FLOOD DAMAGE ESTIMATION OF AN URBAN CATCHMENT USING REMOTE SENSING AND GIS

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ABSTRACT

Estimation of economic loss due to floods often becomes necessary for flood damage mitigation. The present practice is to carry out post flood surveys to estimate the damage, which is a laborious and time-consuming task. In the present paper a framework for rapid estimation of urban flood damage is presented. The economic damage is estimated based on the property distribution within the inundated area, inundation depth and stage-damage functions for different damage categories. The stage-damage functions are derived from past flood data while the property distribution is represented in a detailed GIS for the area of interest. The GIS is developed using lumped statistics corresponding to administrative units and land cover information obtained from satellite image classification. The method is applied to a recent flood in Chiba prefecture, Japan, and estimations compare well with post damage assessments.

KEYWORDS

Damage categories, Depth-damage function, Flood damage modeling, Flood loss, GIS

INTRODUCTION

Estimation of flood damage in urban areas is an important topic for flood control as well as for flood insurance. A quick estimate of economic damage 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 and emergency management. While the potential flood hazard reduces with improved flood mitigation schemes, flood damage potential increases with the accumulation of wealth and urban expansion. A prior estimate of flood damage potential thus helps in crisis management after a large-scale urban flood disaster.

What constitute flood damage as well as methodology for estimating loss in different categories differs from country to country. In general, the flood damage can be categorized as shown in Table 1 (UNSW, 1981).

Table 1. Flood damage categories and loss examples

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

There are basically two methods in carrying out flood damage estimations. One is to carry out a thorough questionnaire survey of affected population and properties to estimate the incurred loss. The other is to use what are known as stage-damage functions which describe the damage extent to different types of property for a given inundation depth and inundation duration. Using such stage-damage functions economic damage to different property categories are estimated and the summation provides the total flood damage. Stage-damage functions are derived either from past flood data analysis, or through analytical descriptions of flood damage to various properties considering the possible damage ratio to a given flood depth and duration. A number of studies are reported in literature that describes stage-damage functions derived from post flood damage analysis (Parker et. al., 1987; Smith, 1994; NTIS, 1996; etc.). In Japan and United Kingdom, the procedures are standardized to estimate flood damage for any part of the country using normalized stage-damage functions. The main purpose of these procedures is appraisal of flood control projects through standardized economic loss assessment. Such generalizations require simplifications and averaging over diverse conditions and the estimated damage could be quite different from the actual case depending on the situation. The estimation of real economic damage can be an extremely difficult task, as even in a detailed survey, the estimates would vary depending on the individual perceptions of respondents as well as the personnel carrying out the surveys. It can be envisaged that the damage incurred would reflect a host of other parameters in addition to the type of buildings, such as preparedness, previous experience, warning time, composition of household members, time of the event, site specific conditions, etc., as well as conditions specific to flood event such as sediment and debris content. In that sense, a generalized damage estimation methodology can be viewed as a kind of consensus on describing the economic damage in monetary terms based on the magnitude of the event and impact on property. Once a generalized approach to flood damage estimation is developed, it can be modified to reflect more site-specific conditions depending on the availability of data as well as the purpose of such estimation.

In the present study our goal is to develop a generalized methodology to carry out damage estimations automatically once the flood extent is provided through the use of a GIS consisting of property information and stage-damage functions describing damage to each property category for a given flood depth and duration. The methodology then can be used to estimate damage potential under different flooding scenarios and can serve as a tool for rapid economic appraisal of flood control project benefits as well as for assessing relative merits of different flood control options through coupled applications with flood simulation.

METHODOLOGY

Damage estimation method used in Japan

In Japan, the Ministry of Construction (MOC) issues an economic damage estimate for each flood. The estimate is carried out based on a standard procedure described in the 'Outline of River Improvement Economic Research Investigation' (MOC, 1996). An accompanying flood survey manual outlines how flood damage assessment surveys conducted in developing these guidelines. In carrying out damage assessment, either a direct survey specific to the particular flood may be carried out, or it can be estimated using past depth-damage statistics for specific property categories, as well as empirical formulae based on past flood damage data.

In Japanese practice, following categories are considered in damage assessment.

(a) General assets, including residential and commercial structures and content, farmhouses and fisherman houses structure and content damage.
(b) Damage to crops.
(c) Public infrastructure which include rivers, streets, roads, railways, bridges, infrastructure of farms, telecommunications and power supply.

The flood survey manual describes the methodology adopted in assessing economic damage in each of the above categories. For example, for estimating damage to residential houses, first inundation maps should be established which describe the flood water depth contours. The number of wooden and non-wooden households and average floor area for each flood depth contour should be estimated and 10 houses are to be picked randomly from each group to carry out a survey to establish the average damage in each flood contour. For the content damage, actual damage is computed for items in a standard list of 81 household items. To carry out the survey quickly, a shortlist comprising of 34 items may be selected and extrapolated using coefficients established through previous surveys. Here too, the actual damage cost is to be established based on the survey of 10 random houses selected in each inundation level.

The flood damage estimation method in Japan has been developed in the 1950s to facilitate the economic appraisal of flood control measures. Over the years, a number of flood damage surveys have been carried out and economic damages for the above categories have been established. Based on those historical data, the flood damage assessment manual also provides depth-damage data for first category, namely the building and content damage, for wooden and non-wooden structures. In order to generalize the depth-damage functions, the total damage is normalized with respect to flooded floor area as well as unit cost prices established for 47 different regions. With this approach, it is possible to use the same depth-damage function throughout the country, and modify the final estimate using the unit cost for the particular region. While the depth-damage functions for residential structures are normalized with respect to unit floor area and regional unit cost prices, the depth-damage functions for industries are normalized with respect to industry type and the number of employees for each structure, for each of the 47 regions. The unit cost prices adopted are upgraded each year based on flood information and economic performance data. For residential content damage, a single unit price is adopted for the whole country.

Procedures for detailed damage estimation are currently available only for the case of urban structural damage. The crop damage is estimated separately by the ministry of agriculture based on the actual flood losses. The business interruption losses, service losses and infrastructure losses are estimated as a fixed fraction of the damage to urban structures.

Grid based computational model

Adaptation of flood damage estimation methodology for GIS based automatic estimation procedure can be outlined as follows. First, by establishing basic maps of topography and inundation (Figure 1, A), flood depth at each grid is estimated. By establishing land use and administrative boundaries representing the smallest units having statistics of various types of property (Figure 1, B) layers corresponding to distribution of different property maps can be derived. The basic method of estimating damage can be expressed as,

$$D_{i,j} = \sum_{1}^{n} UC_l \times A_{l,i,j} \times DD_l(h_{i,j}, t_{i,j})$$

Where, i and j describe the row and column indices in the grid, subscript l denotes the property category, $D_{i,j}$ is the total damage at grid i,j, UC_l is the unit cost for property l, $A_{i,j}$ is the area covered by property A in grid i,j, DD_l is stage-damage function and $t_{i,j}$ and $h_{i,j}$ are duration and depth of inundation at grid i,j.

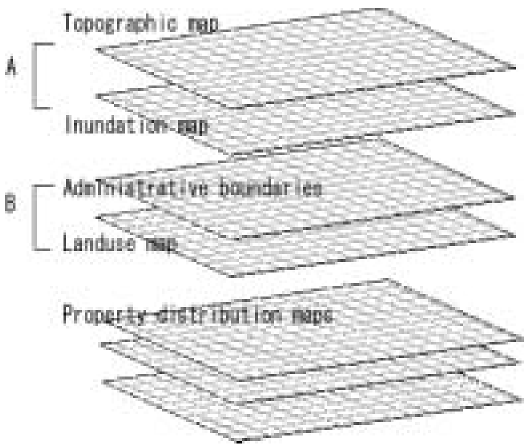

Figure 1 GIS layers for damage estimation

Damage estimation model

The urban damage categories discussed in the paper are shown in Table 2. The damages for all categories are estimated at each grid and the total damage is estimated as the summation of all damage categories. The formulations of damage for each category are described below.

Urban Damage. Urban damage is represented by the five categories shown in Table 2, which describe residential and industry structural and content damage. The following four equations are used to estimate damage in each grid.

a. Urban residential structure damage is represented by,

$$D_s(i,j) = \sum \{FA(i,j) \times N_s \times EC_s(i,j) \times C_s(i,j)\}$$

b. Urban residential content damage is represented by ,

$$D_c(i,j) = NF(i,j) \times EC_c(i,j) \times C_c(i,j)$$

c. Urban industry structural damage is represented by,

$$D_p(i,j) = \sum_{n=1}^{n=NI} NW(i,j,n) \times EC_p(i,j,n) \times C_p(i,j)$$

d. Urban industry content damage is represented by,

$$D_g(i,j) = \sum_{n=1}^{n=NI} NW(i,j,n) \times EC_g(i,j,n) \times C_g(i,j)$$

where for any grid *(i,j)*, *FA* = floor area, *N* = number of residential houses, *EC* = unit price for respective category, NF = number of household, *NW* = number of workers, NI = total number of industry, and *C*= depth-damage coefficient.

Crop Damage. The average damage to agricultural products in any grid is estimated as,

$$Ad(i,j) = \sum_{k=1}^{n} \{D_m(i,j) \times CRP_a \times mn\}$$

$$D_m = CP_k \times Y_k \times DC_k(i,j,d,t)$$

where at any grid *(i,j)* for any crop type *k*, CRP_a = total area of cultivation, *CP* = estimated cost per unit weight, *Y* = yield of crop per unit area, *DC* = crop stage-damage coefficient, *mn* = loss factor to take into account of growing season of crop and *n* = total number of crop cultivated.

Table 2. Damage categories and details considered

Damage Category	Details considered		Normalizing parameters	Influencing flood parameters
Urban Residential	Structure	Wooden	Floor area, region	Flood depth
		Non-wooden		
	Contents	All types	Household unit	
Urban Industry	Structure	Ten types of industry classes	Number of employees, region	Flood depth
	Content	Ten types of industry classes		
Crop Damage	Nine types of major crop classes		Crop area, production per crop, unit price per crop	Flood depth, duration, season

Depth-damage functions

The depth-damage functions describing urban residential and industrial property were developed from the data published by the Ministry of Construction (MOC) from post-flood investigations from different parts of Japan. Five functions for the five categories shown in Table 3, were established with polynomials of the type,

$D = c_o + c_1 h + c_2 h^2 + c_3 h^3 + c_4 h^4$, where *D* is the damage percentage and *h* is the water level in cm.

The coefficients for the damage functions are given in Table 3 for different categories.

Table 3. Depth-damage function coefficients for urban damage

Category	Coefficients for Depth Damage Functions				
	c_o	c_1	c_2	c_3	c_4
Residential Wooden Structure	-1.72519	28.27689	-3.90175	0.17148	0.0
Residential Non-Wooden Structure	0.97754	9.54128	-1.36173	0.06191	0.0
Residential Contents	1.50849	28.58537	-7.17702	0.76296	-0.0291
Industrial Structure	2.47538	35.70193	-8.53051	0.87	-0.03205
Industrial Contents	4.41713	38.5651	-9.11863	0.92241	-0.03377

The damage to crops is expressed in the general form, $D = c_1 \times e^{c2 \times t}$, where *D* is the flood damage in percentage and c_1 and c_2 are coefficients for each crop class and *t* is the flood duration. The damage functions are derived for 3 different crop heights, for 0.2-0.5 m, 0.51-0.99 m and 1m and above, and the coefficients are shown in Table 4. The unit prices of agricultural products were taken from those published by the Ministry of Agriculture, Forestry and Fisheries of Japan.

Table 4. Coefficients of stage-damage functions for different group of crops

Group (Group id)	Coefficient of stage-damage functions					
	Depth: 0.2 m - 0.5 m		Depth: 0.5 m - 1.0 m		Depth: 1.0 m and above	
	c_1	c_2	c_1	c_2	c_1	c_2
Green vegetables (1)	16.152	0.206	21.368	0.1749	29.452	0.1413
Vegetables with roots (2)	30.636	0.1383	47.188	0.0993	55.091	0.0893
Melon (3)	14.901	0.1816	18.216	0.2105	26.962	0.1669
Bean (4)	15.27	0.1599	17.275	0.1968	29.495	0.1329
Sweet potato (5)	25.455	0.1343	29.092	0.1859	65.322	0.0658
Chinese cabbage (6)	6.9692	0.3083	15.998	0.2468	26.765	0.1995
Paddy (7)	12.72	0.2197	13.77	0.2357	34.471	0.1251

APPLICATION

Catchment description

The study area selected for model application is a moderate size basin, named Ichinomiya river basin, with an area of 220 km^2, located in the Chiba prefecture, Japan between latitude 35°18′ N to 35°30′ N and longitude 140°10′ E to 140°25′ E (Figure 2). The mean annual rainfall is approximately 1,700 mm and rainfall distribution is almost uniform for the entire basin. Total population within the basin is about 144,000 mainly concentrated in the urban areas in lower flat part of the basin. Due to rapid urbanization, population of the basin has increased by 45% within the last 15 years.

Topographic information

The topography of the basin varies from hilly areas in the western part with a maximum elevation of about 155 m to lowland flat areas in the eastern part with a minimum average elevation of about 1-2 m from mean sea level. Ichinomiya is the main river of the basin. The river originates from hilly areas in the northeastern part of the basin and flows through upper half of the basin before discharging to the Pacific Ocean in west side of the basin after travelling a total length of 28 km. On its flow paths, many tributaries join this river. The lower part of the Ichinomiya River has backwater effect due to seawater intrusion.

Flood history

Floods frequently affect Ichinomiya river basin, mostly, from intense rainfall brought by typhoons. Urban area is distributed in the lower part of the basin and is the most vulnerable region to floods due to low elevation. Severe damage occurred to the urban areas many times in the past due to major floods. Floods have also affected agriculture areas several times. After major floods in 1970, river administrative department has been carrying out many flood protection measures, such as, increasing the height of river embankments, increasing the carrying capacity of rivers, improvement of drainage networks in the urban areas, etc., which are on going up to present.

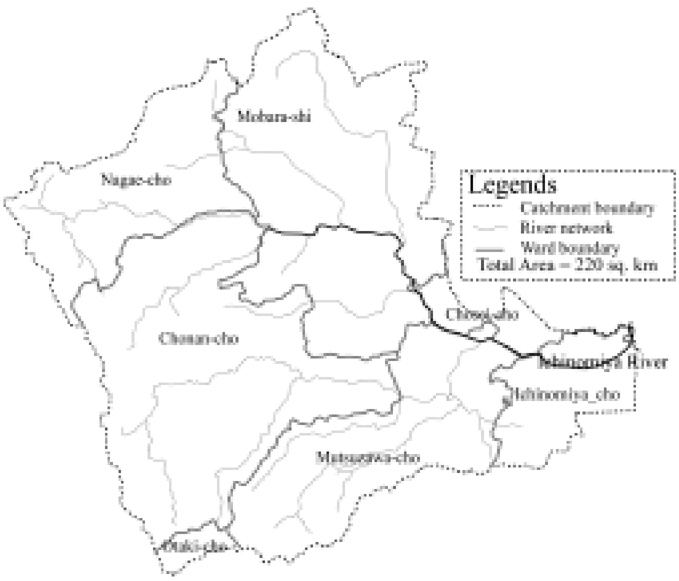

Figure 2. Study Area with administrative boundary and river network

Land cover classification

The Ichinomiya basin consists of six major landcover types, namely, forest, paddy, vegetable, urban area, water body and grass. The existing landcover map of the study is derived from 1:50,000 and is too coarse to estimate detailed urban asset distribution. Therefore, a multi-spectral image of LANDSAT satellite with 30 m ground resolution was used to derive detailed land cover patterns in the study area. The area percentage of different landcover classes obtained from the LANDSAT data classification is shown in the Table 5.

GIS for flood damage assessment

Six wards of the Chiba prefecture are fully or partially located in the Ichinomiya river basin. Various data sets required for urban damage estimation were available at ward level from the local city office, and for agriculture damage at prefecture level obtained from the Ministry of Agriculture. Industry statistics in the different wards within the study area are shown in the Table 6. Land cover distribution map of the study area, obtained from LANDSAT satellite data, was used to derive residential floor area and spatial distribution of industries in each ward. For any grid *(i,j)*, residential floor area is estimated as,

Table 5. Area percentage of different landcover classes as obtained from LANDSAT data

Landcover type	Total Area in the basin (Sq. km)	Area in %
Dense forest	82.50	37.5
Light forest	20.24	9.2
Grass	2.86	1.3
Agriculture	89.54	40.7
Water body	3.08	1.4
Dense urban	12.54	5.7
Light urban	9.24	4.2

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

where, N_l = type of land cover (if urban, N_l = 1, else, = 0), AF = area fraction of urban land cover within the grid, n = total urban landcover types, X = building ratio for urban land cover type k, and F = floor area fraction for urban land cover type k. EC_s (the structure unit cost) for Ichinomiya basin is 0.1692 million yen /m^2 and EC_c (content unit cost) is 5.4 million yen/building. Distribution of industry and household data within the ward is estimated similar way. Distribution of various crop-growing farms within the basin is done based on farm statistics and the land cover pattern map. Table 7 shows the extent of different groups of vegetables grown in the study area and their market price. Paddy and other crops are not included in the table, which were not affected by the flood event considered in this study.

Table 6. Industry statistics of different wards fully or partially located in the Ichinomiya basin

Industry statistics			Wards fully or partially located in the Ichinomiya river basin						
Type	ECp*	ECg*	Number	Ichinomiya	Mutsuzawa	Chonan	Nagae	Mobara	Chosei
Mining	8.164	1.910	Office	0	1	0	0	2	0
			Employee	0	7	0	0	235	0
Construction	1.979	6.607	Office	55	56	77	67	391	52
			Employee	389	254	343	446	3327	368
Production	5.176	3.694	Office	49	32	50	54	248	41
			Employee	653	815	1962	1153	12428	1388
Electricity/Gas /Water Supply	129.872	1.872	Office	0	0	1	2	4	0
			Employee	0	0	14	28	197	0
Transportation	7.810	0.656	Office	10	6	15	11	73	10
			Employee	121	46	115	137	1895	81
Whole sale and Retail sale	2.454	2.898	Office	281	81	158	102	1908	290
			Employee	1344	354	546	292	10753	1987
Finance and insurance	5.718	0.643	Office	5	0	1	0	71	2
			Employee	49	0	13	0	1151	27
Real estate	26.054	34.544	Office	30	3	1	8	110	2
			Employee	96	11	5	50	477	8
Service	5.718	0.643	Office	206	70	105	77	871	87
			Employee	1395	743	766	907	7182	754
Government	5.718	0.643	Office	11	7	10	7	27	8
			Employee	195	75	137	85	865	82

*value in million yen/employee

4. RESULTS

During September 22 to 23 period in 1996, the basin suffered from a flood disaster due to heavy rainfall caused by Typhoon 17. Within 24 hours between September 21 and 22, the whole basin received about 360 mm rainfall. The GIS based damage estimation model was used to estimate damage caused by this flood event. The flood extent map is obtained from the post-flood survey.

Comparison of damage with field survey

Table 8 shows the simulated results of urban floods and their comparison with surveyed damage assessed by the Ministry of Construction. For residential building unit, both simulated content and structure damage are matching well with the surveyed damage amount. However, in case of non-residential building damage, model results show higher estimation of damage than surveyed results. As mentioned in the table, surveyed damage estimation report is available only for three wards out of the four flood affected wards and therefore, the damage amount is less than the estimation for the whole area.

Estimation of Agriculture Damage

The loss estimation model is further used to estimate rural damage due to the September 1996 flood. In case of crop damage, both depth and duration of flood influence the amount of damage to crops. As, there was no observation on varying inundation depth in various flood-affected areas, simulated depth and duration of the flood event have been used in for crop damage estimation. Harvesting of paddy was completed a few weeks before the flood occurred. Therefore, flood caused damage to vegetables only. The total estimated damage to vegetables was 17.43 million yens.

Table 7. Statistics of vegetables grown in the study area

Type of crop (crop group id)	Market price (yen/kg)	Growing season (month)
Welsh onion (1)	230	5 - 9
Lettuce (1)	750	7 - 12
Radish (3)	180	8 - 12
Carrot (3)	250	
Tomato (3)	480	2 - 9
Mini-tomato (3)	480	2 - 9
Cucumber (3)	540	4 - 9
Sweet pepper (4)	720	2 - 10
Eggplant (4)	470	2 - 10
Broccoli (6)	500	9 - 6
Cabbage (6)	150	
Chinese cabbage (6)	130	7 - 12

Distribution of damage according to category

The loss estimation models can provide spatial distribution of economic damage to various objects as the model is designed in grid basis. Figures 3,4 and 5 show the spatial distribution of residential content damage, non-residential structure damage and crop damage respectively as obtained from the damage estimation model.

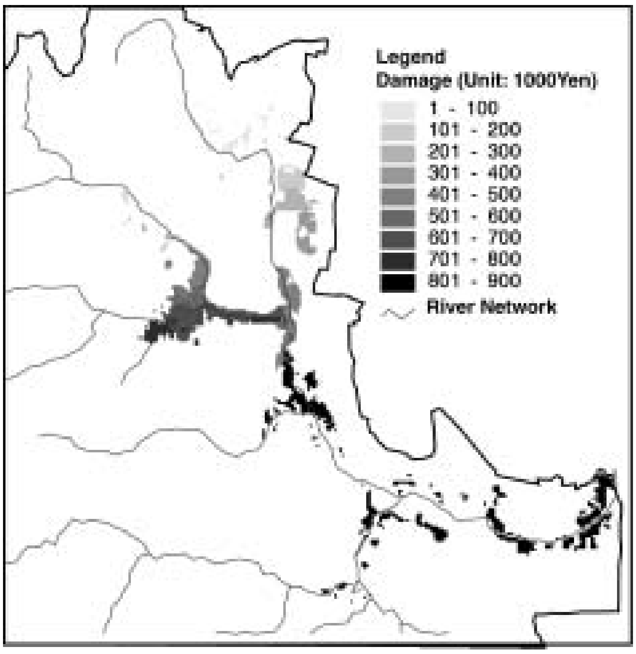

Figure 3. Spatial distribution of residential content damage

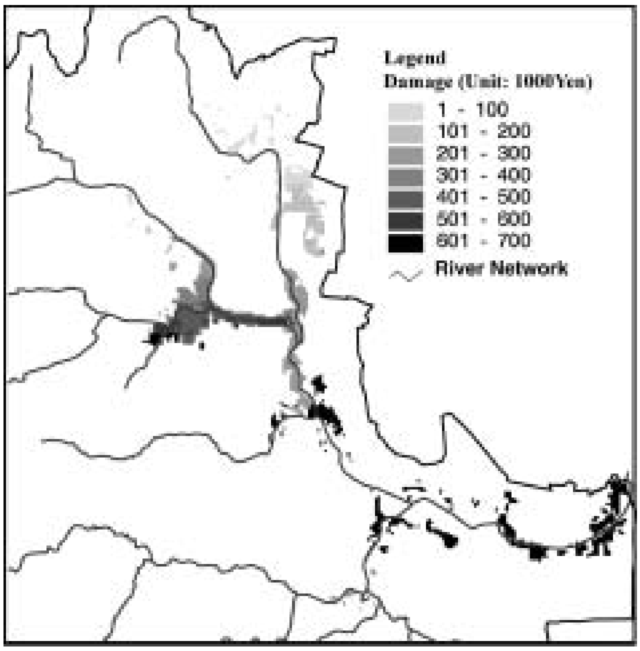

Figure 4. Spatial distribution of industry structure damage

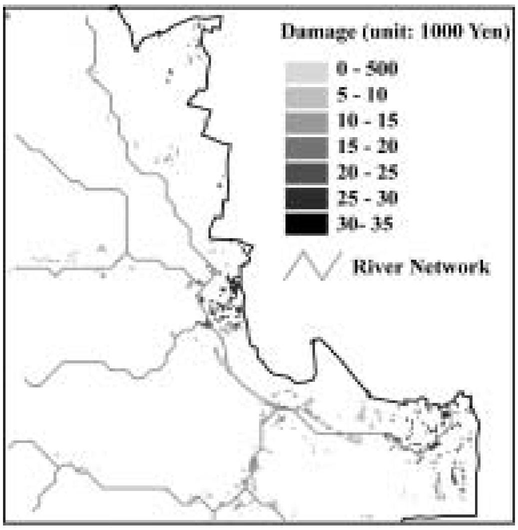

Figure 5. Spatial distribution of crop damage

Table 8. Estimated flood damage by loss estimation model and surveyed output

Urban Damage	Categories of Damage	Amount of Damage (1000 Yen)	
		Simulated Results	Surveyed Result
Damage to Residential houses	Structure	8,738,930	9,023,299
	Content	1,974,900	1,759,160
Damage to Non-residential houses	Structure	10,370,500	9,050,364 (partial coverage)
	Content	3,830,590	1,813,445 (partial coverage)

5. CONCLUSIONS

A damage assessment model for urban catchments utilizing remote sensing data and GIS has been developed which facilitate rapid estimation of urban flood damage. The use of damage-functions normalized with respect to parameters of flooded areas and regional cost coefficients make it possible to generalize the methodology, which make cross comparisons possible. This approach is more realistic in Japan due to near-uniform social conditions observed here. The estimates can be made more accurate by changing the damage functions or cost coefficients, to suit a particular locality.

The most important data were found to be the elevation data used in the generation of DEM and the land cover parameters. Similarly, the 30m resolution LANDSAT data are too coarse for direct estimation of damage areas requiring a model for such estimation. In the present study a hierarchical statistical classification algorithm was used to derive the land cover map as it was found that the derived land cover map is sensitive to the method employed in the classification. However, with the advent of new space borne observation systems, especially high-resolution multi-spectral imagery in the near future, land cover information can be expected to improve.

The scope of present paper was limited to estimation of direct damage to urban structures and crops. Of the other loss categories in Table 1, transportation loss estimation is feasible with the use of transport network modeling while it is more difficult to estimate life-line losses due to site specific nature and lack of detailed past experience. For a reasonable estimate of risk in urban areas, methodologies should be developed to assess these and other indirect damage components using emerging detailed spatial information base.

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