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Hydrological Effects of Landuse Change in the Yasu River Basin

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Synopsis

The effects of land use changes on river flow in Yasu river basin were determined using distributed rainfall runoff model and historical land use data between 1976 and 1997. The rainfall runoff model runs at 500 m spatial resolution. The model calculates vertical moisture and energy balance using a SVAT scheme. During rainfall a Green and Ampt model is invoked to calculate infiltration and excess rainfall. A grid based Kinematic wave model then routes the runoff as overland flow to the basin outlet. Land use data at 100 m spatial resolution was used to define spatially distributed roughness parameter and other vegetation parameters required in the SVAT model. The landuse changes between 1976 and 1997 were determined. Among others there was a 44.6% growth in the urban area, decrease of forest by 4.8% and decrease of paddy fields by 7.6%. Simulation performed show increased peak flows which can be related to the observed land use change. The results indicate that typical typhoon flood peaks might be increased by up to 15%.

Keywords: Yasu river basin, land use changes, distributed hydrological model, floods, urbanization

1. Introduction

The effect of land use changes on river flow is one of the most important environmental problems of our time. Expanding cities due to economic growth, population growth or both often comes at the expense of increased risk of flooding and decreased water quality and quantity. Over the years hydrologists have been concerned with the problem of evaluating the effects of urbanization and land use changes at large on river flows. The immediate concerns are the effects on floods peaks, water yield and water quality. As regards the problem of flooding, it is well known that urbanization tends to increase the speed and magnitude of floods due to increased imperviousness of the urbanized land. This increases the severity of floods in terms of frequency and magnitude.

However the determination of the effects of land use changes on river flow in a specific basin still posses a formidable practical problem. There is difficulty in determining the changes in land use which needs to have high resolution land use data besides the modelling problem encountered when relating these changes to river flow.

This paper deals with effects of land use changes on river flow in the Yasu River basin. The land use changes were determined from 100 m resolution land use data derived from remotely sensed images covering a period of 21 years 1976-1997. A distributed hydrological model utilizing this data was developed with the help of GIS and Object orient programming techniques. Analysis of effects of observed land use changes on the river flow is presented and possible future effects are studied using assumed future land use scenarios.

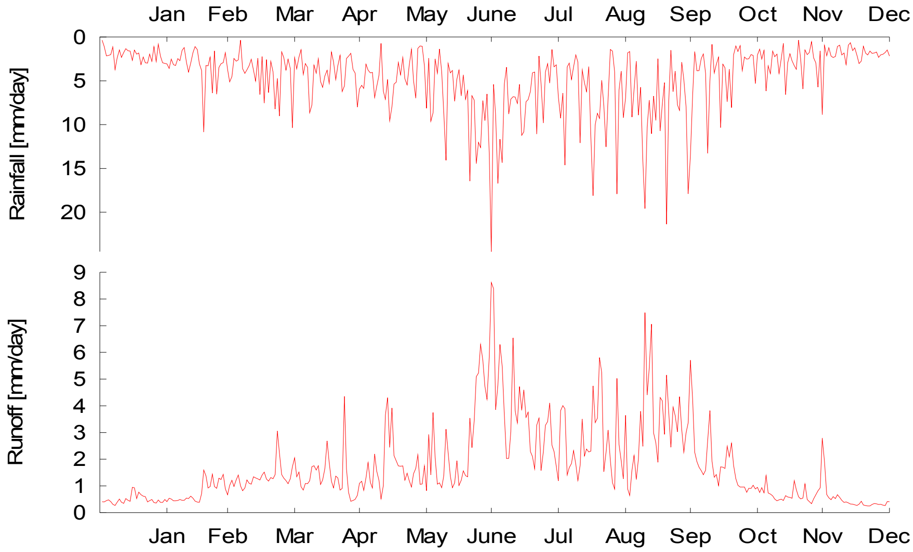

Fig. 1 Long term daily average rainfall and runoff in the Yasu River basin

2. The Yasu River Basin

Yasu river basin is located in the main island of Japan called Honshu. It is in Shiga Prefecture and drains into Lake Biwa which is the largest fresh water lake in Japan. The geographical position is approximately between 136.0 to 136.5 degrees east and 34.85 to 35.1 degrees north. The area of the basin is 377.42 square kilometers upstream Yasu gauging station.

The water resources of the basin are heavily developed for irrigation, water supply and industrial uses. This includes both surface and underground sources. There are two main reservoirs and a number of irrigation schemes supplying water to paddy fields.

Table 1 Recorded floods at Yasu gauging site

Date (mm:dd:yy)	Season	Magnitude 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	Summer	1312
08/16/1988	Summer	1335
09/20/1990	Typhoon	2198
09/09/1993	Typhoon	1040
09/30/1994	Typhoon	1521
05/16/1995	Spring	1439

Source: Ministry of land Infrastructure and Transport (MLIT)

The main irrigation period is during the month of May when the paddy fields are flooded for a new crop.

There are two rainfall seasons in the basin. The first one extends from June to July in the summer season and the next is from end of August to September during typhoon season. Floods are normally experienced during the latter season which has more intense rainfall caused by typhoons. The lag time between the peak of rainstorm and peak discharge is less than four hours. The maximum discharge recorded between 1971 and 1995 was 2198 m^3/s which occurred in typhoon season of 1990 (Table 1). There is an indication that in the last decade ending 2000 the basin experienced more frequent and severe floods as compared to the previous decades.

3. Land use changes in the Yasu River basin

Unlike Osaka and Kyoto prefectures which are more urbanized, Shiga prefecture, where the basin is located is still in the process of urbanization. This provides a good case study for investigating land use change effects as the changes are recent and continuing. It is possible therefore to trace these changes using recent remotely sensed data since considerable changes are expected to have occurred in a period covered by modern remotely sensed products. The driving force for urbanization in the basin is the transformation of the economy from agricultural-based to manufacturing-based economy and by population growth. Many industries were relocated to Shiga prefecture during 60's and 70's to make use of ample land space and abundant water resources as opposed to crowded and polluted downstream costal areas. As a result, the number of people employed in agriculture decreased from more than 50% in 1950 to 5.1% in 1995 (Nakamura and Nakajima, 2002). The growth in population occurred as people moved in to take new jobs in the industries and still other relocating homes from the crowded metropolitan areas. For example in 1970 the

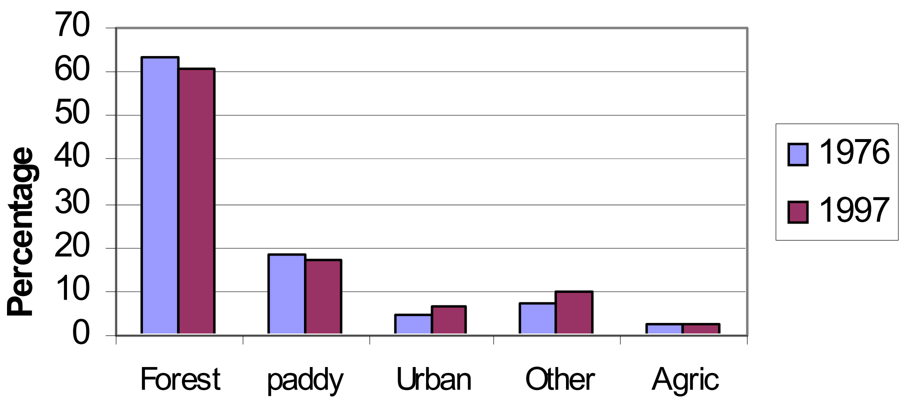

Fig. 2 Land use change in the Yasu River basin between 1976 and 1997

population in Shiga prefecture was about 800,000 and it grew to more than 1,500,000 in 1990. This tendency was also stimulated by improved transport between the prefecture and the surrounding cities. The effects of general trends described above on the land use in the study basin were studied by using land use data spanning 21 years 1976-1997. The overall changes for different landcover types during this period were determined. The main land use/landcover classes are forest, paddy field, urban, water bodies, and agricultural land. The percentage of the basin covered by urban area was 4.4% in 1976 and 6.4% in 1997. This is equivalent to a 50% growth in urban area within the study period. Further analysis indicated that urban area mostly grew into area occupied by paddy fields. The reason for this is that paddy fields are located in populated areas and therefore easily affected by expansion of built-up areas. The growth of the urban area concentrated in the lower part of the basin close to the two main tributaries of Yasu River Kasiki and Ukawa. The percentage changes in land use for different classes between 1976 and 1997 in the basin are shown in Figure 2 above.

4. Effects of land use changes on floods

The major part of this work was devoted to studying the effects of established land use changes on the flood flows by hydrological modeling. Emphasis was placed on flood flows because the urbanization which constituted a major change in land use tends to have more direct impact on flood flows than on the long term water yield. Another reason is that the processes governing flood flows are mainly dependent on surface conditions. It is therefore expected that good representation of the surface conditions in the model will yield a good estimate of the flood flows and allow the effects of land use changes on stream flow to be evaluated. An important requirement here is that the spatial heterogeneity of land surface conditions must be taken into account. This requires both parameters and inputs be spatially distributed. It may be seen immediately here that this provides a basis for studying the effects of land use changes if the spatial distribution of these parameters are related to land use.

5. The hydrological model

A hydrological model is a simplified representation of the hydrological process governing the movement of water in the hydrological cycle. The cycle can be viewed at global scale or at a local scale. Because the hydrological cycle is too complex to be modeled working assumptions to simplify it are necessary. This may be done by neglecting some of these processes depending on the purpose of modeling, the time scale, or the local conditions.

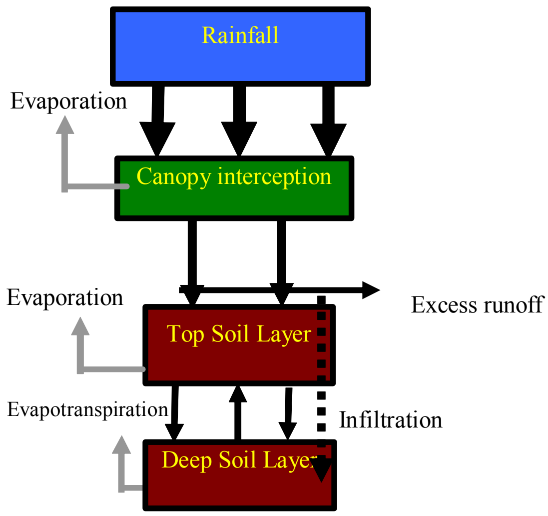

Fig.3 Vertical Processes involved in modeling flood flows

The exact number and types of the processes to be considered can be obtained by trial and error or rather by building the model gradually including at each stage those processes necessary to improve the results for the intended purpose from the previous stage. It can be argued that some watersheds may require complex models to describe their hydrological characteristics while others may only require simple models. This explains why a model which yields good results in one catchment may not perform equally well in another. Since the emphasis was placed on simulation of flood peaks the model was built to include only the surface processes. These included interception, evaporation from interception, infiltration, evaporation from ground surface and evapotranspiration.

6. Process models

Process models describe the evolution of water or energy at each stage of the water cycle by a given set of mathematical equations derived from physical laws or by empirical observations. The physically based process models have advantage that their parameters can be measured at site or inferred from other surface characteristics such as landcover, soil type, vegetation etc. Such parameters can be allowed to vary over time and space making the model more dynamic and accurate in describing the hydrological process. Such kinds of models are ideal for investigation of the effects of land use changes on stream flow. Most of the process models used in the flood flow model of this study (see Figure 3) are those used in the ISBA land surface scheme of Noilhan and Planton (1989). The full description of this scheme is given in Noilhan and Planton (1989) and Noilhan and Mahfouf (1996). This scheme is physically based and parameters can be determined for any site using vegetation and soil data. In addition to this scheme the Green and Ampt model as modified by Chu (1978) is used to describe the net rainfall and infiltration. The Kinematic wave model is used to route the overland flow. The brief description of each process is given below.

6.1 Canopy processes

The processes involved at the canopy level include interception of rainfall or dew by tree leaves, evaporation of the intercepted water and drainage from the canopy. The net output at canopy level reaches the ground where it replenishes the soil moisture and may or may not form a runoff. The equations describing the canopy process are;

$$\frac{\partial w_r}{\partial t} = vegP - (E_v - E_{tr}) - R_r; \quad 0 \le W_r \le W_{r\max}$$

$$W_{r\max} = 0.2 * veg * LAI$$

$$D = Max(veg * (P - Er) * dt - W_{r\max}, 0) / dt$$

Where W_r is the canopy storage, P is the precipitation above the canopy, E_v evaporation from vegetation, E_{tr} evapotranspiration and *veg* the degree of canopy closure. The other are E_r evaporation from the interception reservoir, W_{rmax} the maximum storage of the interception reservoir, *LAI* the Leaf area index and *dt* is the time step. *D* is the drainage from canopy which occurs only when the canopy reservoir is full. Evaporation terms E_v and E_{tr} are calculated by variants of the Penman formula as described in Noilhan and Planton (1989).

6.2 Soil and ground surface processes

Following Noilhan and Planton (1989) the model defines two soil layers - a thin superficial top layer about 10cm and a deep soil layer equivalent to the root zone depth. The exchange of energy and moisture between the soil and atmosphere is modeled within these two layers using force restore method (Deardorff 1977). The net radiation (R_n) at the surface divides into Latent (*LE*), Sensible (*H*) and ground heat (*G*) fluxes.

$$G = R_n(Ts) - H(Ts) - LE(Ts)$$

The ground heat flux causes changes in temperature expressed as

$$\frac{\partial T_s}{\partial t} = C_T G - \frac{2\pi}{\tau}(T_s - T_2)$$

for the top soil layer and

$$\frac{\partial T_2}{\partial t} = \frac{1}{\tau}(T_s - T_2)$$

for the deep soil layer. Where T_s and T_2 are the top and deep soil temperatures, τ is the daily time step and C_T is a coefficient depending on both soil type (textural class) and degree of canopy closer (*veg)*. The change in moisture in the soil layers depends on dew flux or infiltrated rainfall (P_g), evaporation from the ground (E_g) and evapotranspiration (E_{tr}). The processes can be described by the following equations.

$$\frac{\partial w_g}{\partial t} = \frac{C_1}{\rho_w d_1}(P_g - E_g) - \frac{C_2}{\tau}(w_g - w_{geq}) \quad 0 \le W_g \le W_{sat}$$

For the top soil layer moisture and

$$\frac{\partial w_2}{\partial t} = \frac{1}{\rho_w d_2}(P_g - E_g - E_{tr}) \quad 0 \le W_2 \le W_{sat}$$

for the deep soil layer moisture.

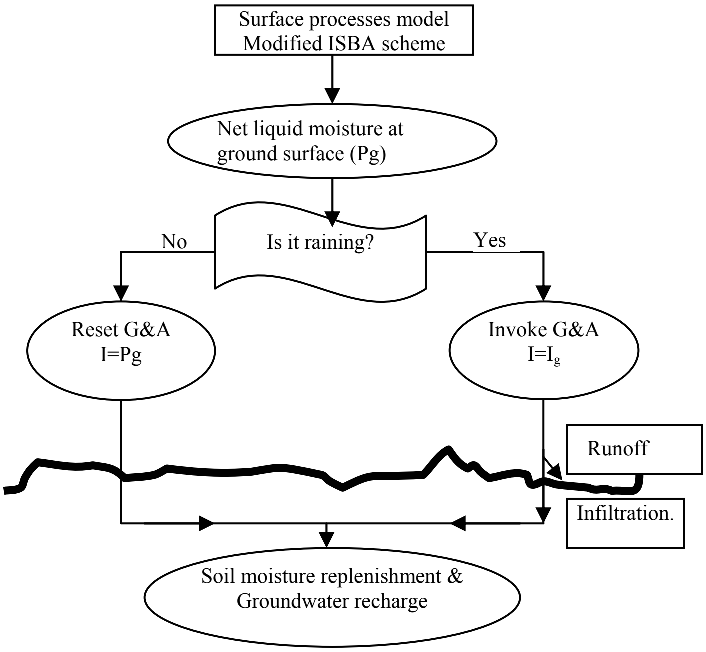

Fig. 4 Layout of implementation of vertical processes model

C_1 is a coefficient depending on soil textural class, d_1 and d_2 the depth of top and deep soil layers respectively. W_{geq} is defined as soil moisture when the capillary and gravitational force balances. All the rating equations above appear in the ISBA scheme with same notation (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996). However in this case P_g is either a dew flux during the time when there is no rainfall or infiltrated rainfall during rain storms. The inclusion of infiltration model into the ISBA scheme and redefinition of P_g are some of the modifications found necessary to adopt it into a hydrological model for simulation of flood flows. The schematic diagram of the model with respect to vertical processes is shown in Figure 4. Soil moisture replenishment and surface runoff during rainfall are calculated using Green and Ampt model as modified by Chu (1978). The Green-Ampt model Green and Ampt (1911) is a physically based model for infiltration with parameters which depends on soil type. Although the evaporation and interception losses were not considered in the original model they are included in the present case by linking this model to the surface processes model calculating those losses.

7. Flow routing

All the process described before are assumed to occur in a soil column with a plan area equal to the spatial resolution of the distributed hydrologic model. It is assumed that the grid size is sufficiently small such that for practical purposes the values of model parameters and inputs within the grid can be considered uniform. The choice of the grid size may however be limited by the computational power available depending on the number of inputs and outputs at each grid. The grid size adopted in this study was 500m. The flow routing component collects the distributed net rainfall on each grid and routes it to the outlet of the basin. The flow routing model essentially uses the kinematic wave model described as follows.

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

$$q = \alpha h^m$$

$$\alpha = \sqrt{\frac{I}{n}}$$

Where *h(x,t)* is the depth of overland flow, *m*=5/3, *q(x,t)* the rate of overland flow, r_{net} the net rainfall, α the conveyance factor, *I* slope and *n* surface roughness. The roughness coefficient in each grid is determined according to its land use and the net rainfall is taken from the output of the surface processes model described above. The flow routing model was built using object oriented programming (OOP) utilizing the Ohymos library (Kimaro, *et al.,* 2002). The architecture of the model is shown in Figure 5 below. The Model grids are defined according to the DEM data. A 500m DEM was constructed from 50m DEM and a flow direction map at this 500m grid size was prepared. An element model which is equivalent to the kinematic wave model for each grid was prepared in the OOP using the Ohymos Library.

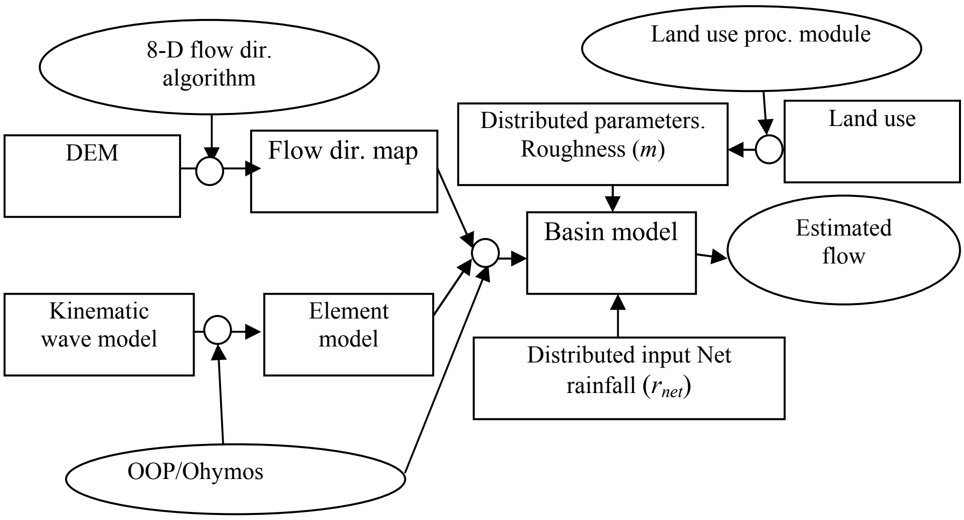

Fig. 5 Layout of the implementation of the routing model

These models are connected together using the flow direction map to form a basin model which receives the inputs and parameters to simulate the flow. The estimated flow can be obtained at any grid in the basin. Land use data for different years can be used to define the spatially distributed roughness parameters.

8. Simulation

The proposed model was applied in the Yasu river basin to study the effects of land use changes on flood flows. The surface model is first executed to provide the distributed net rainfall which is fed into the overland flow model to simulate the flood flow. The estimated flood is also compared with the observed flood to check the accuracy of the assumed parameters. Land use data is prepared in raster format where each land use class is represented by a digital value. The raster data is used by a land use processing module which uses a look-up table to assign the roughness coefficient for each grid automatically. To assign a roughness value for a given land use class an assumption is made on what probable landcover that land use class represents. This brings problem for unclassified pixels where the modeler has to use his own judgment to decide on the type of landcover.
The different landcover classes assumed and their roughness values were; Paddy fields (2.5$m^{-1/3}s$), forest (0.5 $m^{-1/3}s$), Agricultural land (0.3 $m^{-1/3}s$), grassland (0.3 $m^{-1/3}s$), water bodies (0.01 $m^{-1/3}s$), Urban (0.02 $m^{-1/3}s$). The roughness value of each 500 m grid was calculated as an average of roughness values of 100 m grids within the 500m grids since the original land use data is in 100 m spatial resolution. Land use data for 1976 (Figure 6a) and 1997 (Figure 6b) were prepared for simulation.

The surface model requires a number of input data and spatial parameter files. Meteorological variables including air temperature, wind speed, solar radiation, vapor pressure, absolute humidity, air pressure and sunshine hours were obtained from a nearby meteorological station. The distributed rainfall data was generated from four observation station in the basin by Kriging. The parameters of the land surface models are assigned depending on vegetation and soil data. There are 11 different soil parameters depending on soil texture and three vegetation parameters. For simplicity it is assumed that the whole basin is a sandy soil and all parameters are assigned the values accordingly. The simulations were performed for selected floods using different land use data to investigate the effect of land use change from 1976 to 97.

9. Results and discussion

The model was run on event basin at an hourly time step to simulate specific historical floods as recorded in Table 1. Model parameters including those of Green and Ampt and the surface processes model were specified from literature and some of them adjusted to obtain the best fit to the observed floods. This also included the trial and error procedure to obtain the best initial conditions for each flood. During this exercise land use data taken closest (in time) to the observed flood was used. When the observed flood was reasonably reproduced land use data taken at different time was then used in simulation to show the effect of land use changes on simulated floods. This procedure effectively separates the effects of land use changes from other effects such as those of climate which may occur concurrently with land use changes. Figure 7 shows the results of analysis for the floods observed in 1976 and 1994. In both cases the observed flow is fairly reproduced. The deviation between observed and estimated hydrographs seems to be systematic as the estimated curves accurately follow the pattern of the

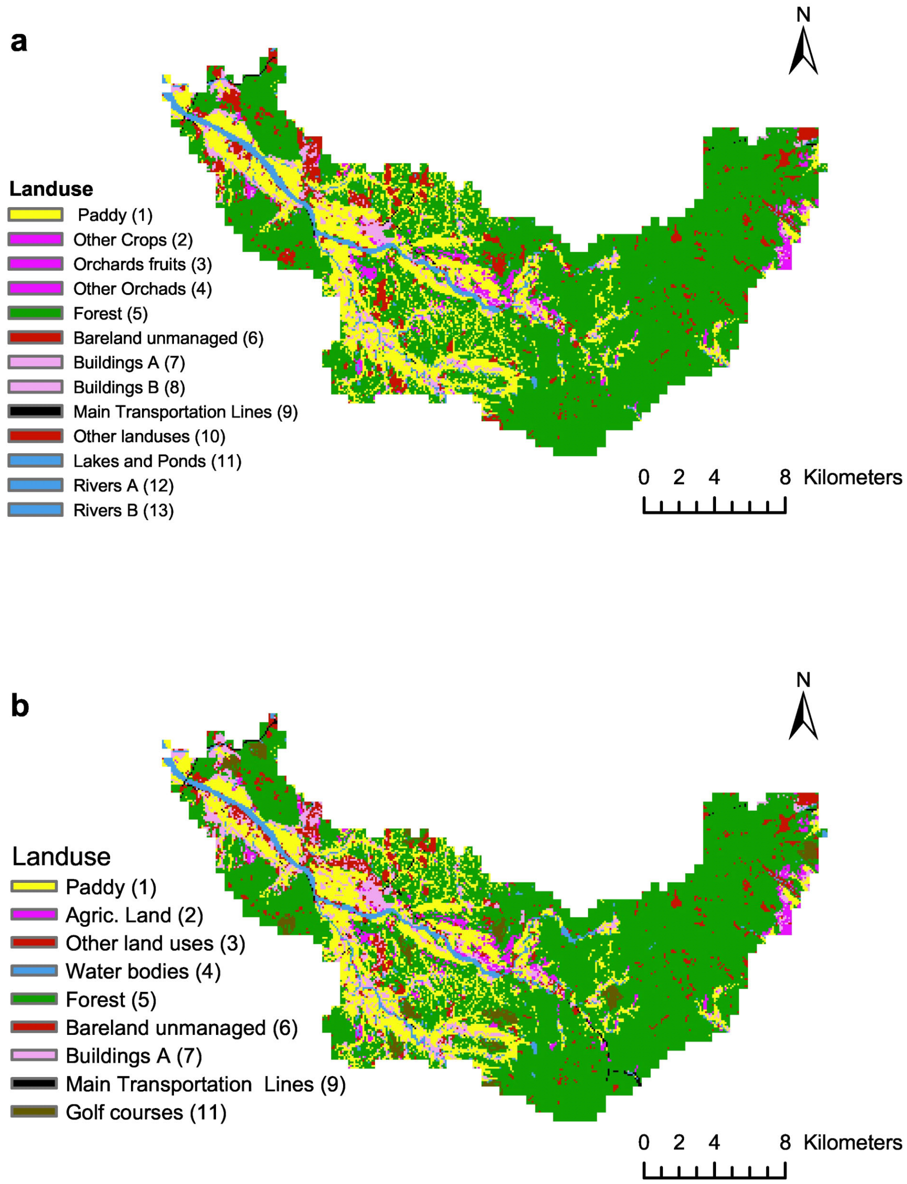

Fig. 6 Land use in the Yasu River basin (a) 1976, (b) 1997

observed flow. Such deviations can be attributed to errors in initial conditions. They may also result from other components of the hydrograph not modeled in this study such as subsurface flows. In all cases however the maximum peaks are very closely estimated. The effects of land use changes can be seen in both cases but they are very evident in case two (Figure 7b). It is clearly shown that the observed flood which is closely estimated using land use data in 1997 has increased peak flow due to land use changes. The same flood is simulated by 1976 land use data has a lower peak flow by 200 m^3/s. The simulation presented in Figure 8 represents a hypothetical case where all paddy fields are turned into urban area. The simulation show tremendous increase in peak flows and demonstrates the role of paddy fields in reducing food peaks in the basin as detention storage.

10. Conclusions

This study has demonstrated an effective use of remotely sensed land use data in hydrological modelling. It has been shown that it is possible to study the effects of land use changes on flood flows by using land use data taken at different time interval representing significant changes in land use. The primary use of land use data in this study was to specify the spatial distribution of roughness coefficient used in modelling the overland flow. The sensitivity of estimated flows to this parameter allows even small changes in land use to be detected. To emphasize the effects of urbanization in the study

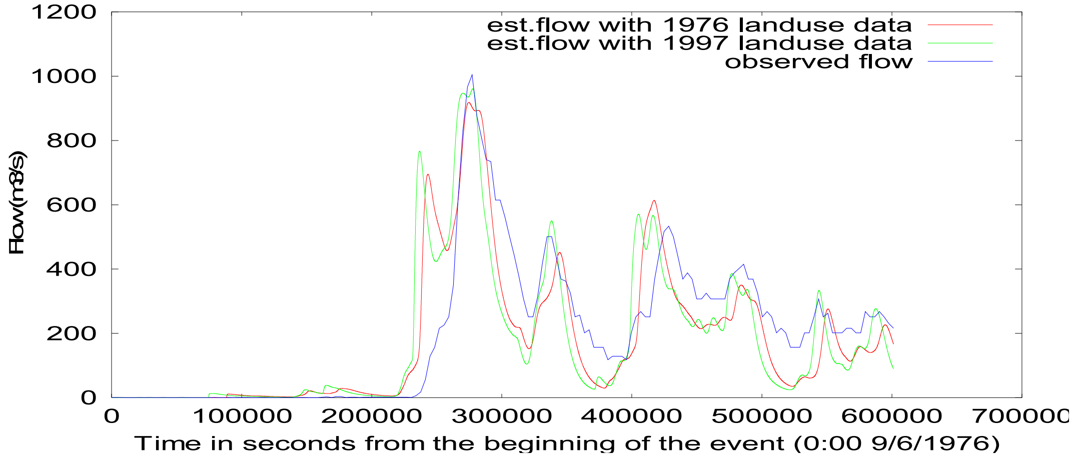

Fig. 7a Estimated and observed flow for the maximum flood in 1976 with different land use data

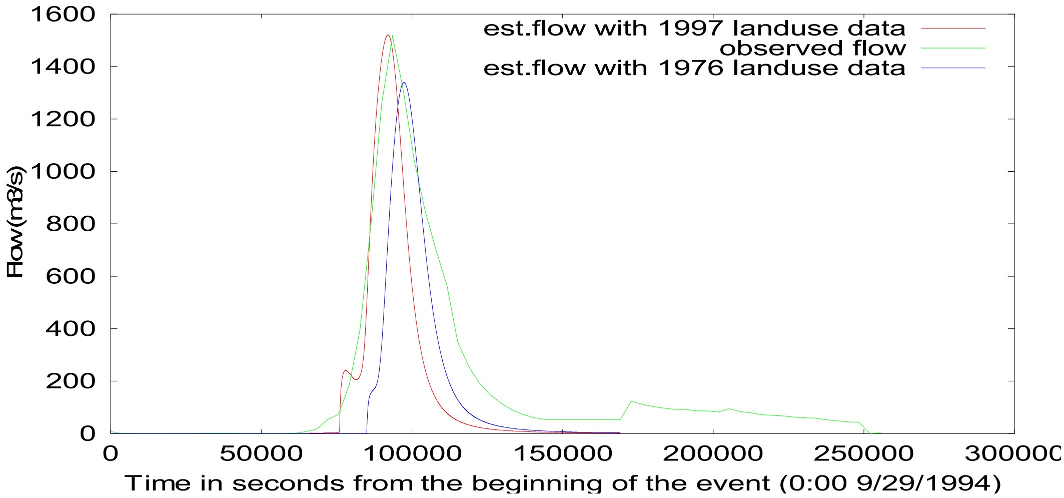

Fig. 7b Estimated and observed flow for maximum flood in 1994 using different land use data

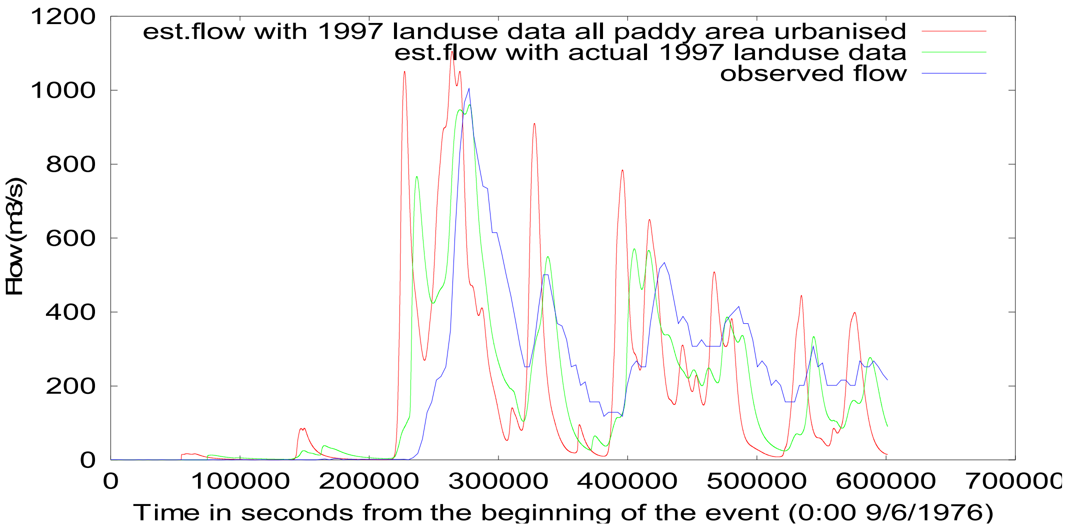

Fig. 8 Effect of urbanization into paddy fields

basin a simulation assuming 100% change of paddy fields into urban area was conducted. Kimaro et al (2003) had found that urbanization has the greatest impact on paddy fields and accounted for about 40% change in land use utilized by paddy fields between 1976 and 1997. The results of this study suggest that if eventually all paddy fields are replaced by built up area flood peaks will be increased. It is therefore important to take other measures to reduce flood peaks as urban area grows in the basin. This may include provision of infiltration grounds in the urban area and other structural measures.

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野洲川流域における土地利用変化の水文流出への影響

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要　旨

分布型降雨流出モデルと土地利用データを用いて，野洲川流域における 1976 年から 1997 年の間の土地利用変化が河川流出に及ぼす影響を分析した。分布型降雨流出モデルの空間分解能は 500m である。このモデルは垂直方向の水・熱バランスを SVAT スキームを用いて表現している。降雨時には Green and Ampt モデルを用いて地中への浸透量と不浸透量を計算する。次に，500m 分解能の DEM を基に作成した地形モデルに従って，地表面流を kinematic wave モデルを用いて流域下流端まで追跡する。100m 分解能の土地利用データを用いて，分布型流出モデルの粗度係数を決定し，SVAT スキームに必要とする植生パラメータを決定した。さらに，1976 年と 1997 年の土地利用データをもとにこの間の土地利用の変化を求めた。この間に市街地域は 44.6%増加し，森林域は 4.8%，水田域は 7.6%減少したことがわかった。1976 年と 1997 年の土地利用データをもとにモデルパラメータを決定し，洪水流出計算を行なったところ，土地利用の変化に応じてピーク流量が増大することを見出した。この結果は，典型的な台風による洪水ピークが 15%程度増加する可能性を示している。

キーワード：野洲川，土地利用変化，分布型流出モデル，洪水，都市化