Weather Radar Information and Distributed Hydrological Modelling (Proceedings of symposium HS03 held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 282, 2003.

Evaluating land-use change effects on flood peaks using a distributed rainfall–runoff model in Yasu River, Japan

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Abstract The effects of land-use changes on flood peaks in the Yasu River basin were investigated using a distributed rainfall–runoff model. The land-use changes over a 20-year period were determined using 100-m spatial resolution data from 1976 and 1997. The main land-use classes in the basin were forest, paddy fields, urban and water bodies. There was a decrease in areal coverage by forests of 2.5% and paddy fields by 1.4% compared to 1976. The coverage of urban area increased by 2% and that of agricultural land by 0.2%. A new land-use category "golf courses" emerged in 1997, covering 2.3% of the basin in areas covered by forest in 1976. Simulation results show that 1997 land-use data produce 6% higher flood peaks and 16-min faster travel times compared to 1976 land-use data. The changes detected indicate the gradual effects of urbanization in the study basin.

Key words distributed rainfall–runoff model; effect of land-use change; Yasu River basin; Japan

INTRODUCTION

The effects of land-use changes on river flow have been a major concern for hydrologists for a long time. Recently, it has become even more important to study these effects in anticipation of global climate changes which are expected to result in increased frequency of extreme events such as floods and droughts. It follows naturally that planners and managers need to be well informed in advance of the possible impacts so that they can prepare better disaster management plans.

The documentation of effects of land-use changes on rainfall–runoff relationships mainly involve those involving studies on deforestation and urbanization. These are considered as the most important manmade impacts to the hydrological cycle. Douglas (1987) showed that clearing 19% of the forest in a basin can increase the peak flows by 13.5%. Several other researchers at different times and places have arrived at the same conclusion including Hewlet & Helvey (1970) in the USA, 11%, Swanson & Hillman (1977) in Canada, 200%, and Nagano (1967) in Japan, 114%. These studies show that changes in the streamflow are expected when modifications in the land-use occur. In some cases such modification can occur over a short period such as harvesting a forest in a drainage basin, but they can also occur gradually as the land-use changes with the socio-economic developments in the basin. Our primary concern is the changes in flood peaks introduced by changes in the land-use over a long time. The investigation seeks to quantify the land-use changes in the Yasu River basin and evaluate their effects on flood peaks and travel time.

STUDY AREA

The Yasu River basin (Fig. 1) is located between 34°50′ to 35°10′N and 136°0′ to 136°30′E, near Lake Biwa in Shiga Prefecture, Honshu Island, Japan. The catchment area upstream of the Yasu discharge station is 377.42 km^2. The basin receives rainfall in summer from May to July and during the typhoon season from the end of August to early October. There is a clear trend of high precipitation in the high elevation areas which requires careful consideration in generating spatial rainfall input for a hydrological model. Typical storm hyetographs show that during storms, the mountainous stations can receive up to twice the rainfall recorded in the lower stations. Most floods occur during the typhoon season which has high intensity rainfall over a short period, normally less than three days. Floods occur immediately after the rain storms, within 2–3 h of the peak rainfall. The major land-use class in the basin is forest (60.9%), followed by paddy fields (17.3%), according to 1997 land-use data. There are five gauging points where the river stage is measured and 10 rainfall stations, which are well distributed within the basin, as seen in Fig. 1. In addition to hourly river water level measurements, river discharge is measured during floods every year at the river gauging stations.

RAINFALL–RUNOFF MODEL

One of the most important uses of a distributed rainfall–runoff model is to predict the effects of future land-use and climate changes on basin hydrology, particularly the extreme events and water yield for water resources evaluation (Beven, 2000). Land-use changes have different effects on the local hydrological cycle depending on the nature

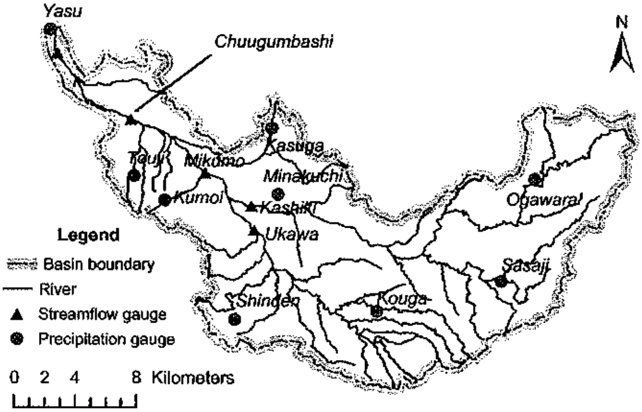

Fig. 1 Location of streamflow and precipitation gauges in the Yasu River basin.

of the land-use cover that existed and that one which results after the changes. To assess the hydrological impacts of land-use changes, temporal and spatially highly detailed land-use data are required. In addition to this, the assessment of the hydrological impacts must be done with a distributed hydrological model which represents the spatial variability in the land cover with appropriate parameters such that the spatially variable response is taken into account in total basin simulation.

In this study a distributed rainfall–runoff model developed by the authors has been used. The model utilizes the kinematic wave equation in routing the overland flow from each cell. The output of the upstream cell is given to the downstream cell and routed together with rainfall over that cell to its outlet. The process continues on with each upstream cell sending output to its downstream neighbour up to the most downstream cell, which represents the basin outflow point. The model is built using the object oriented approach which defines each cell as an element model containing data and functions for converting rainfall to runoff. The connection between grids is defined by a flow direction map derived from a digital elevation model (DEM) of the area. This map is stored in UTM coordinates and is used as a reference point for all point and spatial data. The flow map is based on the selected DEM resolution and it is extracted automatically from DEM data at any feasible resolution. In the current study a 500-m grid flow map was chosen in order to reduce the computational work load. In this case all spatial inputs are rescaled to this grid size.

The model has utility programs for preparation of spatial land-use and rainfall data. Raster files of land-use data and rainfall are created as input to the model and for display in the GIS environment. The spatial rainfall can be allocated by ordinary kriging, Thiessen polygons or inverse distance interpolation (Guillermo & Salas, 1985). The rainfall processing utilities allow the production of the storm hyetograph and cumulative rainfall raster maps to show the evolution of the storm during the simulation. This allows any errors in the data to be identified and the results of the simulated hydrograph to be interpreted properly. The results of the model can be stored in time series of river flows at any desired location on the basin and raster maps of runoff depth distribution over the catchment. The architecture of the model is flexible and permits different process models to be applied for each grid. In order to investigate the effects of land-use changes effectively, the model is also equipped with utilities to extract land-use data based on the DEM-derived flow map and to analyse the land-use changes in pattern and magnitude over the years.

LAND-USE AND HYDROLOGICAL DATABASE FOR CHANGE DETECTION

The successful detection of land-use changes and their hydrological impacts requires the maintenance of a long-term accurate and easily accessible database of hydrological variables and land-use data. It should be possible to easily access this database and extract summary information corresponding to observed floods. This information may include hyetographs of the storm which caused the flood, raster maps of the cumulative rainfall depth before the flood, and river discharges. Such information is useful for documentation and it gives an indication of the variable basin response to different storms over the years. In this study we compiled a database which includes the long-term records (30 years) of rainfall, river flows, observed floods and land-use data. Rainfall and river flow data used were obtained from the local office of the Ministry of Land, Infrastructure and Transportation (MLIT). The river flow data at Yasu, the outlet of the study basin, consist of water level from January 1975 to the present, and rating curves for the same period.

The land-use data was obtained from the Japan Geological Survey Institute for the years 1976, 1987, 1991 and 1997. These data are classified in 15 land-use classes for 1976, 12 for 1987 and 11 for 1991 and 1997, and spatial resolution is 100 m. For our analysis we regrouped those land-use classes into five groups representing land covers with different Manning coefficients. The groups and their Manning's roughness coefficient values ($m^{-1/3} s^{-1}$) in brackets were paddy field (2.5), forest (0.5), water body (0.01), urban area (0.02) and agricultural land (0.3). The values of coefficients for different classes were based on published values (Ministry of Construction, 1997) currently (MLIT). In the preliminary investigations of these data it was found that the rate of land-use changes is small and can only be effectively described with data over a long period of time. In regard to this, all subsequent analyses are based on data for 1976 and 1997.

The primary use of the land-use data was for allocating a spatially variable Manning's roughness coefficient for the kinematic wave model used to route overland flow from each grid. It may be argued that there is uncertainty involved in assigning this coefficient to a specific grid with a certain land-use because the exact value of the coefficient for each landcover is not exactly known. However, it is still true that most of the difficulty faced is to identify the land cover at a certain location rather than the value of the coefficient to be assigned. Once the land-use type of a grid is known the error reduces greatly because the coefficient is selected within a small range of feasible values. Our aim is to study the effect of land-use change by comparing hydrographs simulated with two different land-use data sets using consistent roughness values assigned according to land-use class.

ANALYSIS AND RESULTS

Land-use changes

The changes in land-use were determined by comparing the land-use data in 1976 and 1997. The results are shown in Fig. 2, as well as in Tables 1 and 2. The most visible change between the two periods is the conversion of forest areas into golf courses, as seen on the 1997 land-use map. This shift of land-use has contributed mostly to the decrease of the percentage of the basin covered by forests, which amounts to 2.5%. The golf courses covered 2.3% of the basin area in 1997. The area covered by paddy fields decreased by 1.4%, while the built-up area coverage increased by 2%. A closer examination shows that the expansion of the urban area took place in the lower part of the basin downstream of Kashiki and Ukawa gauging stations. The 1997 land-use map shows an extension of a transportation line further to the southwestern part of the basin, close to the Kashiki River. This explains the growth of urbanized area in this

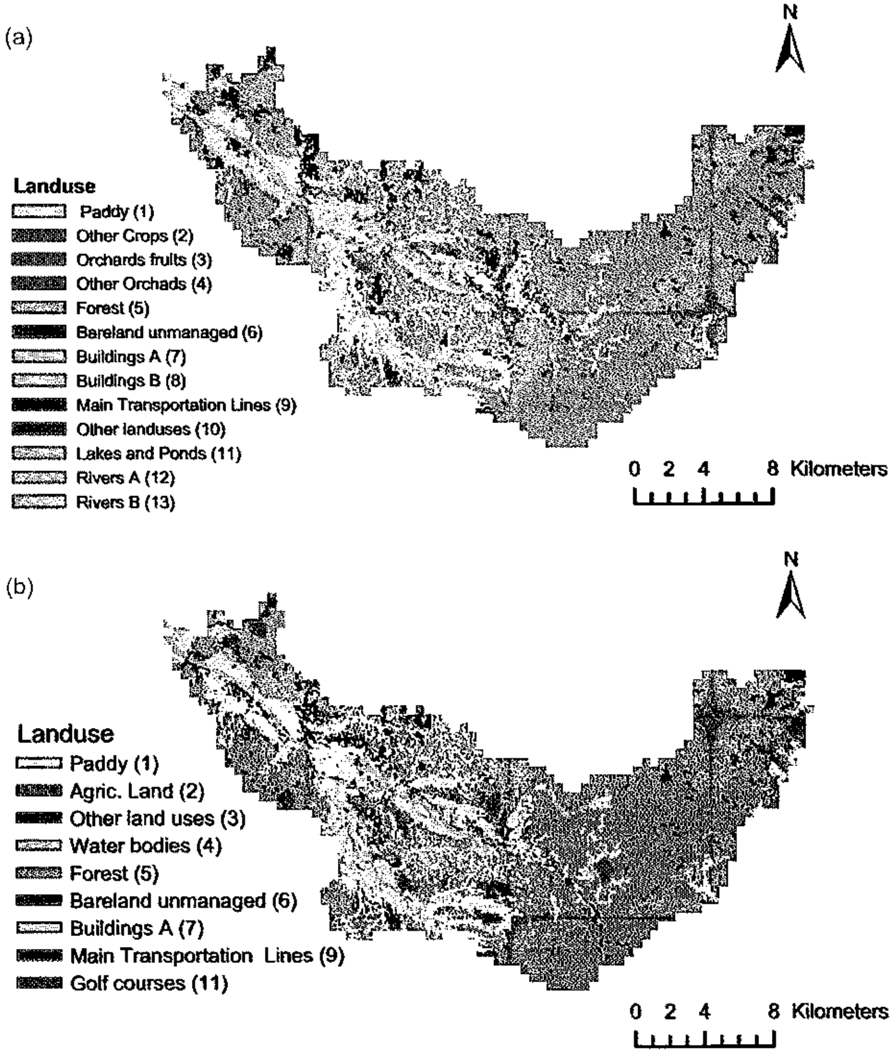

Fig. 2 Land-use map of the Yasu River basin (a) in 1976, and (b) in 1997.

Table 1 Percentage of area of the Yasu basin covered by different land-uses in 1976 and 1997.

Landuse	Coverage in 1976 (%)	Coverage in 1997 (%)
Forests	63.4	60.9
Paddy field	18.7	17.3
Buildings (built up area)	4.4	6.4
Water bodies	3.6	3.8
Other land-uses	4.2	3.4
Agric. land	2.6	2.8
Bare land (unmanaged)	2.9	2.8
Golf courses	0	2.3
Main transport lines	0.27	0.5

Table 2 Distribution of converted land-use for selected different classes from 1976 to 1997.

	Percentage of change contributed by conversion to given land-use in 1997:								
Land-use code in 1976	1	2	3	4	5	6	7	9	11
1		5.2	22.5	7.1	7.2	4.1	38.3	4.3	11.3
5	12.2	6.6	17.8	4.4		3.7	12.1	2.7	40.5
6 & 10	1.6	5.5	46.1	2.9	8.0		18.8	0.6	16.5

Land-use codes are shown in the land-use maps in Fig. 2.

part of the basin. Table 2 also reveals that land-use class that is affected most by urbanization is paddy field. There is only a slight effect of urbanization on the forested area where urbanization accounts for 12% of the change between 1976 and 1997.

Implications for flood runoff

The specific effect of the land-use changes on the hydrology of a given local area are complex and can only be evaluated with high spatial resolution land-use and hydro-meteorological data. The effect of land-use changes on hydrological response is not represented by the change the individual land-use classes, but by the combination of changes of the individual classes replacing each other, forming a new land-use pattern. The resulting pattern may increase or decrease the peak flood, depending on the replaced and replacing land-use. This means that it is not possible to make a prediction of runoff changes based on changes in individual land-use classes and a probable behaviour can only be ascertained by using a distributed hydrological model that specifically accounts for each land-use type. We used the land-use data for 1976 and 1997 to create two different raster maps of Manning's roughness coefficient for overland flow calculations. In assigning the roughness coefficient, land-use classes with similar hydrological responses were given the same roughness coefficient. Due to scale differences in the land-use raster resolution and the runoff model grid resolution, the roughness coefficient for each grid was determined by averaging roughness coefficients of all smaller grids (100 m) that fall inside the model grids (500 m).

The results of this simulation with different storms over the years showed a consistent change in the simulated hydrograph, developing higher and faster peaks using the 1997 land-use data as compared to floods simulated using the 1976 land-use data. A typical case of simulation result with different land-use data is shown in Figs 3 and 4. In these figures the rise in peak flow reflects the changes observed in land-use data between 1976 and 1997. In all cases the hydrographs exhibit higher peaks and shorter travel time. The attenuation of peak clearly indicates the potential effects of land-use changes in the study basin. Although the effects are not so severe at the moment it is still necessary to take precautions by conducting similar studies from time to time and evaluating the impacts.

Based on the land-use data, we note that major land-use classes forest and paddy fields did not experience much change during the study period. This may mean that the simulation results indicate the changes brought about by redistribution of land-use in the lower part of the basin, mainly from paddy fields to building plots. The supposition

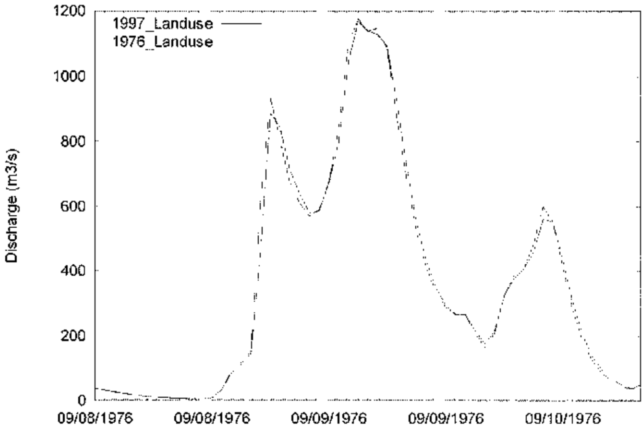

Fig. 3 Simulated hydrograph for a typical storm in 1976 using 1976 and 1997 land-use data.

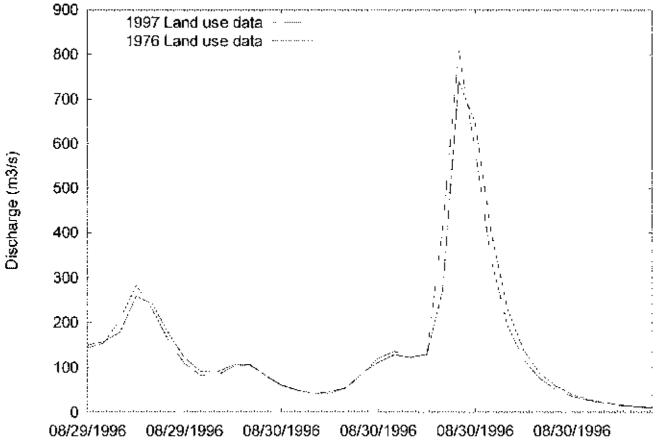

Fig. 4 Simulated hydrograph for a typical storm in 1996 using 1976 and 1997 land-use data.

is in agreement with land-use data which show the largest (38%) change of paddy fields between 1976 and 1997 is attributed to conversion to building plots. On the other hand the changes in forested land were mainly due to conversion to golf courses (40%). The roughness coefficient of golf course assumed in this study (0.3 $m^{-1/3}$ s^{-1}) is not very different to the one assumed for forest (0.5 $m^{-1/3}$ s^{-1}). It was also found that most of the area classified as other land-uses in 1976 was converted to built-up area in 1997. Coincidentally, this class was also assigned the same coefficient as the built up area, assuming that it is likely to be located in built-up areas. A summary of interchange of different land-use classes in 1976 to different classes in 1997 is presented to further highlight this point in Table 2. It is clear from these data and the simulated hydrographs that the effects of land-use changes on the flood peaks can be modelled and explained by using fine resolution land-use data and the distributed rainfall–runoff model.

CONCLUSION

Evaluation of the effects of land-use changes on flood peaks has been performed using land-use data and a distributed rainfall–runoff model. The changes over the 20 years indicate increase in flood peaks by 6% and decrease in travel time by 16 min. It is further shown from land-use data that these changes reflect mainly developments in the lower part of the basin and are due to urbanization. The results of this work show a high potential of distributed hydrological models for explaining changes in streamflows if high spatial land-use data are used. From the experience gained in this study we found out that the response of the catchment to rainfall for a certain land-use change is also dependent on the spatial distribution of the storm used during the study. To gain a full understanding of all possible response be necessary it may be subject to the changed land-use pattern to all possible storm patterns. In anticipation of global climate changes which may change the seasons and patters of storm distribution, such experiments are recommended to evaluate the worst possible response of a changed land-use to rainfall. The effect of land-use changes on flood peaks is a combination of individual changes in different land covers over the whole basin. Land-use data can be used to identify the most probable origin of the effects and proper measures can be taken to address the situation. Remotely sensed land-use data provide hydrologists with valuable data for hydrological models. However, there are few models which can utilize this data directly and estimated parameters still have large uncertainties and hinder more deep analyses into land-use change studies. It is proposed that future hydrological models should concentrate in utilizing high spatial land-use data such as provided by remote sensing images in order to model effectively the effects of changes in land-use.

Acknowledgements We wish to thank Biwako work office of the MLIT, Mr Kudo and Ms Morita at Nippon Construction Consultant for providing hydrological data used in the study. This research was supported by DPRI, Kyoto University, Nissan Science Foundation and CREST program of the Japan Science and Technology Corporation.

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