MODELLING PRE-CHANNELIZATION & LAND USE CHANGE AND THEIR IMPACT ON FLOOD AND SEDIMENT YIELD OF SIX RIVER CATCHMENTS IN HOKKAIDO REGION

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Abstract

The potential for flood and sediment material is strongly affected by river meandering and changes in land use. Therefore the modelling of pre-channelization and land use change is important with respect to prediction of flood, sediment yield and its on-site consequences. However, the impact of sediment yield in difference environments and how this affects sediment materials delivery to downstream area are incompletely understood. Therefore, modelling of the effects on pre-channelization and land use change could help us to better understanding the alluvial river systems. The proposed model obtained from this study was used to simulate possible past and/or future channelization and land use patterns.

As such, pre-channelization and land use change in six rivers of Hokkaido region were analyzed by comparing two scenarios. Performance of the proposed numerical model was applied to simulate flood events in 1975, 1992 and 1998 to test the hypothesis that pre-channelization and land use change would also be an important component of reducing/increasing flood and sediment yield in Hokkaido region. The results indicate that pre-channelization has a significant impact on flood peak, but no significant effect on sediment yield. In contrast, land use change has significant effect on eroded soil from hillslope, but no significant effect on flood for a large scale river catchment in Hokkaido region.

1 INTRODUCTION

In the recent year, there is widespread evidence of morphology change of upland, intermediate land and lowland river systems of the Japan. They may be caused by climate and human-induced land use change, which have linked periods of upland river erosion and deposition to wetter past climates and the human removal of forest cover and channelization of river systems, respectively. Within alluvial river systems, meandering river can be the important controls of regional flood and sediment material transport. They operate as the interface between channel and floodplain where flood and sediment material are eroded and/or deposited during high flood events. Although the precise effect on channelization of sediment transport processes in an alluvial river catchment is still not clear, there seems to be no doubt that channelization influences sediment yield. During the past 100 years, almost of main river catchments in Japan have been channelized and short-cut to reduce flood peak discharge by flood protection objective. However, the impact on flood and sediment yield in difference environments and how this affects sediment materials delivery to downstream area are not completely understood. Land use change influences land cover, surface roughness and erodibility, which controls hillslope flow velocity and discharge, as well as on floodplain area. Furthermore, there may be rapid shot-term fluctuations between erosion and deposition along channel and hillslope. For the effects on long-term land use change are remained unknown. Therefore, modelling of the effects on pre-channelization and land use change could help us to better understanding the alluvial river systems.

Recently, numerical modelling has been shown to answer some of these problems. A number of works have used catchment-based physical models attempting to simulate river catchment hydrological processes of rainfall-runoff and sediment transport processes, as well as, to study the impact of land use change and climate change. In addition, the numerical model has been used to predict hill slopes and river channels through regular and irregular mesh (eg. Abbott et al., 1986; Kirby, 1987; Howard, 1994; Wicks and Bathurst, 1996; Braun and Sambridge, 1997). Thus, it is clear that the numerical models appear to have considerable potential as tools for investigating small scale/sub-catchments over long periods simulation. However, their ability to simulate flow and sediment in natural river systems characterized by complex slope and channel network has not yet assessed fully. The different approach is taken in this study. Therefore, it would be worth to develop the new strategy to achieve a simple 1-dimensional model with higher degree of accuracy, without additional complexity but taking into account the physical characteristics of the whole river catchment.

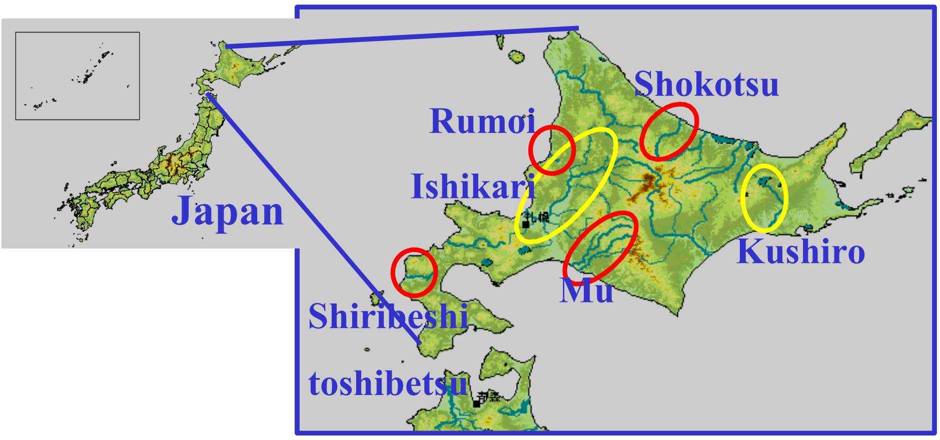

Fig. 1 Study areas.

Table. 1 Characteristics of flow and river catchments.

River Name	Ishikari	Kushiro	Mu	Shokotsu	Shiribeshi-toshibeshi	Rumoi
Area (km^2)	14,330	2,510	1,270	1,240	720	270
Length (km)	268	154	135	84	80	44
Q_{Mean} (m^3/s)	138	27	35	28	25	10
Q_{Max} (m^3/s)	11,330	433	2,949	1,016	1,034	1,166
Population	2,490,000	177,000	15,000	33,000	16,000	30,000
Simulate year	1975	1998	1992	1975	1975	1998

This paper addresses these issues by using a 1-dimensional numerical modelling to simulate the effects on pre-channelization and land use change in alluvial river systems. Performance of the proposed numerical model was applied to simulate flood events in 1975, 1992 and 1998 to test the hypothesis that pre-channelization and land use change would also be an important component of reducing/increasing flood and sediment yields in Hokkaido region.

2 STUDY AREA AND DATA

In this study, the proposed model was applied to six major rivers in Hokkaido Island, which are located at north part of Japan. **Fig. 1** shows the selected six river catchments, which are distributed all over Hokkaido Island. The flow and catchment characteristics of the selected six river catchments are shown in **Table. 1**. The climate in Hokkaido region is temperature with cold, and the precipitation, of which about 50-60% falls as snow, is typically of a relatively low intensity. Mean annual precipitation was 2,200 mm. The types of soil include well drained brown earths (lowlands), peats (lowland and upland), gleys (intermediate land), volcanic ash soil (intermediate land and upland), metamorphic rock and podzols (upland). The land use is closely related to altitude, relief and underlying geology, and varied from wetland and urbanized area in the lowland areas, to arable land and livestock in the lowland and intermediate land areas, shrubbery, pinewood and white birch in the intermediate land and upland areas (**Fig. 2**). **Fig. 3** shows a schematic and conceptual model of the river systems.

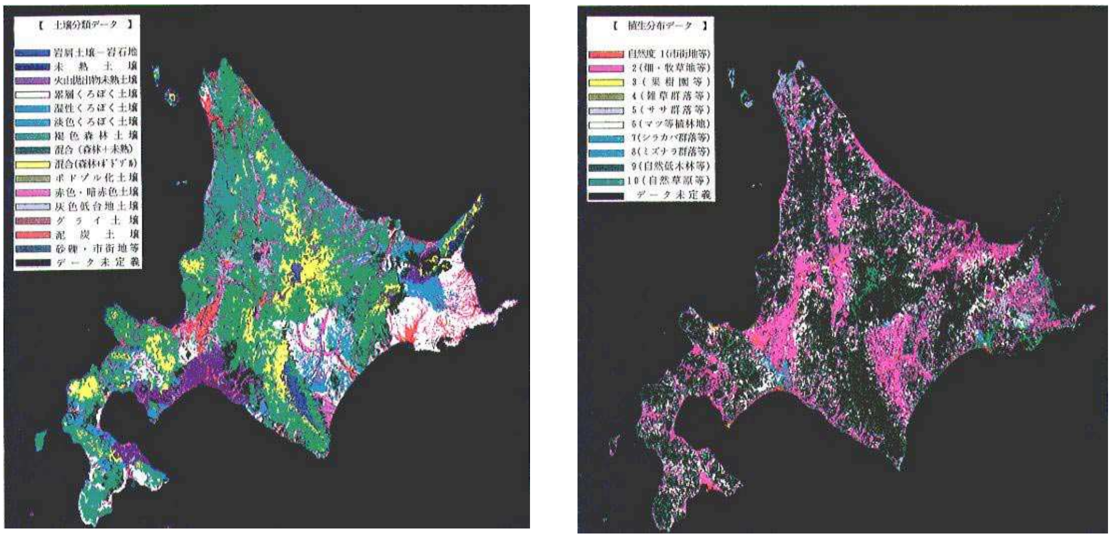

Fig. 2 Geological and land use in study areas.

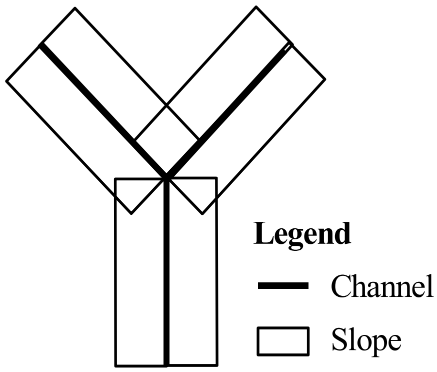

Fig. 3 Schematic and conceptual model of the river systems.

3 METHODOLOGY AND MODEL DESCRIPTION

3.1 Channel flow and sediment model

The set of continuity and momentum equations of 1-dimensional unsteady flow can be expressed as

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial \left(Q^2 / A \right)}{\partial x} + gA\left(\frac{\partial H}{\partial x} + S_f \right) = \frac{q_L Q}{gA^2} \qquad (2)$$

where A = cross-sectional area of flow; Q = discharge; q_L = lateral flowrate; H = water surface elevation ($H = \eta + h$); η = bed elevation; h = water depth; S_f = friction slope; g = acceleration due to gravity; and t, x = time and channel-flow direction coordinate, respectively. The friction slope, S_f, is calculated using rearrangement of the Manning-Strickler's eq. for unsteady flow by

$$Q = \frac{8.9\sqrt{g}}{d_m^{1/6}} A R^{2/3} S_f^{1/2} \tag{3}$$

where d_m = median sediment grain size.

The continuity equation of depth average suspended sediment and volumetric fractional of bed material can be obtained from

$$\frac{\partial}{\partial t}(<c_i> h) + \frac{1}{B}\frac{\partial(Q<c_i>)}{\partial x} = q_{sui} - w_{f_i} c_{bi} + \frac{q_L c_{BLi}}{B} \tag{4}$$

$$\delta \frac{\partial p_i}{\partial t} + p_i^* \frac{\partial \eta}{\partial x} + \frac{1}{1-\lambda}\left[\frac{1}{B}\frac{\partial(q_{Bi}B)}{\partial x} + q_{sui} - w_{f_i} c_{bi} + \frac{q_L c_{BLi}}{B}\right] = 0 \tag{5}$$

where $<c_i>$ = depth average suspended sediment concentration; B = channel width; q_{sui} = pickup rate; w_{fi} = fall velocity (calculated by Rubey's eq.); p_i = volumetric fractional of bed material; q_{Bi} = bedload; c_{bi} = reference concentration; c_{BLi} = reference concentration of lateral flow; δ = exchange layer thickness; and λ = void ratio (λ = 0.4). The time dependent change of bed elevation calculated by the following continuity of bed material transport.

$$\frac{\partial \eta}{\partial t} + \frac{1}{1-\lambda}\left[\frac{1}{B}\frac{\partial \sum_i (q_{Bi}B)}{\partial x} + \sum_i \left(q_{sui} - w_{f_i} c_{bi}\right) + \frac{\sum_i (q_L c_{BLi})}{B}\right] = 0 \tag{6}$$

where $\sum_i$ = summation of bed material transport load. The amount of bedload and suspended load of sediment transport rate per unit width is determined using the Ashida-Michiue (1972) and Itakura-Kishi (1980), respectively.

3.2 Slope runoff and erosion model

A slope runoff is used to generate a combine surface flow and interflow that is governed by the kinematic wave equation, which can be express as

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial X} = r_e \tag{7}$$

$$q = \begin{cases} kS_0 h/\gamma & for \quad 0 < h < \gamma D \\ \alpha(h-\gamma D)^m + kS_0 h/\gamma & for \quad h \geq \gamma D \end{cases} \tag{8}$$

where h = water depth; q = unit discharge; r_e = effective rainfall intensity; k = infiltration rate; γ = void ratio; D = layer thickness; $\alpha = \sqrt{S_0}/n$; S_0 = bed slope; n = Manning's roughness coefficient; m = 5/3; and X = slope-flow direction coordinate. By neglecting the change of slope elevation, mass conservation of the sediment and volumetric fractional of bed material can be given by (Wongsa et al., 2002)

$$\frac{\partial(c_i h)}{\partial t} + \frac{1}{B}\frac{\partial(c_i Q)}{\partial X} = D_{ri} + D_{fi} - D_{di} \tag{9}$$

$$\delta \frac{\partial p_i}{\partial t} + \frac{1}{1-\lambda}\left[\frac{1}{B}\frac{\partial(q_{Bi}B)}{\partial X} + D_{ri} + D_{fi} - D_{di}\right] = 0 \tag{10}$$

where c_i = sediment concentration; h = water depth; Q = flow discharge; D_{ri} = rainfall detachment rate; D_{fi} = overland flow detachment rate; and D_{di} = deposition rate.

3.3 Floodplain and deposition model

Overflow from channel to floodplain or vice versa can be obtained by the broad crested weir type formulas, which can be express as

$$Q_0 = \begin{cases} Ch_{fl1}W\sqrt{2gh_{fl1}} & ,C = 0.36,\ h_{fl2}/h_{fl1} < 2/3 \\ Ch_{fl1}W\sqrt{2g\left(h_{fl1} - h_{fl2}\right)} & ,C = 0.91,\ h_{fl2}/h_{fl1} \geq 2/3 \end{cases} \quad (11)$$

where Q_0 = overflow discharge; h_{fl1} and h_{fl2} = flow depth at channel and floodplain, respectively; W = overflow width; C = overflow coefficient; sub-description $_{fl}$ = floodplain. By neglecting the pick-up rate term, deposited height of sediment in floodplain areas can be obtained from

$$\frac{\partial \eta}{\partial t} - \frac{1}{1-\lambda}\sum w_{fi} c_{bi} = 0 \quad (12)$$

In this study, The CIP (Cubic interpolation pseudo-particle) method was used for application of the equations of channel flow model, an upwind finite difference scheme for sediment transport model, slope runoff, erosion and floodplain deposition model. Calculated time steps were varied according to the CFL (Courant-Friedrichs-Levy) stability condition.

3.4 Set-up for the simulations

In the proposed model application, cross sectional geometry was taken from analysis of the surveyed channel cross-sections, and for simplicity, rectangular cross-sections were used. Initial conditions were set for discharge at most upstream end, normal depth and zero depth for channel and hillslope, respectively. For the boundary conditions, water depths were set at confluents, assuming discharge and free flow conditions were adopted for upstream and downstream boundaries, respectively. Before the hillslope runoff and channel sediment calculation was carried out, the model was run to provide the steady state of necessary flow variables.

For channel model; Δx = 1,000 and 500 m, slope runoff model; ΔX = 200 and 100 m, n = 0.5-1.0, k = 0.025 m/s, γ = 0.2, D = 0.3-0.5 m and Δt = 2.0 and 1.0 s; have been used for model simulation. Averaged drip height from canopy, percentage of canopy drainage falling as leaf drips, and drip diameter from canopy are 2.0 m, 80%, and 0.0025 m, and for the sediment components k_r, k_f, C_g, and C_c are 20.0, 0.0005, 0.8 and 0.8, respectively. In this study, 15 particle sizes of 0.01 to 400 mm from the surveyed were used to represent bed material grain sizes distribution at each computational grid, which was initialized by standard distribution.

4 RESULTS

4.1 Model validation

Performance of the foregoing numerical scheme was applied to simulate flow and bed material load of the extreme flood events in 1975 for Ishikari River, Shokotsu River, Shiribeshi-toshibeshi River, Rumoi River, 1992 for Mu River, 1998 for Kushiro River (**Table. 1**). The comparison of time series of measured and simulated flood discharge at major gauge stations are shown in **Fig. 4**. It was found that the overall magnitude of the flood discharge and peak are simulated well and reasonably good accuracy. By contrast, the simulated results of recession period are slightly faster than the measured data for all simulation. As such, when the model of effect on overflow and return flow from floodplain/swamp area was included in the proposed model, better results were obtained. It suggests that the overflow and return flow from floodplain/swamp area are important in controlling the flood phenomena. A possible explanation for this might be influenced from the storage of water in dams during the initial phase of the flood and return flow from floodplain/swamp, which cannot be explained by only 1-dimension floodplain model.

The ε of Nash and Sutcliffe (1988) and coefficient of determination (R^2) have been used as the main criteria to judge whether the data fitted between measured and simulated. They were observed that the values of ε and R^2 for Hokkaido region at major gauge stations for calibration period are greater than 0.9, indicating well fit between measured data and this proposed model (**Table. 2**). However, the values of ε and R^2 for Kushiro River catchment was less than 0.8, which was caused by the complexity of geological and soil cover in this area, of which, volcanic ash (intermediate land and upland areas) and wetland areas at downstream.

Fig. 5 shows time series of sediment materials at Ishikari Bridge and Mukawa gauge stations for Ishikari River and Mu River, respectively. The changes of eroded soil materials were synchronous with the rainfall, however, it had not much apparent effect on bedload. It is very interesting that a time lag between suspended load and bedload has been observed and the amount of suspended load was remarkably 5-6 times larger than bed load during the high flood periods. The sediment yield for Ishikari Bridge gauge station of eroded soil from hillslope, bedload, suspended load and total load from channel for simulated present scenario are 4.73, 271, 1,190 and 1,461 tons, comparing with the values of 1,423 tons, in which determined from empirical suspended load formula of the major gauge stations during the same period. It was found that eroded soil from hillslope during simulated period is only 0.4% of suspended load, of which reproduced the same trend in the other river catchments. However, the amount of measured data and/or empirical formula for bedload and eroded soil is not available.

4.2 Model simulation

For model simulation, the selected six river catchments were analyzed by comparing with pre-chanelized and land use change scenarios. The simulation used the same calculated conditions as a model validation case.

4.2.1 (1) Pre-channelization simulation

The pre-channelization scenarios were used, in which the main channel length was increased to 15 and 30%, respectively. The comparison of time series of measured and simulated flood discharge at the major gauge stations are shown in **Fig. 6**. It was found that the magnitudes of the flood peak decreased between 5.8-20.7%, and times to peak were delayed when main channel lengths were increased. Good performance of simulated results was observed in both flow and sediment characteristics, therefore, indicating that model validation is reasonable. **Fig. 7** shows sediment deposited height distribution for Ishikari River, of which about 0.10-0.30 m deposited in floodplain areas. The sediment yield of bedload, suspended load and total load in two scenarios were decreased between 0.4-5.3% when comparing with the result from present scenario. Similarly, the deposited height of sediment on floodplain areas also increased. It can be caused by the effect on channel bed slope, which is going milder when a channel length is increased and prolonged period of inundation. There is a decrease in magnitude of the flood peak discharge, but no significant change was observed on sediment yield by pre-channelization simulation study.

4.2.2 (2) Land use change simulation

Although the effect on land use change from forest and swamp to arable land or vice versa is still not clear, there seems to be no doubt that land use change influences the river catchment hydrologic processes. The effect on land use change on the Hokkaido region catchments were investigated by running the model with several land use scenarios. The ground cover and canopy cover was decreased for reproducing the effect on the vegetation in increasing eroded soil from hillslope. Possible past and/or future land use patterns were generated by reducing forest and grassland area (**Fig. 2**), in which the sediment components C_g, C_c were alternated to two scenarios (0.9 and 0.7). The hillslope surface cover roughness coefficients were also altered in the same time.

Fig. 8 shows time series of simulated flood discharge when the decreasing/increasing of land cover coefficients flood peak changed between ∓ 2.5% for a large scale river catchment (Ishikari River), but flood peak changed upto ∓ 15.0% for a small scale river catchment (Mu River, Rumoi River, etc.). The eroded soil materials were increased between 2.5-7.1% when land cover coefficients were decreased, but bedload materials were decreased. The time to peak flood was faster than present condition when land cover was decreased, in which this characteristic is adverse from pre-channelization simulation study. It was indicated that land use change from forest to arable land or vice versa, influences land cover, surface roughness and eroded soil. This effect consequently increased flow velocity and erodibility on hillslope. It is noteworthy that hillslope eroded soil did not respond to dwy and scanty rainfall event, but there was substantial response to prolonged period and intensive rainfall event. However, the effect on land use change within the Hokkaido region has been very small compared with the predominant factor controlling the generation and severity of flood events, the rainfall. The overall of simulated performance with rainfall runoff and eroded soil on hillslope, flow and sediment transport in channel indicated that the proposed model might be expected to give accurate results for unsteady flow problems. As a consequence, it is difficult to quantify accurately and to make a comparison with measured data.

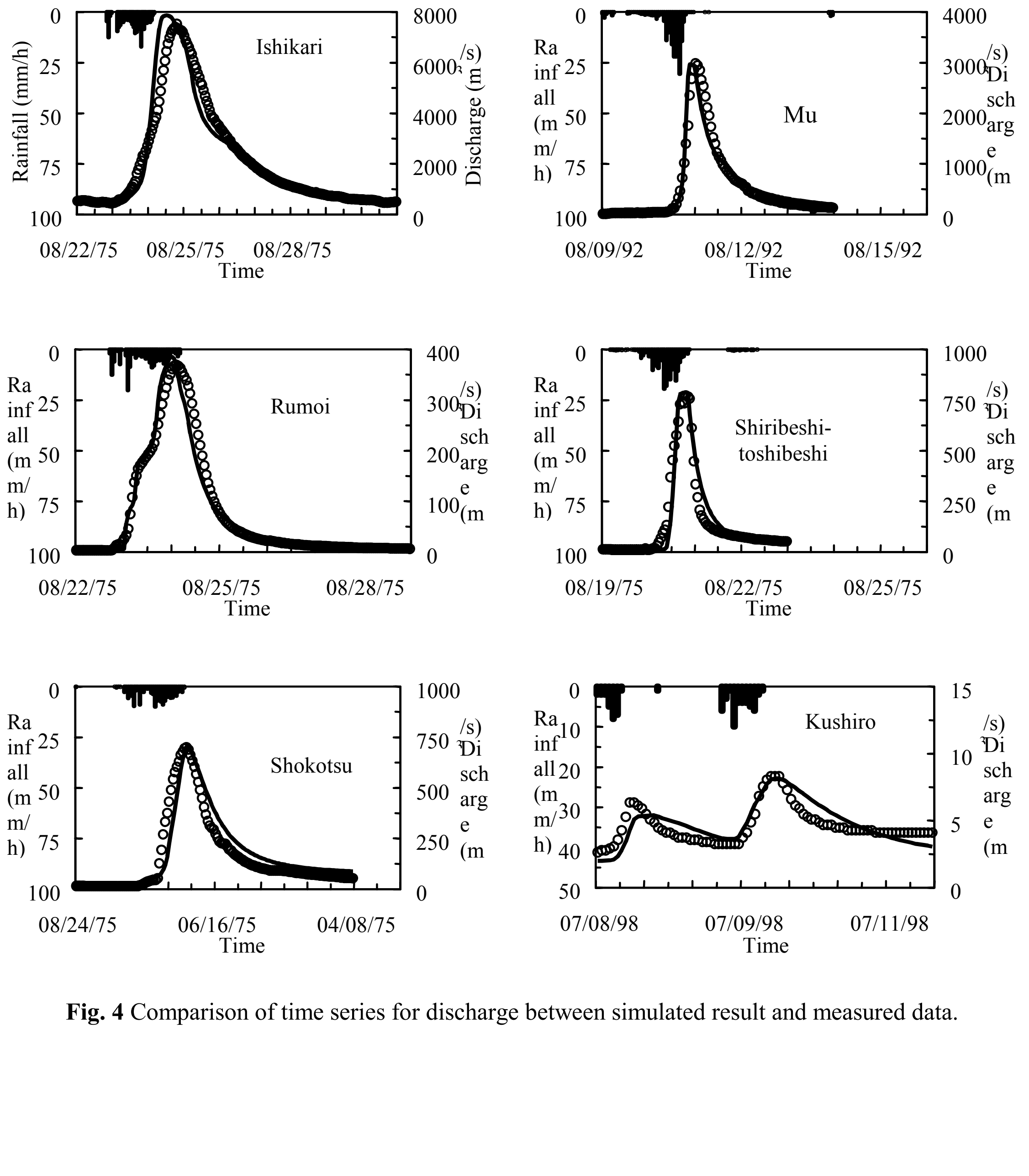

Fig. 4 Comparison of time series for discharge between simulated result and measured data.

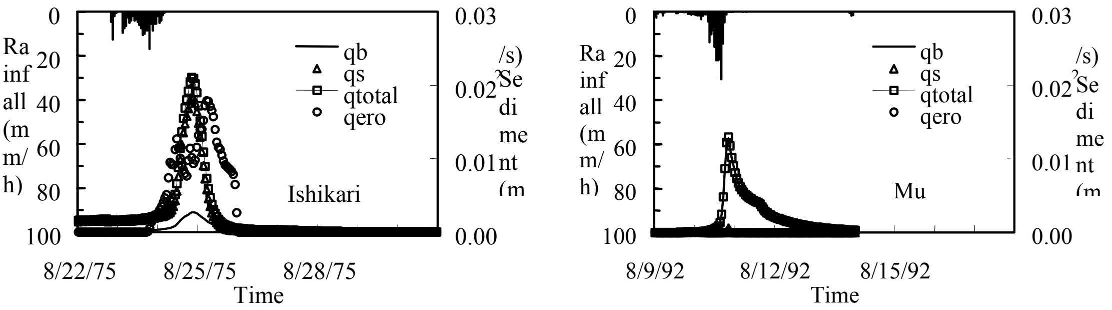

Fig. 5 Characteristics of sediment materials for Ishikari Bridge and Mukawa gauge stations.

Table. 2 The values of ε and R^2 for Hokkaido region at major gauge stations.

River Name	Ishikari	Kushiro	Mu	Shokotsu	Shiribeshi-toshibeshi	Rumoi
ε	0.9237	0.6709	0.9335	0.8783	0.9261	0.9601
R^2	0.9705	0.8497	0.9670	0.9423	0.9666	0.9768

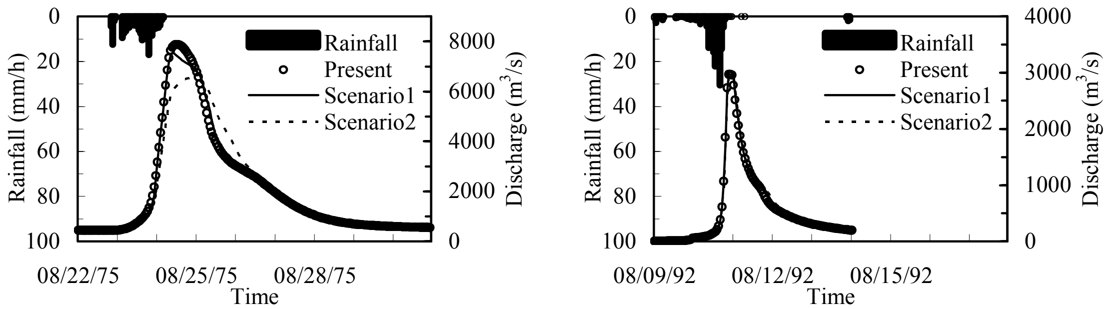

Fig. 6 Pre-channelization effect on flood for Ishikari River and Mukawa River.

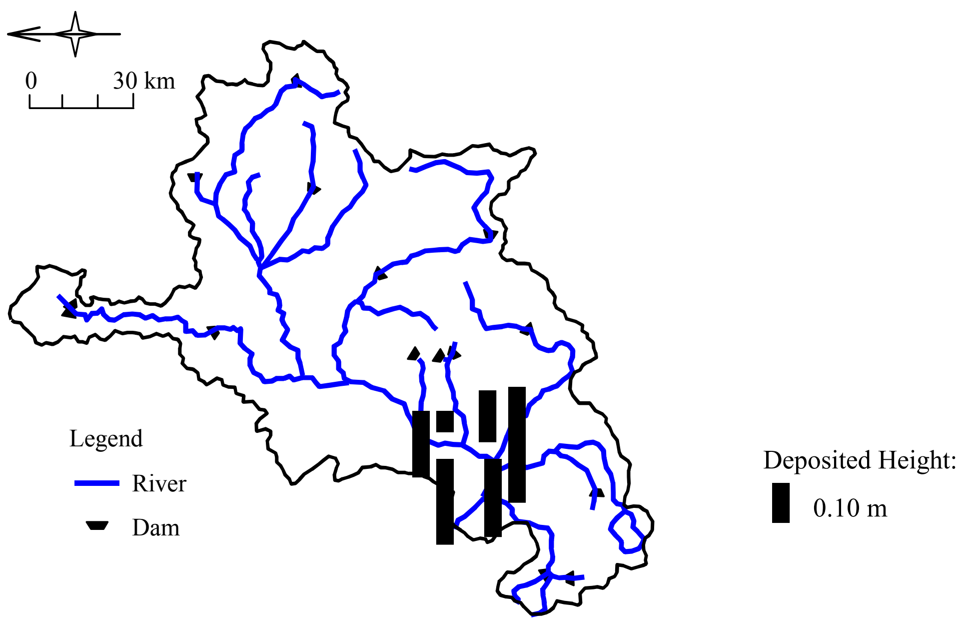

Fig. 7 Deposited height of sediment on floodplain areas for Ishikari River.

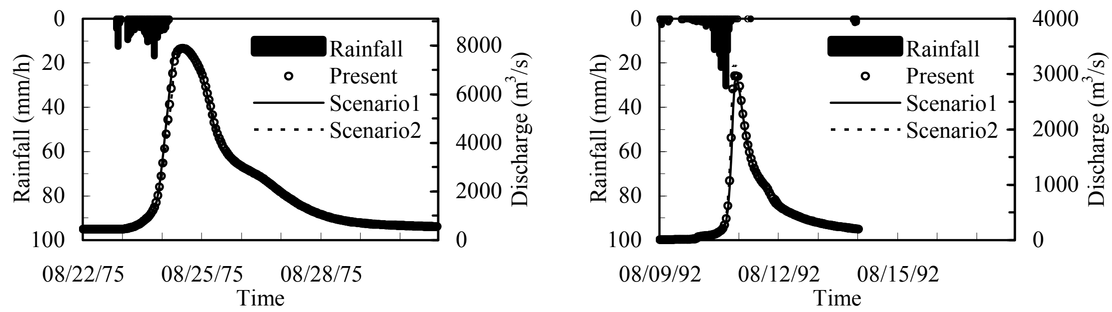

Fig. 8 Land use change effect on flood for Ishikari River and Mu River.

5 CONCLUSIONS

In this paper, a 1-dimensional model considering slope runoff and channel flow with sediment material transport is presented to assist in predicting the consequences of pre-channelization and land use change. The outcome of this simulation can be used to assess flood, sediment material and eroded soil risk planning. The extreme flood events in 1975, 1992 and 1998 of the six selected river catchments in Hokkaido region were used to verify the numerical model. This proposed model satisfactorily predicted the flood discharge and sediment yield with good agreement, excepted for Kushiro River. In addition, the proposed model was exploited to simulate possible past and/or future pre-channelization and land use patterns. The results indicate that pre-channelization has a significant impact on regional flood, but no significant effect on sediment yield of river catchments in Hokkaido region. In contrast, land use change has no significant effect on flood, but has significant effect on eroded soil from hillslope for Hokkaido region. Furthermore, it should be extended to simulate by considering mainly the scale of months to a year. It should also include a snowmelt module. Such developments are in progress.

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