Distributed hydrologic simulations to analyze the impacts of land use changes on flood characteristics in the Yasu River basin in Japan

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ABSTRACT

In most parts of the world, land use data from remote sensing have been accumulated for more than 30 years. Historical images of land use can be used to know the location and types of land use change as a step towards investigating the impact of such change on floods. In this paper, we present a distributed watershed model developed for using land use data for investigating the impacts of land use changes on floods. The output of the model includes hydrographs and runoff maps simulated with different land use data to show the impact of land use change. The model has been applied in the Yasu River basin in Japan to evaluate the impact of land use changes between 1976 and 1997. The results show that land use changes during this period can be associated with an increase of up to 18% in peak flow and decrease in travel time. The changes in flood peaks appear to be largely influenced by the spatial distribution of land use change, and the changes are explained by a physically based distributed hydrological model considering the spatiotemporal distributions of surface water storage and surface roughness derived from land use data.

1. INTRODUCTION

Although there are many studies on a hydrologic model utilizing land use data, only a few of these have focused on explaining the effects of land use change on river flow with hydrologic modeling. This fact is partly represented in the remarks of Beven (2000) that techniques for analysis of the effects of land use change on a modeled hydrological response are still very much at an early stage. A review of the few studies available shows that general conclusions and guidelines are difficult to establish because the case studies presented differ in key issues such as temporal and spatial scale of investigation, type of hydrological model and model sensitivity to land use change. The results of investigations are influenced by these factors, and their applications may be limited to the specific conditions under which they were obtained. One important limitation of studies on hydrological impacts of land use change is the formulation of a realistic land use scenario for analysis. To answer the question of how much river flow will be affected by a 50% change of forest, a researcher may decide to convert 50% of forested area into another land use type. However, the basin response will depend on the land use to be replaced, and how the land use will change is very uncertain.

Generally speaking, the hydrological impacts of land use change depend not only on the overall changes in land use types but also in their spatial distribution (Schumann and Schultz, 2000). To predict these effects meaningfully, one needs to estimate land use changes properly by using archived remotely sensed land use data. Another important problem in investigating the hydrological impacts of land use changes is the modeling of hydrological processes that are affected by land use change. This problem needs to be addressed by appropriate physically based modeling of hydrologic components to capture the effects of land use changes on a simulated hydrograph. It is desirable that a model used in investigation is able to reasonably simulate a river hydrograph during a flood event using land use-dependent parameters derived from concurrent land use data, before it is used to predict changes in runoff induced by land use change. The scale of investigation also needs to be considered because effects of land use changes are not expected to be the same at different spatial and temporal scales of analysis.

The availability of fine-resolution land use data from satellite remote sensing in recent years has prompted studies on rainfall-runoff simulations aimed at investigating the impacts of land use change and change on river flow. A few examples of studies in this area include Dagnachew *et al*. (2003), Niehoff *et al*. (2002), Kim *et al*. (2002) and Schumann and Schultz (2000). An important difference between this study and other similar works is that land use data are rigorously used in runoff simulations with more emphasis on evaluating the impacts of observed land use changes on flood runoff. Somewhat similar works by Schumann and Schultz (2000), Dagnachew *et al*. (2003) and Niehoff *et al*. (2002) either did not emphasize specifically the evaluation of the hydrological impacts of land use change, or differed from this study in the approach and scale of investigation. A more specific difference in the approach is that these studies and many other previous works relied on scenario analysis to describe the impacts of land use

KEY WORDS: Land use change, Distributed hydrological model, Floods

changes rather than using observed land use changes as emphasized in the current work. Schumann and Schultz (2000) compared river flow simulated with different land use data in the Sauer basin. Their study did not directly compare simulated runoff and observed runoff under the influence of concurrent land use data. Although changes in runoff could be detected between periods where land use changes are expected to have occurred, changes in runoff during the same period could not be established. The difference between the work and this research also concerns the scale of investigation and modeling approach. The Hydrologically Similar Units (HSU) concept was adopted in their work to characterize spatial variability, and runoff simulations were performed on a daily time step. A similar scale of investigation was used by Dagnachew *et al*. (2003), while this study uses a grid-based model with 500-m spatial resolution and 1-hour time resolution to represent flood runoff processes in detail. The models used by Schumann and Schultz (2000) as well as that used by Dagnachew *et al*. (2003) required model parameter calibration that may introduce land use-based parameters and affect the contrast between the simulation results of different land use data. In this study, previously determined model parameters are used to avoid this problem.

Although the main objective of investigating the hydrological impacts of land use changes is to quantify their effects, most previous works in this area have rather presented or analyzed the sensitivity of model output to land use changes. These researches are different from evaluating the real impact of changes, requiring more rigorous use of concurrent land use data in simulation. The use of the assumed land use scenario can be suitable for the former case but not for the latter. The analysis also needs to be carefully designed to show that predicted changes in runoff are consistent with observed changes in land use and runoff.

The emphasis of this paper is to quantify the effects of land use changes observed in the study basin over a period of 20 years. Concurrent land use and runoff data are used in runoff simulations to study changes to flood hydrographs during this period using a distributed rainfall runoff model. This paper presents the details of the model used and results of evaluation of the impacts of land use changes on flood hydrographs in the Yasu River basin, Japan, between 1976 and 1997. Land use changes are determined with land cover data generated based on a topography map in 1976 and remote sensing data in 1997 with 100-m resolution.

2. MODELING METHODOLOGY

The effects of land use changes on river flow are well appreciated but less understood. The main problem is that runoff generation is a spatially distributed process that depends on several influencing factors including slope, soil type, surface roughness, imperviousness, surface storage as well as distribution of rainfall and initial conditions. Some of these factors such as roughness, imperviousness and surface storage depend on land use. Their effects on simulated runoff are accounted for by using physical process models parameterized with land use data.

The main focus of the modeling work in this study is to develop a watershed model that can be used for detecting the impacts of land use change on floods. A distributed watershed model taking into account the effects of surface factors on flood simulation is developed and applied in the study basin. The model consists of two main components for surface water balance and routing as described below.

2.1 Surface Water Balance Model

A grid-based surface water balance model is used to estimate the amount and onset of runoff from each grid under the influence of land cover. This component simulates the effect of surface detention storage and the degree of surface perviousness on runoff generation. Maximum surface storage D_l is defined as the limiting holding capacity of the ground that is filled before the occurrence of surface runoff. A large value of surface storage is assigned for land cover such as forest or paddy fields to delay runoff occurrence at the beginning of a rainstorm. On the other hand, a small value is assigned to quickly draining surfaces such as urbanized areas. The value of D_l depends on land use, and the following simple relationship is assumed to generate spatially distributed D_l values for different land use classes.

$$D_l = \frac{n_l}{n_p} D_p \tag{1}$$

where D_l and D_p are the maximum surface storage for land use class l and for paddy, respectively. Parameters n_l and n_p are the Manning's roughness values of land use class l and that of paddy.

The infiltration intensity to the ground is calculated using the Green and Ampt formula for unsteady rainfall events (Mein and Larson, 1973; Chu, 1978). The governing equations for infiltration rate f_p and cumulative infiltrated depth F is:

$$f_p = K_s\left(1.0 + \frac{MS_{av}}{F}\right) \tag{2}$$

$$F - MS_{av}\ln\left(1.0 + \frac{F}{MS_{av}}\right) = K_s\left(t - t_p + t_p'\right) \tag{3}$$

where M is the initial soil moisture deficit equal to difference between the saturated soil moisture content or porosity θ_s and initial soil moisture content θ. S_{av} is the average suction head across the wetting front; K_s is the saturated hydraulic conductivity; t is the actual time; and t_p is the time to ponding. The shift in time scale t_p' is defined to consider unponded conditions at the beginning of the infiltration process. Equations 2 and 3 are derived by applying Darcy's law to the situation of infiltration under ponded conditions from the start of the infiltration process (Mein and Larson, 1973).

For unsteady rainfall events whereby the surface is not ponded at the beginning of the event, the infiltration rate is assumed to be equal to rainfall intensity whenever such unponded conditions are encountered. This means infiltration occurs at the same rate as rainfall intensity. All parameters of the infiltration model depend on the soil type (Rawls *et al*., 1993). Equation 3 is solved iteratively using the Newton-Rapson method to determine F at the end of the current simulation step. The infiltration rate calculated by Equation 2 is used to determine net rainfall intensity r_{net}, which is supplied to the routing model (see **Fig. 1** and the following section) as described by Equation 4.

$$r_{net} = \begin{cases} 0 & if \quad F < D_l \\ r - f_p & if \quad F = D_l \end{cases} \tag{4}$$

2.2 Distributed routing model

Distributed runoff routing aims to capture the impact of surface conditions such as roughness and slope as well as artificial effects such as diversions and reservoirs on simulated river flow. This enables the effects of changes in surface conditions on stream flow to be investigated and is also necessary for investigating the effects of land use changes on floods.

A distributed routing model in this study is constructed by linking grid-based models routing net rainfall r_{net} calculated using the surface water balance model described in the previous section. A schematic layout of the distributed routing model is given in **Fig. 1**.

The Digital Elevation Model (DEM) is used to construct the whole watershed model in the same outlay as shown in **Fig. 1**. A kinematic wave model is used to route flow over each grid with upstream boundary conditions defined by inflow from upstream grids that drain into the particular grid. This creates a watershed model accumulating flow along the DEM-defined flow paths that can simulate flow routing under the real morphological conditions of the watershed. DEM data are also used to define the slope, area and length of each grid cell.

Although any other model can be used to define the routing process, the kinematic wave model seems to be preferred by many researchers in constructing distributed routing models. Examples can be seen in a number of models including the KINEROS model (Smith *et al*., 1995), LISFLOOD model (De Roo *et al*., 2000, 2001) and Cell Distributed Model (Takara *et al*., 2002; Kojima *et al*., 2003). The use of the kinematic wave model is also advantageous in the study since its main parameter, the Manning's roughness coefficient, depends on land use (Engman, 1986). This helps to include the effect of land use on the routing process.

The kinematic wave model is implemented at each grid assuming the grid as a flow plane sloping in the direction defined by the digital elevation flow map (Kimaro *et al*., 2002, Kimaro, 2003). The upstream boundary condition q_{in} (see **Fig. 1**) is defined by the sum of flows q_o from all upstream grids. The grid model also receives net runoff depth r_{net} calculated by the surface water balance model as lateral inflow. In the present formulation, r_{net} is calculated prior to running the routing model. The governing equation of the routing component considering unit width of grid is

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = r_{net} \tag{5}$$

where $h(x,t)$ is the flow depth, $q(x, t)$ is the flow discharge per unit width, and $r_{net}(t)$ is the output of the surface water balance model. The meaning of r_{net} in this equation is the lateral inflow per unit length along flow direction x per unit width perpendicular to x. Equation 5 is a continuity equation obtained by applying the mass balance principle to infinitesimal control volume along a flow plane. This equation is combined with momentum equation adopting the kinematic wave assumptions:

$$q = \frac{\sqrt{S_o}}{n} h^{\frac{5}{3}} \tag{6}$$

where S_o is the slope of the grid and n is the Manning's roughness coefficient. Equation 6 assumes that uniform flow over a flow plane governed by Manning's equation and that the width of flow is much larger compared to the flow depth. Equations 5 and 6 are combined and solved to obtain flow discharge q and flow depth h by various finite difference schemes (see, for example, Beven, 1979; Chow *et al*., 1988 for details). The solution scheme requires upstream boundary conditions that are defined to maintain the continuity of flow from upstream grids to the outlet along the DEM flow paths as follows:

$$q_{in}(t) = \sum q_{o,up}(t) \tag{7}$$

where $q_{in}(t)$ is the upstream boundary condition for any grid and $\Sigma q_{o,up}(t)$ is the sum of outflow from upstream grids draining into that grid as defined by the flow direction map. $q_{in}(t)$ for all cells at the upstream watershed boundary is assumed to be zero. The watershed model is constructed using object-oriented programming features using C++ with the advantage of flexibility to change, increase or decrease the process models within the watershed model as desired for different modeling objectives (Kimaro, 2003).

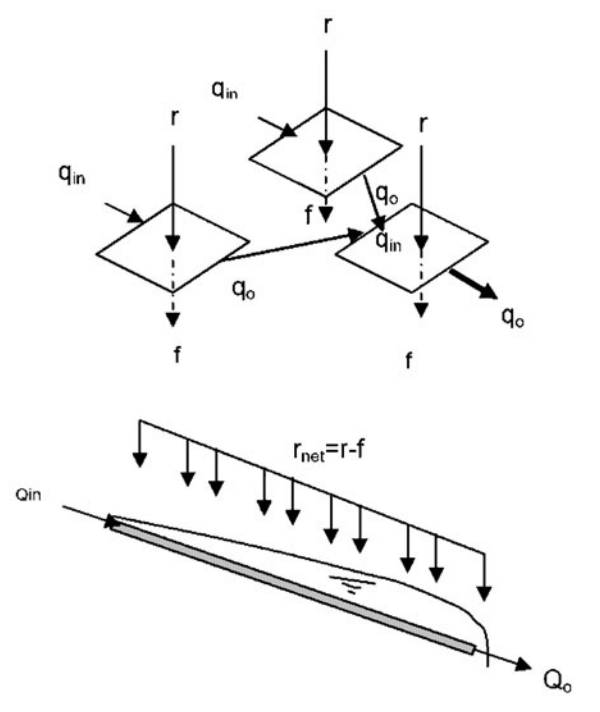

Fig. 1 Schematic representation of distributed routing model.

3. STUDY AREA AND DATA SETS

The study area in this research is the Yasu River basin located on the main island (Honshu) in Japan. The watershed drains into Japan's largest freshwater lake, Lake Biwa. The altitude in the basin ranges from 97 to 1300 amsl. The catchment area upstream of the Yasu gauging point is 377.1 km^2. Annual rainfall varies from 1300 mm in the lower part of the catchment to 1900 mm in the upper part due to influence of the attitude. The basin receives much of the rainfall in June and July due to the seasonal rain front and in September and October due to typhoons. A large part of the basin (60%) consists of mountainous terrain covered by evergreen forest. The main land cover in the lower part of the basin is paddy fields. This area also has a slowly growing urban center that tends to concentrate along the main tributaries of the Yasu River as discussed later in Section 3.1. The map of the Yasu River basin showing the locations of gauging stations and the river network is given in **Fig. 2**.

3.1 Land use data and land use changes

Land use data in the study basin are available from the Japan Geographical Survey Institute (GSI). These data are available at 100-m spatial resolution and are classified into 15 land use classes developed for 1976 and 11 land use classes for 1997, which cover all of Japan. The data (see **Fig. 3**) clearly show forested areas, paddy fields, river channels, built-up areas, golf courses, roads and agricultural land.

Land use data were processed to quantify the coverage of different land use classes as well as changes that occurred between 1976 and 1997. The results of this analysis are shown in **Figs. 3-6**. Forest and paddy fields cover the largest part of the basin. The upper part, the Kashiki subcatchment, is predominantly covered by forest and the main land use in the lower part is paddy fields. These two land use classes experienced only small changes between 1976 and 1997 as shown in **Fig. 6**. The coverage of forest decreased from 63.4% of the whole basin in 1976 to 60.9% in 1997. The area occupied by paddy fields also decreased slightly from 18.7% in 1976 to 17.3% in 1997.

It may be noted from the map of land use change in **Fig. 5** that the Ukawa tributary experienced more changes in land use compared to the Kashiki tributary. The pattern of urbanization is also clearly mapped in this figure, and it shows that urbanization tends to grow into the Ukawa subbasin from the lower part of the basin and is concentrated along the river. There are also indications that extension of a major communication route towards the southeastern part of the basin (see **Fig. 4**) has stimulated the urbanization of this area. The notable change in land use within the forest area is conversion to golf courses, which can be distinguished clearly between the two land use maps for 1976 and 1997 in **Figs. 3** and **4**. Land use data also show that the percentage coverage of the urban area increased from 4.6% in 1976 to 6.9% in 1997, which is equivalent to 50% growth. The distribution of land use changes in the basin between 1976 and 1997 is shown in **Fig. 5**.

3.2 Rainfall data

The Yasu River basin is covered by an extensive network for rainfall gauges. Hourly rainfall data are available from gauges operated by the Ministry of Land Infrastructure and Transport (MLIT), and the Japan Meteorological Agency collected through the so-called AMEDAS (Automatic Data Acquisition System) stations. **Fig. 2** includes the stations used in this study. There are two rainfall seasons in the basin. The first extends from June to July during the rainy season and the second is from the end of August to September during the typhoon season. Floods are usually experienced during the latter season, which has more intense rainfall caused by typhoons.

Distributed rainfall data at spatial resolution for the distributed hydrologic model (500 m) were generated by the ordinary Kriging method for each event using these stations. The spatial distributions of rainfall during major flood events show considerable variability influenced by topography. Most of the precipitation is observed on the highlands towards the northeastern part of the watershed (the Ogawara station) in the Kashiki subbasin. This tributary contributes more to flood runoff at the lower part because of high precipitation and steep river gradient that cause faster drainage. Rainfall intensity during typical flood events ranges between 15 mm/h in the lower part to 70 mm/h in the upper mountainous area.

3.3 Stream flow and flood records

The stream flow data used in this study were obtained from the Ministry of Land Infrastructure and Transportation. Continuous water level records and regularly updated rating curves for the Yasu gauging site from 1975 to 2000 were collected from the Lake Biwa River office of the MLIT. MLIT also keeps a record of high flows during typhoon events at the Yasu gauging site, which can be used as independent source of data to verify the accuracy of stream gauge data for high flows. The two sources of

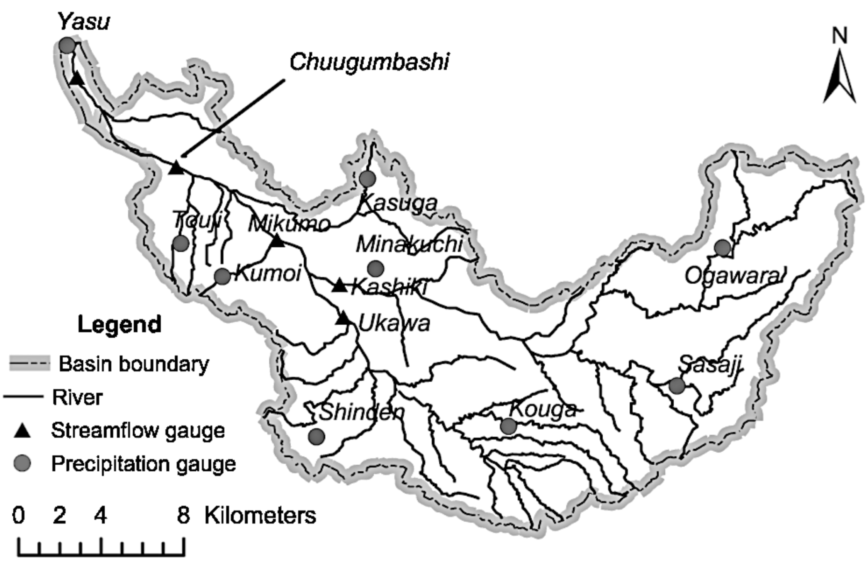

Fig. 2 Hydrometeorological gauges and river network in the Yasu River basin.

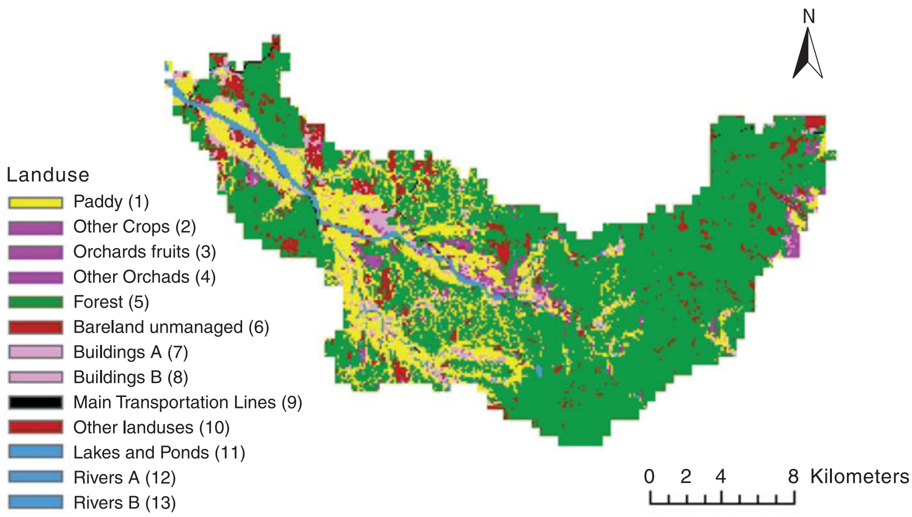

Fig. 3 Land use classification in the Yasu River basin in 1976.

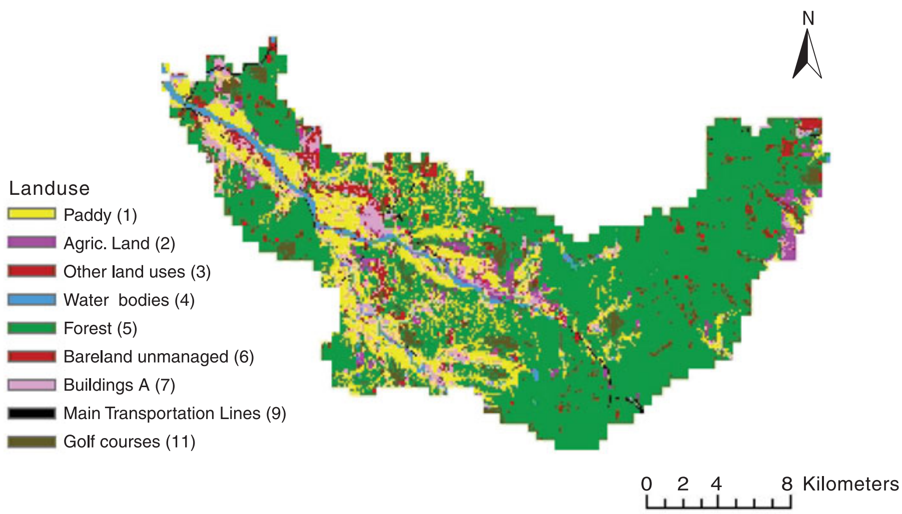

Fig. 4 Land use classification in the Yasu River basin in 1997.

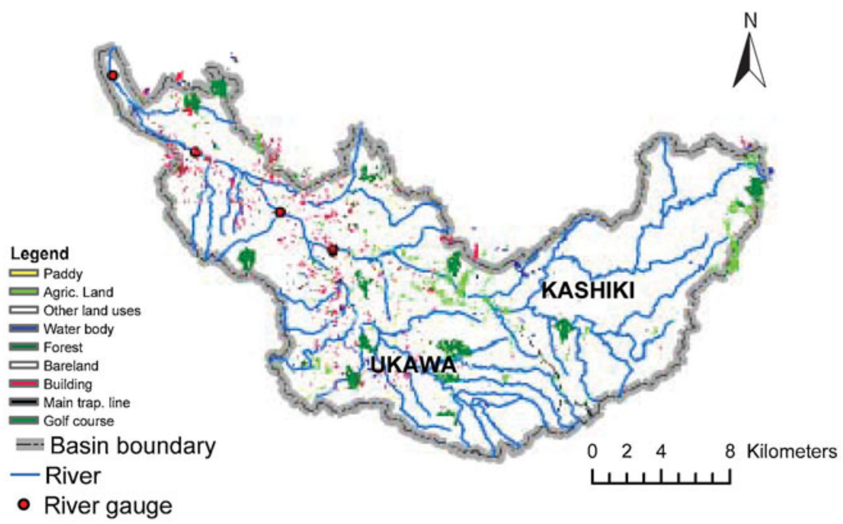

Fig. 5 Pattern of land use change from 1976 to 1997 in the Yasu River basin.

data compare well for the flood events used in this study. A continuous stream flow database was compiled that can be accessed to extract stream flow during any flood event for comparison with simulated river flow. **Table 1** lists the major floods that have occurred in the Yasu River basin.

According to the observed data, the Yasu watershed responds very quickly to intense rainfall such as during typhoons events. Peak river flow is observed within 3 to 4 hours after the peak of rainfall, and the flow recedes to almost zero soon after the flood peak. This behavior indicates a relative dominance of surface runoff or sub-surface water transfer over a very small distance, with a short residence time in the soil layer as suggested by (Gaume *et al*., 2004). There is also an indication that floods in more recent years at the Yasu site have sharp rises and quick recessions compared to the past (**Figs. 7** and **8**). This situation may be caused by changes in the storage characteristics of the watershed, including possible effects of land use changes.

4. MODEL APPLICATION AND RESULTS

The hydrologic model described in Section 2 is applied to the Yasu River basin (377.1 km^2) to investigate the effects of land use changes using selected flood events between 1976 and 1997. The target of the simulation experiment was to study the qualitative and quantitative changes on flood hydrographs due to land use change during this period.

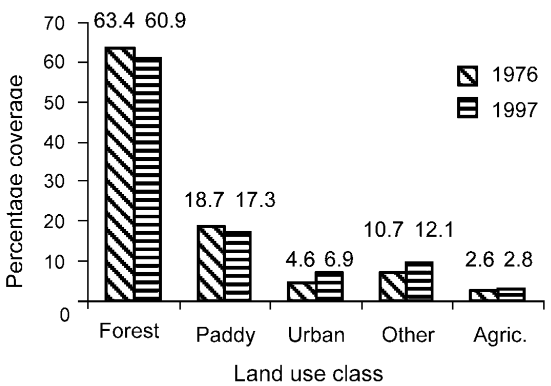

Fig. 6 Percentage coverage of different land use classes in 1976 and 1997 in the Yasu River basin.

Table 1 Major floods at Yasu gauging site.

Date (month/day/year)	Rainfall factor	Peak discharge* (m^3/s)
08/31/1971	Typhoon	2021
09/21/1972	Typhoon	1570
09/09/1976	Typhoon	1054
08/02/1982	Typhoon	1604
07/21/1984	Rain front	1312
08/16/1988	Rain front	1335
09/20/1990	Typhoon	2198
09/09/1993	Typhoon	1040
09/30/1994	Typhoon	1521
05/16/1995	Rain front	1439

* Source: Ministry of land Infrastructure and Transport (MLIT)

The effects of land use changes are studied from hydrographs simulated at the Yasu gauging site where observed flow is available for comparison with simulation. To trace locations with remarkable changes in runoff generation, differential runoff maps produced with different land use are used. The model is applied without the calibration of parameters except for tuning the initial soil moisture deficit M as an initial condition and the saturated hydraulic conductivity K_s to obtain the best fit of simulated hydrographs. The initial soil moisture deficit M is assumed depending on the events with spatially uniform distribution. For the 1975 and 1994 flood events, the value of M was set to 0.187 and 0.242, respectively. **Table 2** summarizes the model parameter values used in the flood simulations.

The procedure adopted to study changes to flood generation and propagation as a result of land use changes is as follows:

(1) Simulation is performed using the land use map "A" for flood events for which land use map "A (land use in 1976)" is believed to be representative of the prevailing land use condition. Infiltration parameter K_s and initial soil moisture deficit M are tuned to produce the best representation of the flood hydrograph by visual inspection of the observed and estimated hydrographs.

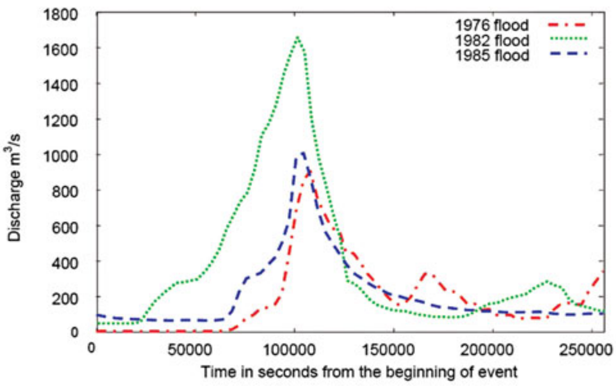

Fig. 7 Typical flood hydrographs in the Yasu River basin between 1976 and 1985.

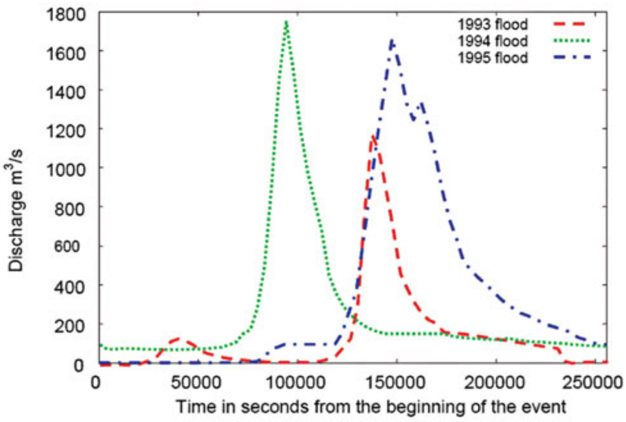

Fig. 8 Typical flood hydrographs in Yasu River basin between 1993 and 1995.

(2) After obtaining satisfactory results in the step above, similar initial conditions and rainfall input are used with the land use map "B (land use in 1997)" in runoff simulations. Changes in flood peaks and timing are determined from the simulation results using the two different land use maps.

(3) The differential runoff map generated using runoff maps produced with land use A and B is used to locate areas with remarkable changes in runoff generation to reveal the effects of spatially distributed land use changes. The results are discussed with a map of land use change between "A" and "B" to understand the type of land use changes and their impact on runoff generation processes.

Table 2 Parameter values used for flood simulations.

Parameter	Paddy	Forest	Agric.	Glassland	Urban
Manning roughness coefficient n ($m^{-1/3}s$)	2.5	0.5	0.3	0.3	0.02
Maximum surface storage D (mm)	50	10	6	6	0.4
Hydraulic conductivity K_s (mm/s)	0.0034	0.0034	0.0034	0.0034	0.0034
Average suction head S_{av} (mm)	210	210	210	210	210

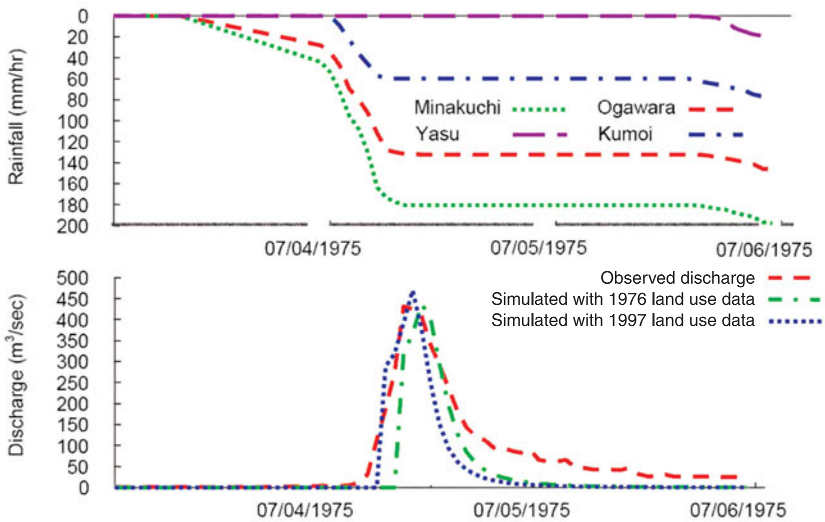

Fig. 9 Simulation results for flood event in July 1975 with 1976 and 1997 land use data.

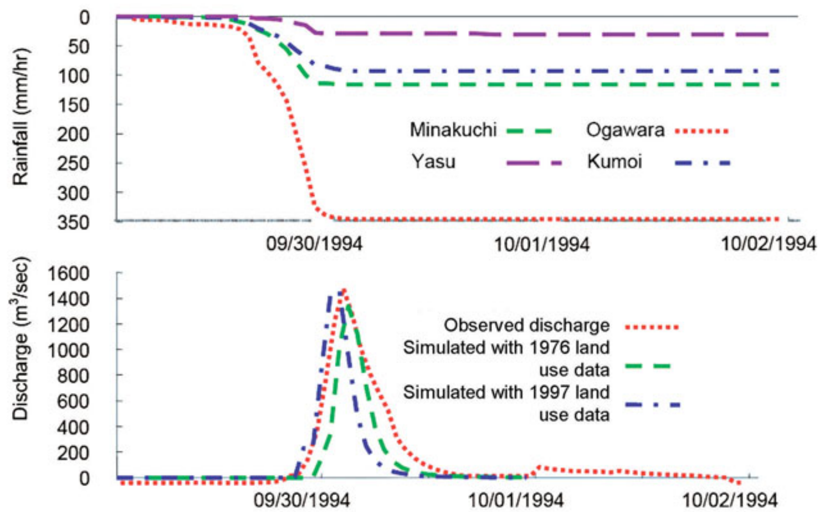

Fig. 10 Simulation results for flood event in September 1994 with 1976 and 1997 land use data.

4.1 Changes of flood peaks in the basin

A total of five flood events between 1975 and 1994 were simulated with land use data for 1976 and 1997 to investigate changes in flood peaks. Applicable land use data at the time of occurrence of the flood are those that are captured within the shortest time from the date of occurrence of the flood. For example, for a flood event in 1980, land use data of 1976 are assumed, while for a flood event in 1994, land use data of 1997 are assumed.

The results of runoff simulations with 1976 and 1997 land use data for different flood events are shown in **Figs. 9** and **10** and are also summarized in **Table 3**. The distributed hydrological model has reasonable ability to predict flood peaks and timing as can be seen in observed and estimated flow with the land use condition in 1976 in **Fig. 9** and observed and estimated flow with the land use condition in 1997 in **Fig. 10**. In these figures, both the peak and timing of floods are well reproduced when the land use data most representative of the land use situation at the time of flood occurrence are used. The model matches well the rising limb of the hydrograph, which represents a quick flow, while the falling limb is not well reproduced. This is due to subsurface processes that are not considered in the current hydrologic model. However, the results suggest that quick overland flow as modeled in the current study may be used to estimate flood peak and timing.

It is found in **Figs. 9** and **10** and **Table 3** that the runoff simulation results using 1976 land use data give consistently lower flood peaks and delayed peak timing compared to those using 1997 land use data. The land use changes over a period of 20 years from 1976 to 1997 results in the highest increase in flood peak simulated being 18.2% and the lowest being 7.41%. Although the changes are small in this case, this only depends on the magnitude of land use change. Definitely more changes in land use leads to more changes in simulated runoff, which could be captured using the proposed hydrologic model structure.

4.2 Spatial changes in runoff generation

The effects of localized land use changes on floods need to be examined in order to control the spatial distribution of land use or evaluate the impacts of different spatial patterns of activity within the basin. As the proposed hydrologic model simulates the spatially distributed process of runoff generation, the difference in spatially distributed runoff production maps produced with different land use patterns delineates the areas where runoff changes have occurred. The analysis reveals the effects of different types of land use change at different locations on flood magnitude and timing of flood routing. Runoff production maps using the land use patterns of 1976 and 1997 were generated for the 1994 flood simulation by summing the total flow volume from the beginning of the flood event to the end for all grid cells. A difference in the runoff production maps by subtracting the cumulative runoff volume for each corresponding cell is shown in **Fig. 11(a)**.

To understand how the land use change affects runoff generation and propagation, the difference in land use map is also made as shown in **Fig. 11(b)**. It is found that more runoff tends to be generated from the southern part of the catchment, which also experienced a higher concentration of land use changes. A large area of the basin on the northeastern part does not show increase in runoff. Apparently, the Ukawa subcatchment has experienced more urban activities as shown by the increase in concentrated built-up areas and golf courses. This is causing a gradual change in the rainfall runoff relationship as revealed by both flood runoff simulations and land use data analysis. The use of differential maps for runoff productions and land use patterns seem to be suitable for evaluating the impacts of spatially distributed land use changes on floods.

5. CONCLUSIONS

This study investigated the effects of land use changes on flood characteristics using a distributed hydrological model and land use data. The distributed hydrological model consists of infiltration excess overland flow process defined by the Green and Ampt infiltration model and routing process with a DEM-based kinematic wave model, which well represents the rising limb of flood hydrographs, peak discharge and timing of floods. The results encourage the utilization of land use data in hydrologic modeling to describe the impact of land use changes on floods. The results of the study also indicate that a DEM-based kinematic wave routing method provides an effective way of understanding the effects of the spatially distributed runoff-generating process on stream flow. The model is especially suitable for investigating the impacts of land use changes because it takes into account the effect of land use change on the flow generation mechanism.

Despite the complexity of analyzing the effects of land use change on catchment response, the simulation study shows the impact of land use change on the distributed overland flow process. In this case study, the impact of land use change on flood forma-

Table 3 Summary of simulation for different events with 1976 and 1997 land use data.

Date	Observed peak flow	Estimated peak flow with 1997 land use data	Estimated peak flow with 1976 land use data	Difference between observed and estimated peak with fitted land use data (%)	Estimated changes of peak discharge with land use changes (%)
Apr. 7, 1975	431.9	470.1	437.7	1.3 (with land use in 1976)	7.4% increase (with land use in 1997)
Sept. 9, 1976	1004.3	1105.0	960.9	4.4 (with land use in 1976)	15.0% increase (with land use in 1997)
June 1, 1980	606.8	699.3	591.9	2.5 (with land use in 1976)	18.2% increase (with land use in 1997)
Sept. 20, 1990	2236.6	2261.4	2061.6	1.0 (with land use in 1997)	8.8% decrease (with land use in 1976)
Sept. 30, 1994	1516.0	1521.0	1338.8	0.3 (with land use in 1997)	12.0 % decrease (with land use in 1976)

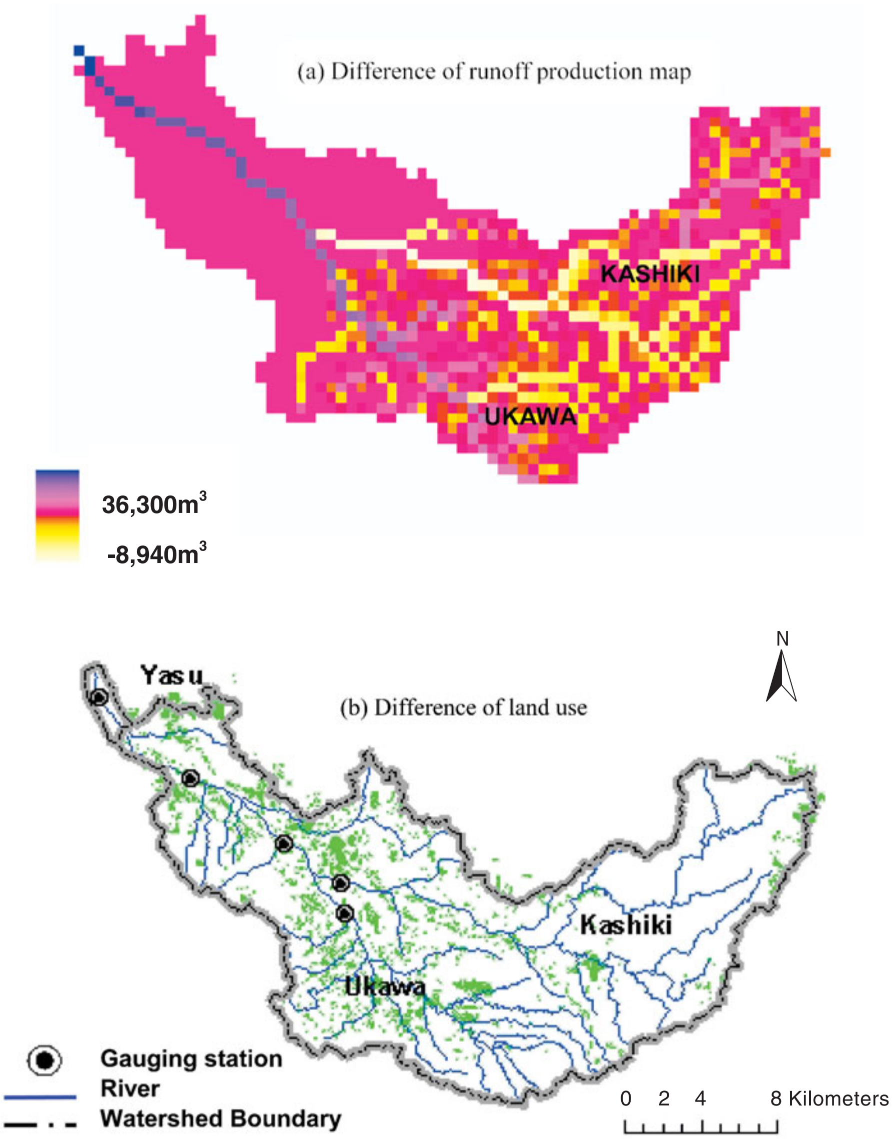

Fig. 11 (a) Differential runoff production map induced by land use change from 1976 to 1997 for the 1994 flood event. (b) Differential land use map that shows the cells converted to different land use cells between 1997 and 1976. Note that the central southern part of the basin (Ukawa sub-catchment) has a high concentration of changed pixels.

tion in the Yasu River basin does not appear to be alarming due to a low degree of land use change. However, the proposed distributed model well captures flood change and, if it is applied in a drastic land use change environment, a greater understanding of the effects of land use changes on floods can be gained.

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