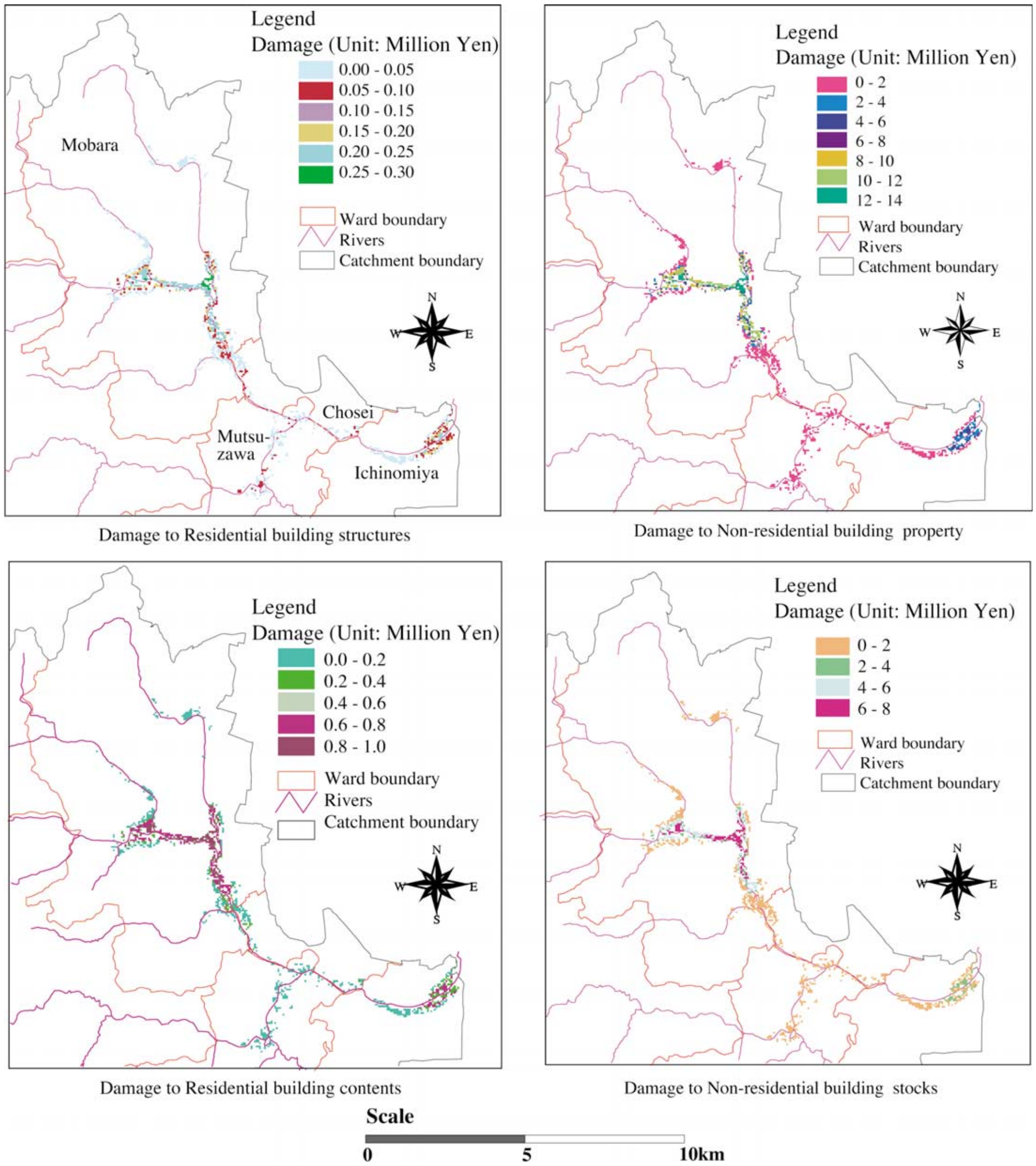

Fig. 13. Spatial distribution of simulated urban damage of different categories.

Estimated different categories of rural damage by the model are shown in Table 11. The 1996 flood occurred during September 21–23 and harvesting of paddy was complete a few weeks before the floods in the region. In addition, floods inundated mainly the urban areas, inundated agriculture land was much less compared to urban areas and due to that there was not

Table 11
Simulated rural flood damage

Damage category	Damage in Million Yen
Farm house property	1.55
Farm house stock	1.31
Crops and vegetables	236.98

Table 12
Simulated traffic interruption loss

Damage category	Damage in Million Yen
Marginal costs	1.05
Delay costs	552.11

much damage to agriculture. Total estimated agriculture damage was about 2% of the urban damage.

Traffic losses are of two kinds, marginal costs and delays. The estimated marginal and delay costs due to the 1996 floods are shown in Table 12. From this table, it can be seen that delay costs is much higher than the marginal costs, which is due to the larger costs per unit time for a vehicle. Overall traffic interruption loss was much less in this flood event compared to urban flood damage, that is only about 4%, as the duration of flood was very short and only a few major roads were inundated.

Simulated rural damage and traffic losses could not be verified with actual damage as there was no observed data of actual damage available for rural and infrastructure damages for this flood event.

3.3.3. Scenario analysis for extreme floods

For flood disaster mitigation in a river basin, it is important to analyze the extreme flood characteristics. The integrated model can be used as a tool for conducting such analysis effectively. To demonstrate the applicability of the model for extreme flood analysis, a simulation was carried out with 100-year return period rainfall in the basin. For estimation of 100-year return period rainfall, first the intensity–duration–frequency function was used with the local coefficients for the basin. The alternative block method was used to develop a design hyetograph from the intensity–duration–frequency function. Finally, using this hyetograph and previous rainfall patterns, 100-year return period rainfall for different gauging stations in the basin were estimated. Fig. 14 shows the basin average 100-year return period rainfall.

The simulated maximum flood inundation map is shown in Fig. 15. By comparing this with the flood inundation map due to 1996 rainfall (which is of about 50-year return period) as shown in Fig. 10, it can be observed that the flood extent is larger in this case. However, the increase of floodwater depth is larger in lower part of the basin compared to upstream. This is because of the lower height of embankment in this area. Thus, the lower part of the basin along the main river has more risk of high floods compared to the upstream. Fig. 16 shows the comparison of flood damage due to 100-year return period rainfall with the damage of 1996 floods. It can be seen from this figure that both urban and agriculture damage were increased by more than 20% and traffic interruption loss was increased by about 5%. With the increase of flood inundation heights, urban damage increases largely and with the extension of flood inundation areas, more agricultural areas were damaged, however, total agricultural damage was much less significant compared to urban damage.

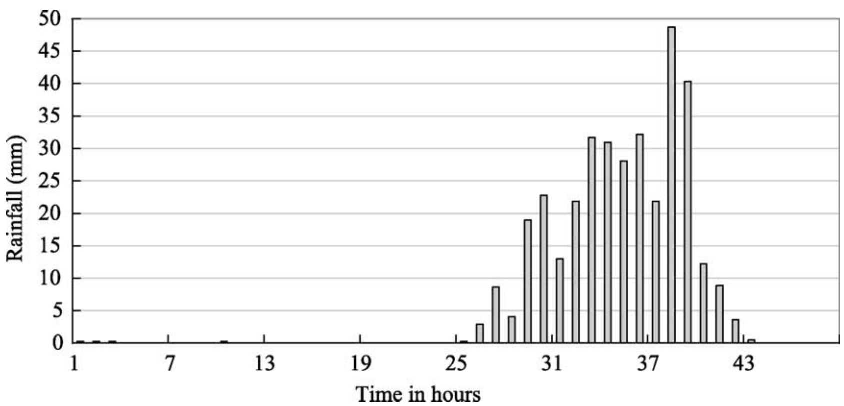

Fig. 14. 100-year return period basin average rainfall.

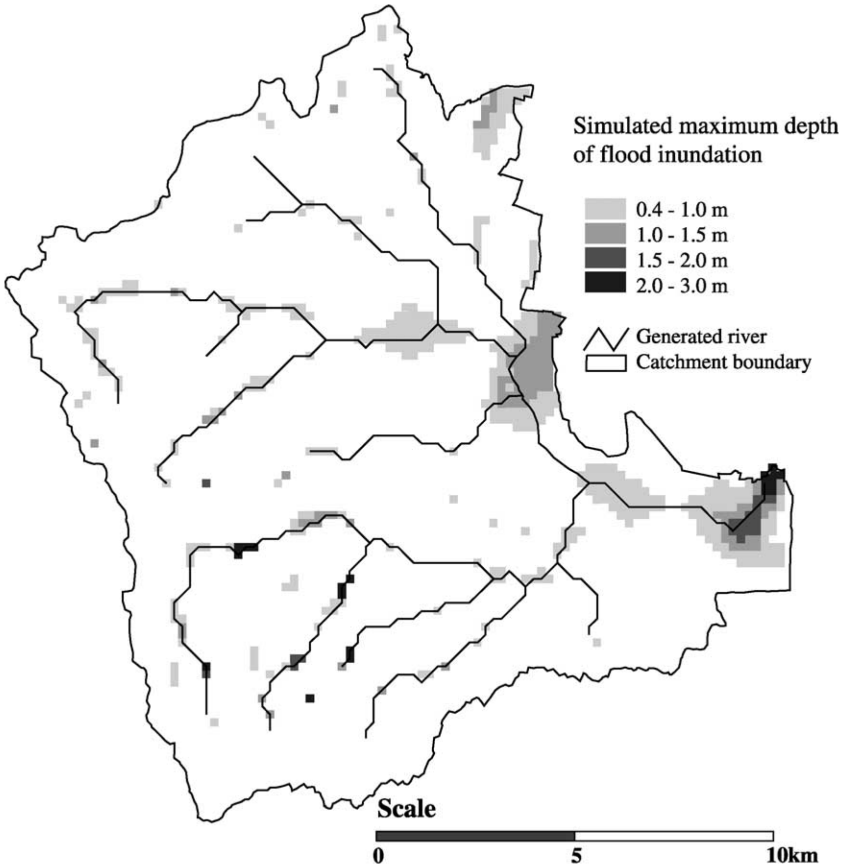

Fig. 15. Simulated maximum flood inundation map due to 100-year return period rainfall.

4. Conclusions

In this paper, an integrated mathematical model for simulation of flood inundation and loss estimation and its preliminary application in a river basin in Japan are discussed. The model considers the major physical processes in a river basin for flood inundation simulation and takes into account of stage-damage relationship between flood parameters and different land use features for economic loss estimation. The integrated and grid based flood loss estimation model presented here is a new approach of its kind. Due to dynamic linking of flood inundation model with loss estimation model, it can provide spatial distribution of flood losses at any given time as well as total losses for any given flood event.

The results of the model application in the Japanese river basin show that model can simulate the flood inundation parameters well. The damage estimation model performs satisfactorily with the limited input data in urban damage estimation, however, its applicability for rural and infrastructure damage estimation was not duly verified due to lack of observed data. Further study is required to carefully validate the model results for rural and infrastructure damage estimation.

There is scope to improve the model for both flood inundation simulation and loss estimation. In flood inundation simulation, there is a need to consider highways and urban structures separately in surface flow simulation in order to improve simulated flood parameters. Stage-damage functions are the building blocks in formulating the loss estimation model. At present, only a few categories of stage-damage functions were constructed on average data due to the limitation of comprehensive

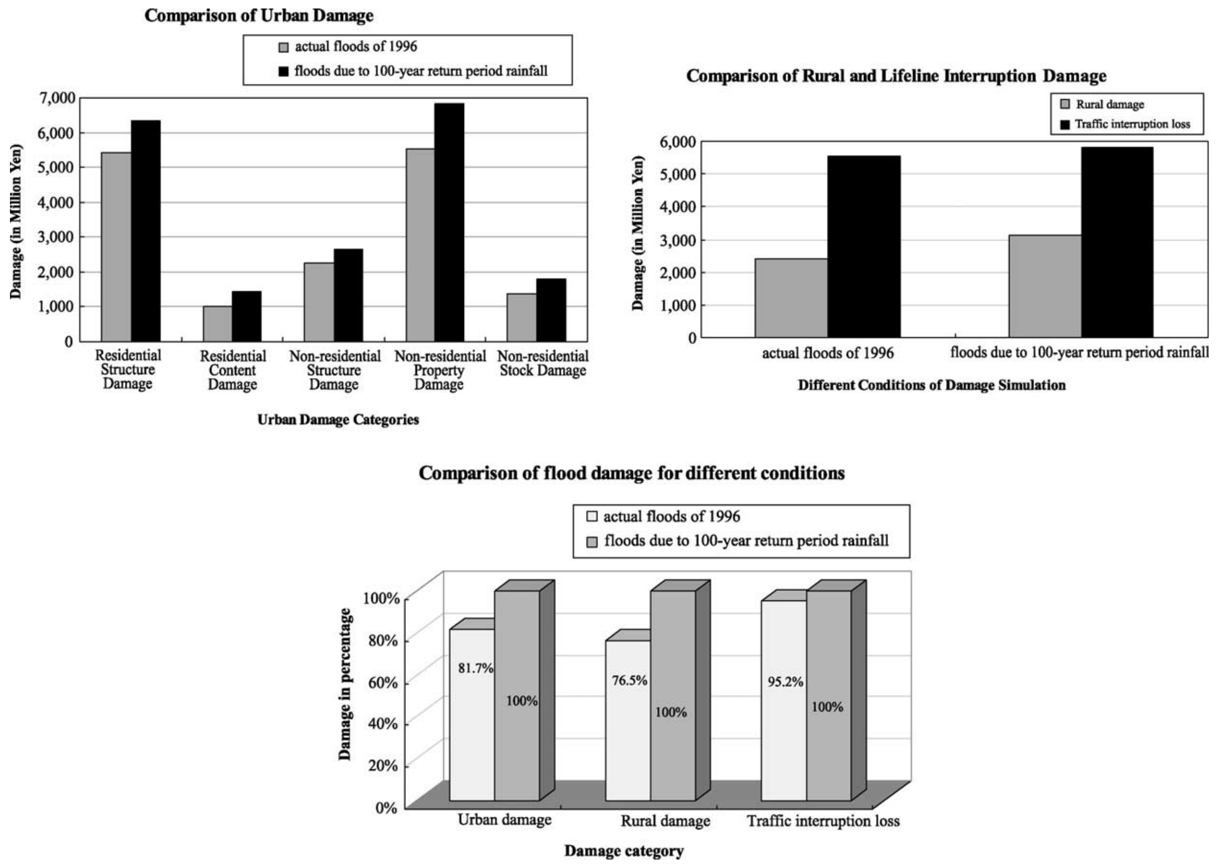

Fig. 16. Simulated flood damage due to 100-year return rainfall and comparison with damage of 1996 floods.

datasets. More detailed regional and local stage-damage functions are needed to increase the accuracy of loss estimation. Further, other categories of tangible flood losses are needed to be included in the model such as indirect flood losses due to business interruption, etc.

With the advancements in computational resources, distributed hydrological modeling approaches have become increasingly popular due to their ability to consider heterogeneity of input parameters and to provide distributed outputs. Generic distributed flood damage estimation model integrated with flood inundation model can be viewed as one of the important tools in flood disaster reduction. However, their applicability to real world problems is limited by their complexities and requirement of the large amount of spatial and temporal datasets. This research study was a compromised approach of distributed modeling for flood inundation and damage estimation in the view of real-world application. In this study, SPOT and LANDSAT satellite data were used for derivation of detailed land cover information and for estimation of urban floor area. It was found that estimation was adequate in dense urban areas, however, in light urban areas, errors were large. Such limitations in input topography and property distribution are expected to be overcome in the near future with the advancements in global positioning system and remote sensing technology.

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