Monitoring, Prediction and Mitigation of Disasters
by Satellite Remote Sensing (MPMD), pp. 61-69, 2004

Application of Remote Sensing for Describing Spatial-Temporal Changes in Flood Characteristics

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ABSTRACT: Land use changes captured by remote sensing over a period of 21 years (1976-1997) were used to study changes in flood peaks and travel times in the Yasu River basin Japan. The impacts of these changes were simulated by a spatially distributed watershed model (SOWM-YRB). The model generates spatially distributed infiltration excess runoff and integrates the flow in the downstream direction using digital elevation model (DEM). Floods in the study basin originate in steep slopes and are caused by high intensity rainfall during typhoon events. Simulation results indicate the flood simulation component within SOWM-YRB captures properly the effects topography and surface conditions on spatially distributed runoff, flood peak and travel time. Simulation results with 1976 and 1997 landuse data indicate land use change during this time might have caused 18% increase in flood peaks and reduced the travel time. Spatial analysis of runoff maps suggest that urbanizing areas in the basin are contributing significantly to changes in flood characteristics downstream.

1 INTRODUCTION

Flooding is one of the oldest known natural disaster which hydrologists have sought to understand for long time. Despite many years of research this problem continues to cause huge economic losses and deaths globally. This indicate how much is yet to be known about how to deal with floods. In Japan and other South East Asian countries, floods constitute a major natural hazard due to unique morphological and hydrometeorological conditions in this area. Most basins in these countries have rivers flowing through steep narrow gorges on highlands where floods normally originate during typhoon events. Recent examples of flood events which happened under these conditions include the famous typhoon RUSA floods in South Korea in 2002 and floods in Nagoya city, Japan September 2000. It is estimated that The two event above caused economic losses amounting to staggering 1400 billion Japanese Yens and a loss of 246 lives (Takara, 2003). With expected growth of economy and population in this region such losses and even higher ones are likely to happen again in the future. This emphasizes the importance of studying the phenomenon of flood formation in order to mitigate flood disasters.

One of the earliest needs to model river flows seems to have been prompted by the need to study the mechanism of flood formation. Green and Ampt (Green and Ampt , 1911) developed an infiltration model based on the physics of porous media flow as governed by Darcy’s law. Their model appear to be the main basis for understanding the infiltration process and have contributed to the development of many other physical and conceptual approaches for modeling this process. Mein and Larson (1973) used the Green and Ampt concepts to developed an infiltration model applicable for modeling infiltration process under steady state rainfall conditions. Further work on model are reported by Shu (1978) who presented an algorithm for simulation of infiltration process in unsteady rainfall events. The author estimated runoff from a catchment by hand calculations using the developed algorithm and results matched very close to the observed flows. (Shu, 1978).

The understanding of flow phenomenon in river and over land surfaces also have received more less the same attention following the development of infiltration models. Lighthill and Witham (1955) were the first to propose the use of kinematic wave model for river flow routing and specified conditions where the assumptions for kinematic wave approximations hold (Kimaro, 2003b). Other early efforts in this direction include the works of Iwagaki (1955) who examined schemes for solution of the kinematic wave equation and the development of kinematic wave based watershed models by Ishidara and Takasao (1963).

Although most of these pioneering efforts showed a high potential for developing physically based watershed models, the development of such models were hindered by computational constraints and the fact that the enormous amount of information required to make the such models, was not obtainable. These two factors have always been cited as reasons for developing watershed models which have less data and computational demands.

In more recent times the need to understand diverse ecological and environmental problems in integrated water resources management (IWRM), have renewed the interest among hydrologists to develop and apply physically based watershed models. In addition to this, advances in computational technology including storage and processing capacities, geo-spatial sciences and remote sensing support and encourage research and development in the field physically based hydrology. The computational constraints have largely been overcome and remote sensing seems to provide almost an inexhaustible source of information for hydrological applications. Considering the new technology available today one may ask how can it help to solve the traditional hydrological problems such as floods? Can we have more understanding of the hydrological problems using this techniques as compared to time when they were lacking?

This paper attempts to demonstrate how remotely sensed data can be used with a physically based watershed model to understand the formation of floods and their spatial-temporal changes with land use. The study uses a physically based watershed model referred to as SOWM-YRB (Spatial Object Watershed Model of Yasu River Basin). The model is being developed and tested in the Yasu River Basin for assessing the hydrological impacts of catchment environmental changes (Kimaro, 2003b). The structure of the model is flexible and is developed in object oriented environment which can allow different physical models to be linked to simulate most hydrological variables of interest including flow of pollutants. In this paper the structure of the flood simulation component will be introduced with the aim of showing the applicability of remotely sensed land use data to simulate floods. The paper also present a case study of the effects of land use changes on flood flows in the Yasu River basin, Japan caused by land use changes between 1976 and 1997.

2 OVERVIEW

2.1 The Need for Physically Watershed Models (PWM)

Physically based distributed hydrological models aim to represent physical process in a watershed with the effect of physical futures such as vegetation and soil types. The models have different levels of complexity and may require inputs such as rainfall, wind speed temperature etc. Water and energy movement is simulated by applying the laws of mass and momentum conservation. In nature changes in land cover cause changes in the hydrological cycle and in most of the mass energy fluxes which sustain the biosphere and geosphere. The developments in Agriculture, forest management and urbanization affect the physical characteristics of the upper soil layer as well as vegetation which changes the rates of energy moisture fluxes at the soil surface. This in turn affects the amount of runoff, soil moisture and ground water recharge. To describe these effects and their spatial variability, integration of moisture and energy over a watershed required. This seems to be the major reason for efforts made to develop physically based watershed models. In addition to this physical watershed model are being developed to overcome the recognized limitations of their conceptual counter parts. The important feature of a physical watershed model is spatial variation of parameters and inputs which is necessary to capture the variability of the catchment response to hydrometeorological inputs. Investigation of effects of landuse changes which requires spatially integrated catchment response can only be performed using physically based distributed watershed model. Another important factor which seems to have increased a demand for physically based watershed models is the change in management philosophy which now required integrated approach and in managing resources. Integrated Water Resource Management (IWRM) requires physical watershed models of various complexity to investigate the effects of various management options in watershed including landuse planning. These tasks often require models which can give spatially distributed estimates and capture the effects of spatially distributed controls on water quality and quantity which may not be possible using most of the existing models. Advances in GIS, computational technology and Remote Sensing are also contributing to development of Physical watershed models (PMW's).

2.2 Efforts in Modeling the effects of landuse changes on floods

Hydrological effects of landuse changes may be described properly if hydrological processes which are affected by land use changes can be understood and modeled. This does not seem to be an easy task and the effects of landuse changes on the movement of water and pollutants in a catchment are still largely unknown. The main problem seems to be how to represent the effects of landuse on different hydrological process vulnerable to landuse change and how to sum up their spatially variable effects over the catchment to determine how land use change affect the hydrology of the catchment.

Niehoff *et. al*, (2002) modified and used the WaSIM-ETH model to study the influence of alternate land use characteristics on floods in Lein catchment S.W Germany. The study utilized a land use modeling Kit (LUCK) to generate scenarios of land use in the future based on the current trends in land use. One of the important findings in their study is that land use change tends to have more impact on floods in catchments or flood events where infiltration excess overland flow is the dominant flow generation mechanism. The flood simulation in their model included representation of micro-pore and macro-pore infiltration which together determine the total infiltration in modeling overland flow. The micro-pore component also included the effect of saltation on the infiltration rate which was modeled with land use dependent parameters (Niehoff *et. al*., 2002). Their model was able to detect changes in flood peaks for different scenarios of land use and demonstrated the applicability of physical concepts in watershed modeling.

Kim *et. al.* (2004) applied a fully distributed process based model hydrological model for investigating the impacts of land use changes on base flow in Anseong-Cheong watershed, South Korea. The model was grid based and calculated water balance of each grid with sub-models whose parameters depend on land use. Land use maps for different years were used to detect changes which occurred to river flow between 1989 and 1996. The inclusion of the effect of impervious land-cover in base flow formation enable the effect of the growth of the urban area in the catchment on the base flow to be detected. The model is also said to be accounting for changes in water holding capacity of the grid cells the fact which enabled it to detect decrease of average discharge at two stations in the study basin. The incorporation of the evapotranspiration component in the model which is affected by land use change through albedo enabled this model to simulate the impact of growth of the urban area and decrease in forest cover on river flow.

In another study Kim *et. al.,* (2002) used a WMS-HEC-1 model to investigate the effects of land use changes on runoff in Anseong-Chen watershed, South Korea. WMS-HEC-1 model simulates floods based on the curve number (CN) method of the Soil Conservation Service (SCS) of the department of Agriculture USA. The Curve numbers are related to runoff empirically (Rawls, 1993) In their study the landsat images were used to map land use changes between 1986 and 1999 at four year intervals. Seven land use classes were distinguishable in the classified data including forests, paddy fields, uplands/orchards, grasslands bare fields and water bodies. The CN based methods represent the effects of landuse by a numerical value related to flood generation potential of an area such as watershed. A comparatively high CN value after landuse change indicates increased runoff while a low value indicate decrease in runoff. In the study at Anseong-Cheong (Kim *et al*., 2002) changes in runoff were detected using this methods with CN numbers calculated from remotely sensed land use data at sub basin level.

One important limitation of CN based models in detecting the effects of land use changes is that the hydrological response is lumped at the sub catchment level and therefore some effects of land use changes may be lost through averaging. Another problem of applying this method is that CN information must be available which is generally possible in USA (Rawls, 1993) but difficulty else where. However if this information is available the method may present the most useful technique for simulating the impacts of land use changes. The CN method utilizes much information and is therefore expected to have much higher accuracy if soil and landuse information is sufficiently available. The basic parameters defining the CN are soil group (A-D), the antecedent moisture condition (AMC), and land use (Rawls, 1993). Detailed information such as land use treatment, textural soil classes and assumed initial conditions attempt to capture more spatial variability in catchment response which is highly desirable for modeling the hydrological impacts of land use change. This suggests that if a grid based watershed model which integrates runoff spatially is used, the method could possibly yield better results. Further examples of using the CN based watershed models are discussed by Schultz and Engman (2000).

It must be noted also that the CN method require highly detailed landuse information and this may need to be considered in selecting the resolution of land use data or when acquiring and processing remotely sensed data. For example within the urban area CN numbers may vary depending on treatment and soil types. However most studies do not have such detailed information including the case studies reviewed here. The use of this method therefore may involve a considerable subjectivity in allocation the curve numbers which can affect the expected results.

This brief discussion of watershed models used for investigating effects of land use change on floods suggest that care must be exercised in selecting the type of models to be used for studying the effects of landuse changes. It appears as suggested by (Niehoff *et. al*, 2002) that infiltration excess over land flow is one of the hydrological processes most vulnerable to land use change and where such process dominates the formation of flood then the effects of land use change can be studied by modeling this component with land use dependent parameters. It may be observe here that the effects of land use changes on the infiltration and surface storage seems to be well recognized and incorporated in different models and methods such as CN based models and the WaSiM-ETH model (Niehoff *et. al,* 2002). On the hand the effects of land use change on the water movement over the catchment do not seem to be well considered. From the modeling point of view it may be seen that the effects of land use on water movement over the basin may have considerable impact on the shapes of flood hydrographs and therefore need to be considered explicitly. The inclusion of this effect in simulated results depends on how the spatially produced run off is integrated downstream. This means that parameterization of this process with land use dependent parameters is necessary if the effects of landuse changes on the movement of flood downstream is to be modeled.

3 THE STRUCTURE OF SOWM-YRB FLOOD SIMULATION COMPONENT

The objective of developing this model is to make a modeling system which can simulate water and pollutant movement in a watershed considering the effects of management and natural factors. The Object Oriented approach is adopted such that the watershed model can incorporate process models as well as physical features controlling water movement such as dams, diversion, etc (Kimaro 2003b). The flood simulation component of the model is introduced briefly below.

3.1 Infiltration component

The model consist of component at each grid to generate infiltration excess runoff depth which is provided as input to the routing scheme (Kimaro, 2003b). The infiltration component is based on the Green and Ampt infiltration model (Green and Ampt, 1911). Gross rainfall at ground surface is converted into time variable runoff depth depending on soil and surface conditions. The governing equations of this component as appear in Kimaro (2003b) are;

$$t_p' = \frac{1}{K_s}(F_p - S_f M \ln(1 + F_p / MS_f)) \tag{1}$$

$$f = K_s + K_s S_f M \ / F_p \qquad for \quad t > t_p \tag{2}$$

$$M = \theta_s - \theta_i \tag{3}$$

$$P_g \Delta t = \Delta F + \Delta S + RO \qquad 0 \le S \le D \tag{4}$$

where F is the infiltration volume, tp' is time required to infiltrate volume Fp, θ_s is soil porosity, θ_i is initial soil moisture, S_f is the effective suction head, K_s is saturated hydraulic conductivity and f is the infiltration rate. Others are D surface storage capacity, S variable for water stored in D, runoff volume RO and M initial soil moisture deficit. Important parameters in this model as regards the current study are K_s, M and D. These parameters control the volume of generated runoff depth depending on the initial soil moisture, soil type and surface conditions. The parameter for surface storage D is related to landuse in such a way that it allows runoff to form quickly in well drained surfaces and delays runoff from rough and rugged surfaces. Lower values of D indicate well drained surfaces such as urban areas while higher values indicate poorly drained areas.

This formulation is mainly expected to enable the model capture the effects of soil types land use on flood volumes. However It may be argued that the parameterization can also influence the flood peak and travel time downstream. Water retained on the surface continues to infiltrate into the ground after the rainfall event and a balance of this amount between storms contributes to the initial conditions in subsequent events. The infiltration component may be subject to further improvements such as inclusion of the effects of macro-pores and siltation Niehoff (2002) but the current formulation seems to be sufficiently detailed to reveal effects of land use changes on floods.

3.2 Routing scheme

The model uses the DEM data (Geographic Survey Institute (GSI), Japan) for delineating the watershed and to provide a flow direction map used for integrating runoff spatially. Topography of the watershed is represented by both flow direction and slopes as defined at arbitrary spatial resolution by aggregating the original 50m DEM grids into coarser resolutions.(Kimaro, 2003a). The integration of flow downstream is performed by kinematic wave routing over grids intended to capture the effect of land use on the movement of runoff downstream. It is considered that one of the main causes for changes in flood characteristics associated with landuse changes comes from the effect of landuse on the routing process.

Considering the routing process, it may be seen that the model uses only one parameter and it does not necessarily require calibration to obtain it. This seems to be an important advantage for analysis of the effects of land use changes which would not be possible or at least biased if calibration was necessary.

It may be seen here that the applicability of the model is mainly dependent on availability of spatial data of land use, soil, DEM and distributed rainfall as input. The inclusion of process models utilizing these data sets is the primary research topic in this study which is expected to lead to development of improved process models and recommendations on the quality of collected spatial data for flood simulation purposes. It may be noted here that issues of uncertainty in hydrological predictions which have become exceedingly important in hydrological sciences recently, can be addressed using the proposed approach by investigating how improved process description and data collection can reduce the uncertainty of model prediction.

4 APPLICATION OF THE MODEL

The proposed model was applied in the Yasu River basin, Japan to test it's applicability for investigating the effects of land use changes. Remotely sensed Landuse data (GSI, Japan) for 1976 and 1997 at 100m spatial resolution was used. The data has a legend which distinguish 14 different types of land use (Kimaro, *et. al.*, 2003a). The basin is predominantly forested in the upper part and has paddy fields in the lower flat lands. Notable changes in land use obtained by comparing the two land use maps indicate growth of the urban area, conversion of forest patches into golf courses and decrease of paddy fields.

River channels run through steep narrow gorges in the north eastern highland area where the main river originates and precipitation is high during typhoon events. A digital elevation model of the basin at 50m resolution was used to derive the flow network which compares fairly close with the digitized channels.

Water level data at the target station for this analysis (Yasu) is available at hourly time intervals from 1975 to date. Regularly updated rating curves which consist of different curves for every season within the year are available for most of the years at the station. During floods independent measurements are of flow rates are also taken and they show that flows estimated by rating curves make a good estimate of flood flows. (Kimaro, 2003b). This relatively high quality flow data has advantage for investigation of the effects of landuse changes since the model is not calibrated using the measured flow and errors in the flow data may exaggerate the predictions.

Rainfall data obtained at four selected stations was used to generate the distributed input by ordinary Kriging. Other possible options available for generating distributed rainfall include Thiesen polygon and distance weighted method (Kimaro, 2003a). The effect of the spatial model of rainfall on simulations is subject to further analysis but ordinary Kriging was selected since it has been recommended in comparative studies including (Guilermo and Salas 1985). The soil map of the basin is not yet compiled and soil parameters in the model were assumed and kept spatially constant. Land use data was used to specify spatially distributed roughness coefficients and the surface storage effects were neglected in the current application.

5 RESULTS AND DISCUSSION

The results of modeling exercise are presented using runoff maps and hydrographs. The model is configured to output hydrograph and runoff map for any location in the basin for visual analysis. All spatially distributed inputs and results are in raster format importable to common GIS software for presentation.

5.1 Changes in flood peaks and travel time

Fig. 1 shows the hydrograph at Yasu gauging station during flood event on 30th September 1994. The hydrograph produced with 1997 landuse data is assumed to be more closely related to the expected hydrograph by assuming that land use conditions in 1994 are similar to 1997. The trial and error tuning of the initial soil moisture (parameter M eq.3) was necessary to match the observed and estimated peak flows. The infiltration parameters for this event are K_s =0.0034 and M=0.242. Similar parameters and conditions were used in simulating the same event with 1976 land use data. The simulated hydrograph in this case deviates significantly from the estimated hydrograph produced with 1997 land use data. The timing of the flood peak at Yasu is delayed and the magnitude of the peak flow is reduced. The results shows that the model is able to capture the effects of land use change on these parameters as emphasized in the model structure. The qualitative effects of land use changes seem to be sufficiently described and a hypothesis that landuse change in the study basin do not have effects on flood peaks and travel time may be rejected.

The results also indicate the importance of proposed structure of flood simulation component as described in section 3.2 It may be noted that different methods for routing spatially generated flow to downstream location are available and they way they include the effects of land surface on the routing process may differ. The results of this study seem to suggest that if the effects of landuse is properly included in routing model, estimates of flood peaks and travel time and their changes with land use can be made. This may also help to improve flood forecasting using physical watershed models.

In addition to these observations it may also be seen that components of hydrograph or spatial data which were neglected in this simulation are important for simulation of the volume of floods. This is highlighted by the fact that even though the raising limb and flood peak are fairly close to observed graph, the falling limb is obviously far from the observed hydrograph. The reason for this may be due to that the fact that the model only routes the infiltration excess runoff which at grid level stops immediately after the storm. The need for including other hydrograph components to increase the accuracy of estimated flood volumes is recognized. Together with the recommendation for further modeling efforts, data collection to describe the spatial variability of soil properties and if possible initial soil moisture is suggested.

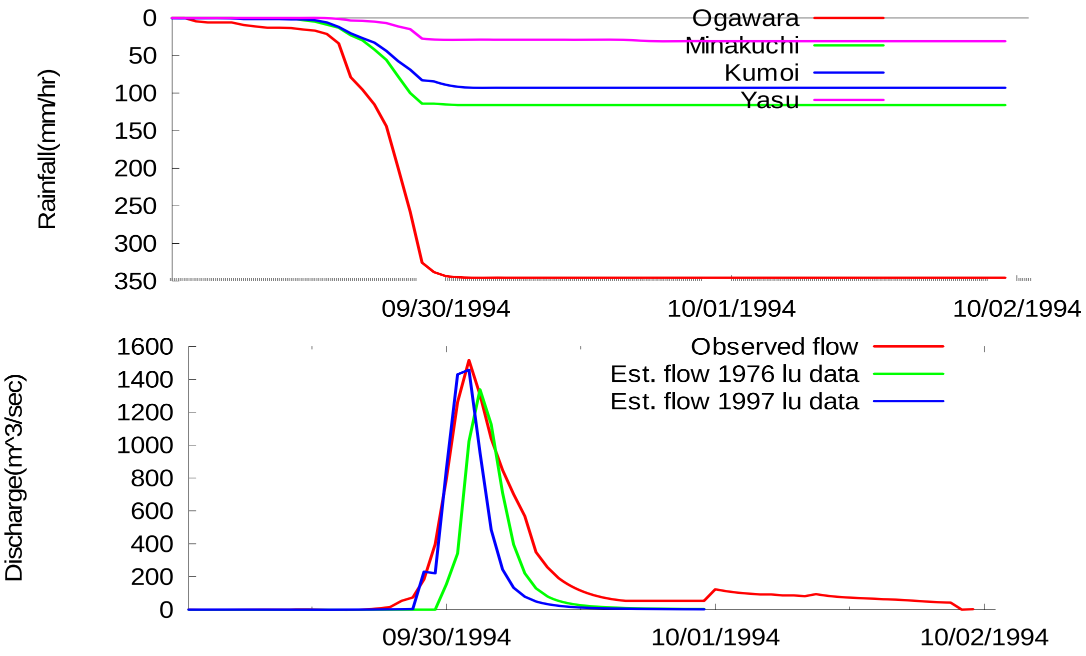

Figure 1. Effects of landuse on estimated floods at Yasu River Gauging station during typhoon event in 1994.

5.2 Spatial Integration of flood runoff using DEM

The proposed structure of flood simulation component in SOWM-YRB integrates the flow downstream using the digital elevation model and a kinematic wave analogue. This provides runoff maps as shown in Fig. 2 which may be useful in studying the flood generation process in detail. The runoff maps presented are for the same flood event discussed in 5.1 above and in this case land use data for 1997 is used. The effect of topography and rainfall distribution is clearly seen by tracing the development of the flood with time. The flood developed on the northern part of the catchment (Kashiki sub catchment) and moved faster to the downstream because of higher elevation in this area. The profiles of Kashiki and Ukawa rivers shown in Fig. 3 explains this clearly. Fig 2 shows clearly how the model captures the effects of topography and surface conditions in generating a flood. This may enable the timing and magnitude of the developing flood at any location in a catchment to be estimated. Although estimates at the outlet compares well with observation further studies to check the accuracy of the spatially estimated runoff e.g by periodic observation of runoff during floods at more points upstream is considered helpful in understanding the response of the watershed to typhoon events. Obviously this data will help a great deal in improving the model by showing which processes need to be captured at different locations to improve the runoff estimation at watershed outlet. The greatest advantage of this model in addition to providing runoff estimates is that it helps to identify the data needed for water resources management by suggesting which data is necessary and which places to sample.

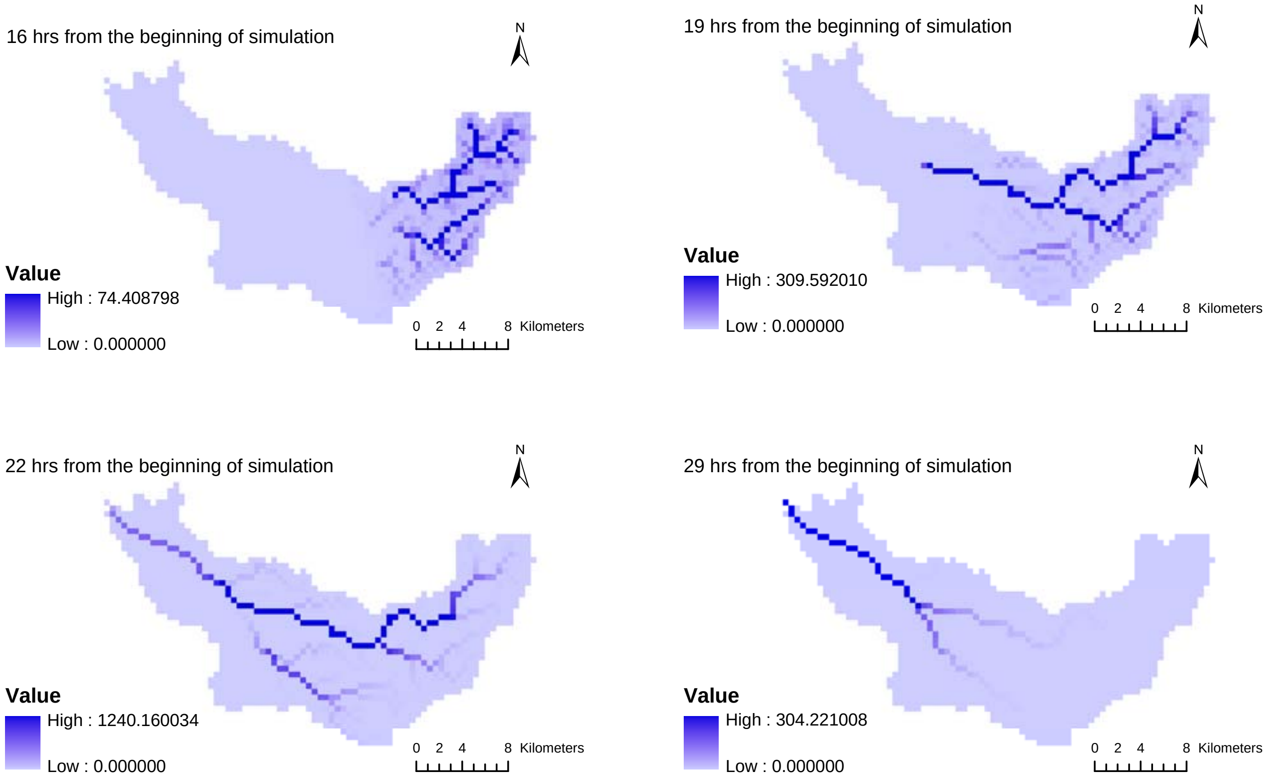

Figure 2. The generation of flood runoff during a typhoon event in Yasu River basin in 1994

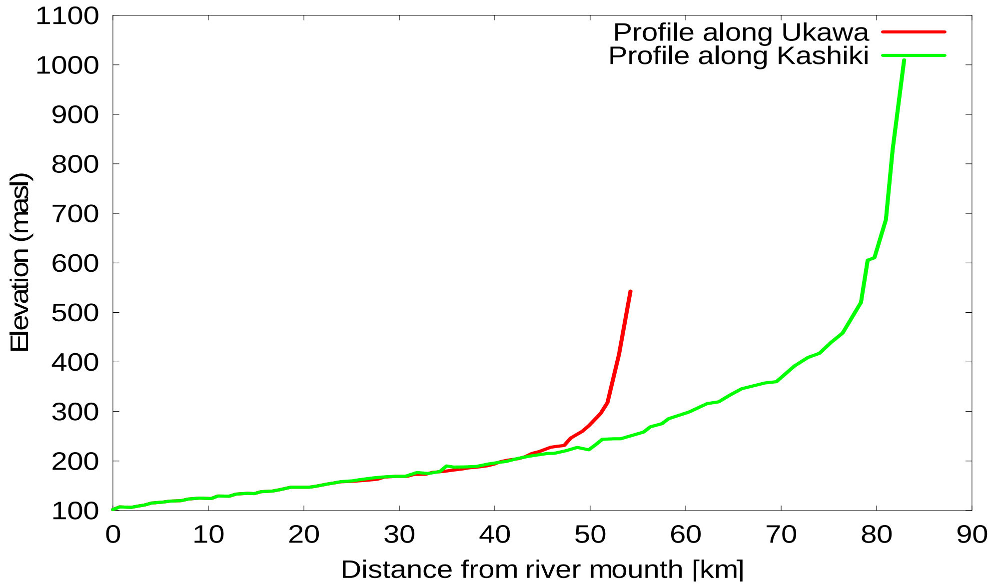

Figure 3. River profiles for main tributaries in Yasu River basin

5.3 Detecting the effects of localized land use changes

Detecting the effects of local land use changes on floods is desirable for landuse planning to reduce the volume and flood peaks. If such effects can be detected then effects of proposed developments in the basin can be evaluated and proper decisions be made. We propose to investigate the effects of localized land use changes by comparing the runoff maps produced with different land use data. Considering the structure of the current flood simulation component, the runoff maps will look very different if soil data and storage capacities are used in simulation. The choice of which flood characteristic to map to show the effects of localized landuse changes on flood runoff downstream is also subjected to further investigations. In the present work a differential map of total runoff at the end of the storm is used to detect effects of localized landuse changes. Fig. 4 shows the distribution of land use changes in the study basin. The scattered dots shows the landuse pixels(100m) whose landuse type changed between 1976 and 1997. Fig. 5 shows the difference in total runoff generated on each grid using 1976 and 1997 land use map at a selected instant from the beginning of the storm. It may be seen that the pattern of land use change and the runoff changes is similar which indicate that effects of land use on spatial pattern of runoff generation might have been well captured

The interpretation of the land use data for this case indicate that more runoff is generated because of urbanization in the area comprising of the Ukawa sub basin.. The analysis highlights the significance of the types of land use changes which happened in this area on flood generation behavior of the catchment. Further studies on this may pave way for developing techniques for investigating the effects of localized land use changes on flood runoff downstream. It appears that with more close estimation of other surface properties such as storage and soil parameters more close estimates of quantitative effects of land use change in the basin can be made.

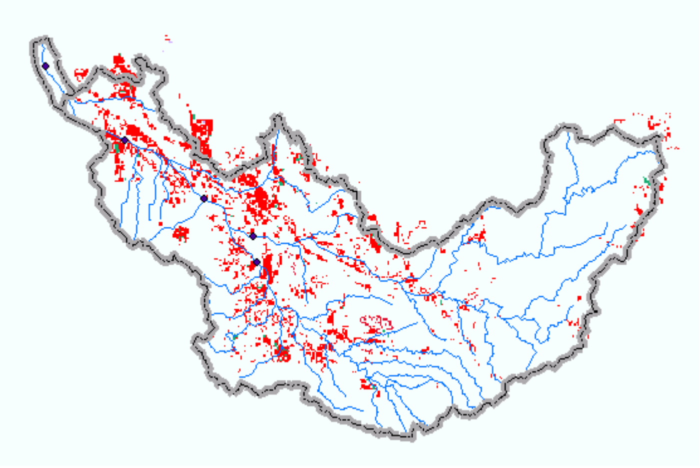

Figure 4. Spatial pattern of land landuse changes in Yasu River basin between 1976 and 1997

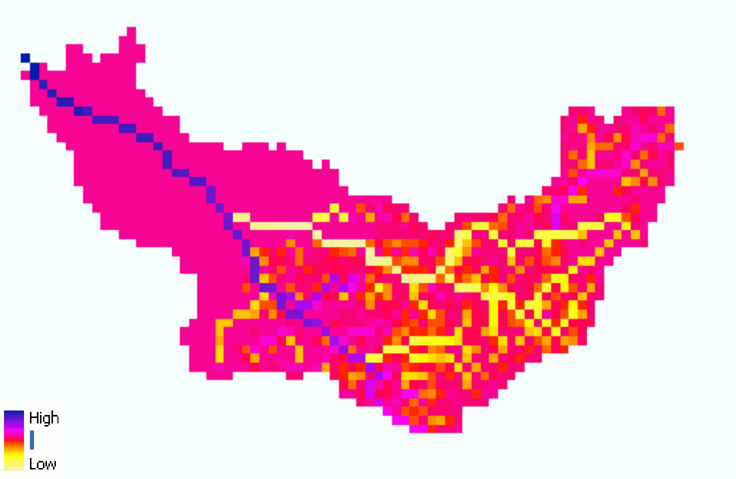

Figure 5. Spatial pattern of changes in flood runoff generation between 1976 and 1997.

6. CONCLUSIONS

This paper has discussed the effects of land use changes on flood peaks and travel times using a proposed structure of the flood simulation component in SOWM-YRB. The effects of land use changes on these two indicators of flood severity seem to be well captured using the current formulation of model. It is therefore recommended to retain the present components in the model even when the need to improve simulation results requires accounting for neglected processes and data. The results have indicated that taking into account factors affecting generation and movement of flood explicitly using data and process models may improve forecast and reconstruction of flood events.

In the realm of hydrology the study seem to suggest that elaborate description of the catchment with data and process models at appropriate scale can help to reduce the uncertainty involved in model predictions. It may interesting to see how more data types and process models reduce the estimation error using simulation experiments as proposed in this study.

The Model setup also may help to understand the problem of prediction on ungauged locations. It may be interesting to see how the estimates of flow further upstream obtained by tuning parameters using flow at the outlet deviates from real observation. This may lead to decision of how many gauging points are necessary in the basin or help to develop techniques for prediction in ungauged sites.

The results seem to confirm the findings of earlier work by Niehoff *et. al* (2002) that the most vulnerable component of flood hydrograph to landuse changes is the infiltration excess overland flow. However it seems that other components of the hydrograph can be affected and they are important to estimate the volume of floods and more investigation of their roles is suggested.

The study indicate remotely sensed data can be very useful for monitoring and prediction of flood disasters. For flood prediction purposes using hydrological models it seems that the most useful data is landuse. The parameters to be derived includes surface storage and roughness. The quality and resolution of remotely sensed landuse data for flood prediction purposes may be determined by considering how such parameters can be derived from the data with high accuracy.

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