MODELLING PRE-CHANNELIZATION AND THEIR IMPACT ON FLOOD AND SEDIMENT YIELD IN ISHIKARI RIVER BASIN

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The potential for flood and sediment material is strongly affected by river meandering and changes in land use. Therefore the modelling pre-channelization and land use change are important with respect to prediction of flood, sediment yield and its on-site consequence. A combination of land use transformation maps and soil properties shows certain decision rules for the conservation of forest into arable or vice versa. The proposed model obtained from this study was used to simulate possible past and/or future pre-channelization and land use patterns. Consequently, the outcome of this simulation was employed to assess flood, sediment material and eroded soil risk under different scenarios. Pre-channelization and land use change in the Ishikari river basin were analyzed by comparing three scenarios. The results indicate that pre-channelization has a significant impact on flood peak discharge, but no significant effect on sediment yield. In contrast, land use change has no significant effect on flood and sediment yield for Ishikari river basin.

Key Words : *pre-channelization, land use change, sediment yield, eroded soil, numerical simulation*

1. INTRODUCTION

Within alluvial river systems, meandering river can be the important controls of regional flood and sediment material transport. It operates as the interface between channel and floodplain where flood and sediment material are eroded and deposition during high flood events. Although the precise effect of pre-channelization on sediment transport processes in a river basin is still not clear, there seems to be no doubt that pre-channelization influences sediment yield. Land use change influences surface roughness and erodibility, which controls hillslope and floodplain flow velocity and flow rates. Furthermore, there may be rapid short-term fluctuations between erosion and deposition along channel and hillslope during rainfall event. However, the effects of long term land use change have remained unknown. During the past 100 years, most of main river basins in Japan have been channelized and short-cut to reduce flood peak discharge to flood protection objective. However, knowledge about the impact of sediment yield in different environments and how this affects sediment materials delivery to downstream areas are incompletely understood. Therefore, modelling the causes and effects of pre-channelization could help us to better understanding the alluvial river systems.

This paper addresses these issues by using a 1-dimensional numerical model to simulate the effects of pre-channelization in alluvial river systems. Performance of the proposed numerical model was applied to simulate extreme flood events in 1975 and 1981 to test the hypothesis that pre-channelization and land use change would also be an important component of reducing and/or increasing sediment yield in Ishikari river basin.

2. DESCRIPTION OF ISIKARI RIVER BASIN

In this study, a numerical model is applied to Ishikari river basin, which is located at central part of Hokkaido with total catchment area of 14,330 (km^2), and the lower reach is subjected to the influence of tides (**Fig. 1**). Numerous canals, streams and open ditches are connected to the main river, and 17 of small and medium size dams are located in the river basin[1]. The Ishikari river basin was divided into 29 sub-basins, consisting of a channel and slope on both side (**Fig. 2**). Channelization and short-cut in main and tributaries of Ishikari river basin started from 1918 to 1981, with totaling 58.13 and 5.75 (km), respectively. The main land use type is forest area. Areas of urbanization are located throughout the basin with predominance in the lower reaches.

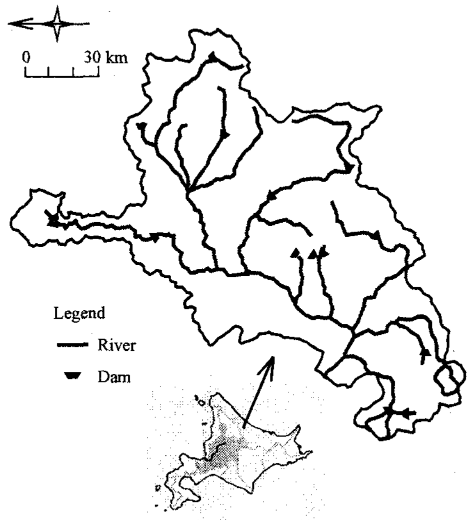

Fig.1 Map of Ishikari river basin.

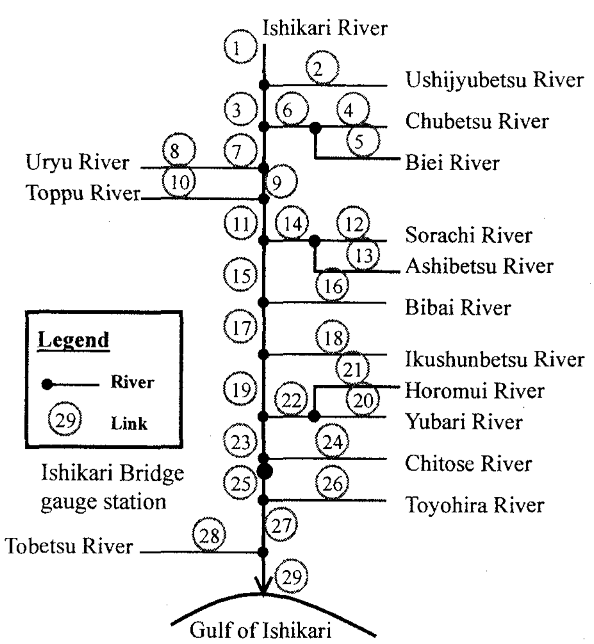

Fig.2 Schematic of Ishikari river basin model.

Fig. 3 shows the variation of monthly averaged suspended load at Ishikari Bridge gauge station during 1994 to 1998. The highest peak occurred during typhoon season in August, and two other peaks occurred during snowmelt season and rainy season, respectively. The annual average rainfall, flow discharge and suspended load are 1,027 (mm/year), 310 (m^3/s) and 41.24 ($m^3/km^2/year$), respectively. **Fig. 4** shows longitudinal profile of mean bed elevation, channel width of Ishikari River, in which these profiles can be simplified in simple exponential functions. The characteristic of sediment grain size profile of d_{10}, d_{50}, d_{90} and d_m along Ishikari River is shown in **Fig. 5**. The overall sediment materials at downstream reach were dominated by fine material with medium sediment grain size diameter about 1 (mm).

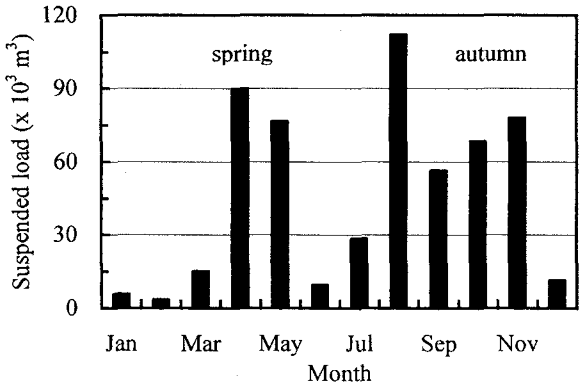

Fig.3 Characteristic of suspended load.

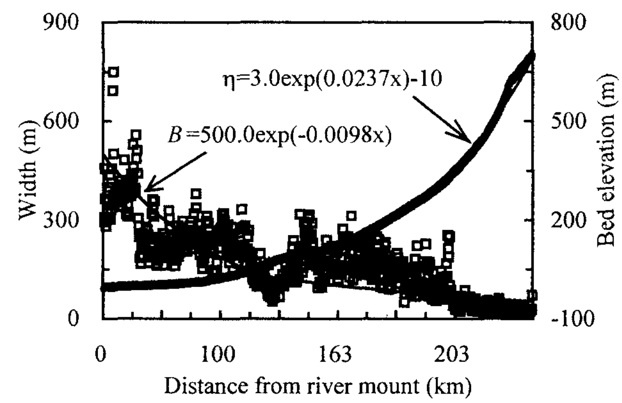

Fig.4 Longitudinal profile of bed elevation and channel width of Ishikari River.

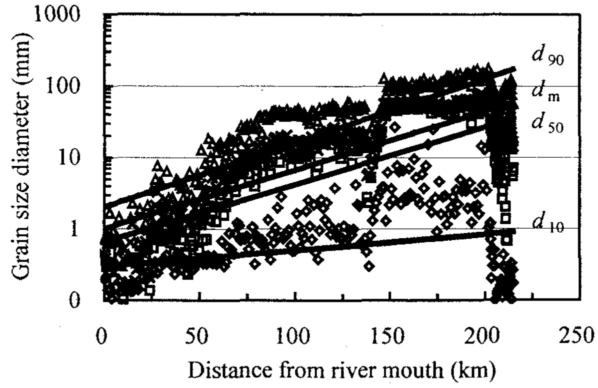

Fig.5 Variation of sediment grain size along Ishikari River.

3. GOVERNING EQUATIONS

(1) Channel flow and sediment model

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

$$\frac{\partial A_c}{\partial t}+\frac{\partial Q_c}{\partial x}=q_L \quad (1)$$

$$\frac{\partial Q_c}{\partial t}+\frac{\partial (Q_c^2/A_c)}{\partial x}+gA_c\left(\frac{\partial H}{\partial x}+S_f\right)=\frac{q_L Q_c}{gA_c^2} \quad (2)$$

where A = cross-sectional area of flow; Q = flow 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; sub-subscript $_c$ = channel; and t, x = time and channel-flow direction coordinate, respectively.

The continuity equation of cross-sectional average suspended sediment and volumetric fractional of bed material can be obtained as

$$\frac{\partial}{\partial t}(\langle c_{ci}\rangle h_c)+\frac{1}{B_c}\frac{\partial (Q_c\langle c_{ci}\rangle)}{\partial x} = q_{sui}-w_{f_i}c_{bi}+\frac{q_L c_{BLi}}{B_c} \quad (3)$$

$$\delta\frac{\partial p_{ci}}{\partial t}+p_{ci}^{*}\frac{\partial \eta_c}{\partial x}+\frac{1}{1-\lambda}\left[\frac{1}{B_c}\frac{\partial (q_{Bci}B_c)}{\partial x} + q_{sui}-w_{f_i}c_{bi}+\frac{q_L c_{BLi}}{B_c}\right]=0 \quad (4)$$

where $\langle c_i\rangle$ = cross-sectional average suspended sediment concentration; B = channel width; q_{sui} = pickup rate; w_{fi} = fall velocity; 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 ($\lambda = 0.4$).

The time dependent change of bed elevation calculated by the following continuity of bed material transport.

$$\frac{\partial \eta_c}{\partial t}+\frac{1}{1-\lambda}\left[\frac{1}{B_c}\frac{\partial \sum_i (q_{Bci}B_c)}{\partial x} + \sum_i\left(q_{sui}-w_{f_i}c_{bi}\right)+\frac{\sum_i (q_L c_{BLi})}{B_c}\right]=0 \quad (5)$$

where $\sum_i$ = summation of bed material transport load. Bedload and suspended load of sediment transport rate per unit width can be obtained from Ashida and Michiue[2] and Itakura and Kishi[3], respectively.

(2) Slope runoff and erosion model

A slope runoff with interflow model is governed by the kinematic wave equation, which can be expressed as (Ichikawa et al.[4])

$$\frac{\partial h_s}{\partial t}+\frac{\partial q_s}{\partial X}=r_e \quad (6)$$

$$q_s=\begin{cases} kS_0 h_s/\gamma & for\ 0<h_s<\gamma D \\ \alpha(h_s-\gamma D)^m + kS_0 h_s/\gamma & for\ h_s \ge \gamma D \end{cases} \quad (7)$$

where h = water depth; q = unit width flow 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; sub-subscript $_s$ = slope; 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 (Sanit et al.[5),6)])

$$\frac{\partial (c_{si}h_s)}{\partial t}+\frac{1}{W_s}\frac{\partial (c_{si}Q_s)}{\partial X}=D_{ri}+D_{fi}-D_{di} \quad (8)$$

$$\delta\frac{\partial p_{si}}{\partial t}+\frac{1}{1-\lambda}\times\left[\frac{1}{W_s}\frac{\partial (q_{Bsi}W_s)}{\partial X}+D_{ri}+D_{fi}-D_{di}\right]=0 \quad (9)$$

where c_i = sediment concentration; Q = flow discharge; W = slope width; D_{ri} = rainfall detachment rate; D_{fi} = overland flow detachment rate; and D_{di} = deposition rate.

4. NUMERICAL METHODS

The CIP[7] (Cubic interpolation pseudo-particle) method was used for application of the equations of channel flow model, and to handle transition of flow from supercritical to subcritical situation, and vice versa. An explicit upwind finite difference scheme was used for sediment transport model, slope runoff and erosion model. Simulation time steps were varied according to the CFL[8] (Courant-Friedrichs-Levy) stability condition. 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.

5. NUMERICAL RESULTS

(1) Model validation

The foregoing numerical scheme was applied to simulate for flow and bed material load of two extreme flood events in 1975, and 1981. All of simulated results were at Ishikari Bridge gauge station.

The simulated conditions are as follows, channel model; Δx = 1,000 (m), n_c = 0.05, and slope runoff model; ΔX = 200 (m), n_s = 0.5, k = 0.02 (m/s), γ = 0.2, D = 0.5 (m) and Δt = 2.0 (s), respectively. Initial conditions were set for water depth, flow discharge and sediment distribution in channel. For the slope erosion model, soil was eroded by raindrop impact, leaf drip impact and overland flow. The eroded soil was transported down the slope into channel with no addition soil from channel banks. Averaged drip height from canopy, percentage of canopy drainage falling as leaf drips, and drip diameter from canopy are 2.0 (m), 80%, and 0.025 (m), and for the sediment components k_r, k_f, C_g, and C_c are 20.0, 0.0005, 0.9 and 0.9, respectively. To represent the different sediment grain sizes for channel and slope, 15 particle sizes from 0.01 to 400 (mm) were used to represent bed material size distribution at each computational grid, which was initialized by standard distribution.

The comparison of time series of measured and simulated flood discharge at Ishikari Bridge gauge station is shown in **Fig. 6**. It was found that the overall magnitude of the flood peak and discharge are simulated well, and that a reasonably good accuracy for extreme flood event in 1981. However, simulated results of recession period are slightly faster than that of the measured data. A possible explanation for this might be due to the storage of water in dams during the initial phase of the flood and return flow from floodplain/swamp, which were not yet included in this model. Nash and Sutcliffe[9] criteria, ε, is used as the main measure of model fit. Values of ε for Ishikari river basin at Ishikari Bridge gauge station for calibration period of 1975 and 1981 are 0.92 and 0.93, respectively. **Fig. 7** shows time series of sediment materials that changes of sediment materials are synchronous with the rainfall, however, it does not have 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 is remarkably 5-6 times larger than bed load. The sediment yield of eroded soil, bedload, suspended load and total load from slope for simulated present scenario are 2, 276, 1,230 and 1,506 (tons), comparing with the values of 1,423 (tons), in which determined from empirical suspended load formula of Ishikari river basin at the gauge station during the same period. However, the amount of measured data and/or empirical formula for bedload and eroded soil are not available. It is necessary to include the data from other floods in order to introduce more reliable conclusions.

(2) Model simulation

For model simulation, Ishikari river basin was analyzed by comparing with 3 pre-channelization scenarios, in which the main channel length was increased to 5, 10 and 15%, respectively.

The comparison of time series of measured and simulated flood discharge at Ishikari Bridge gauge station is shown in **Fig. 8**. It was found that the magnitudes of the flood peak decreased between

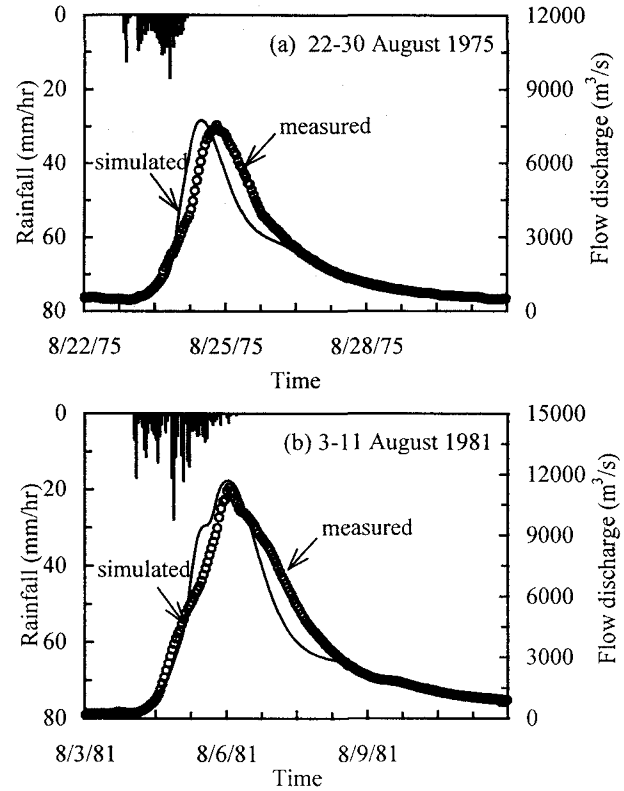

Fig.6 Comparison of simulated and measured flood discharge.

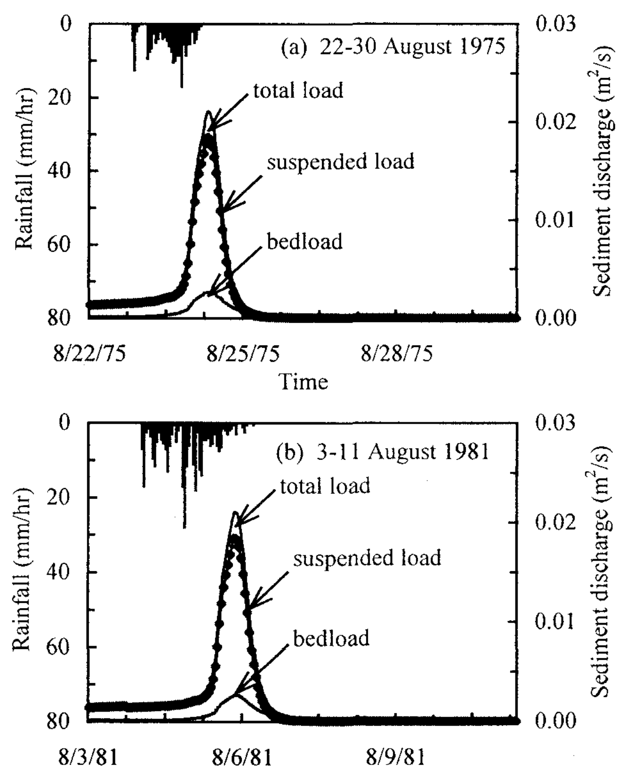

Fig.7 The time series of simulated sediment discharge.

2-12%, and a time to peak was delay when the main channel length is increased. This explains that a meandering channel was able to reduce the flood peak discharge and extend the time to peak period. **Fig. 9** shows the change in bed elevation of main tributaries during simulated periods, in which dramatical bed change occurred near the junction with main channel during high flood rising and recession periods. The suspended load and bedload in scenarios 1 were increased when comparing with the result from present scenario in both flood events. However, suspended load in scenarios 2 and 3 was increased in 1975 flood event, but it was decreased in 1981 flood event, and eroded soil from hillslope was increased from 2 to 5 tons (**Fig. 10**). There is a decrease in magnitude of the flood peak discharge, but no significant change was observed for the sediment yield after pre-channelization.

Although the effect of 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 hydrologic processes of river basin. **Fig. 11** shows land use change statistics for the whole Ishikari river basin from 1896 to 1985. The effect of land use change on the Ishikari river basin was investigated by running the model with several land use scenarios. Possible future land use patterns were generated by reducing forest and grass land area, in which the parameter values of ground cover C_g and C_c were alternated to 0.80 and 0.80, respectively. **Fig. 12** shows time series of simulated suspended load at Ishikari Bridge gauge station, where the increasing of eroded soil material has contributed to suspended load. The effect of land use change on

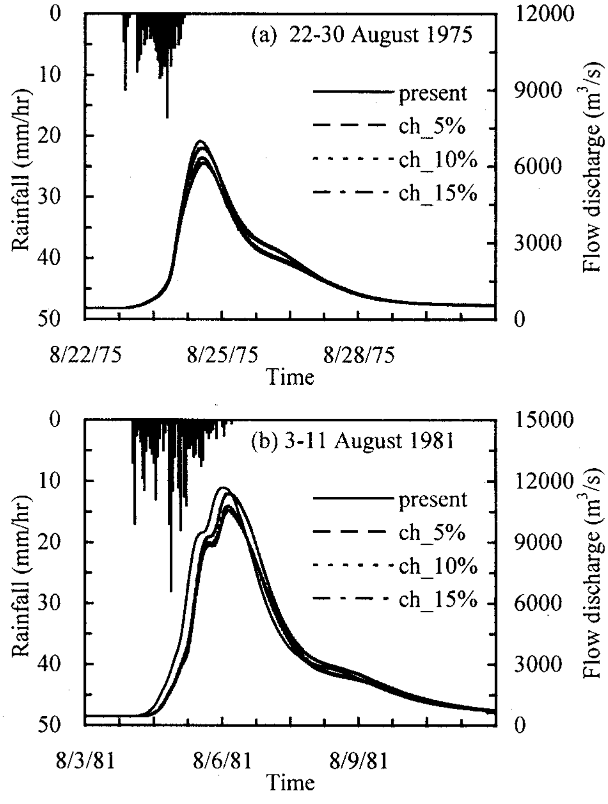

Fig.8 Comparison of simulated flood discharge.

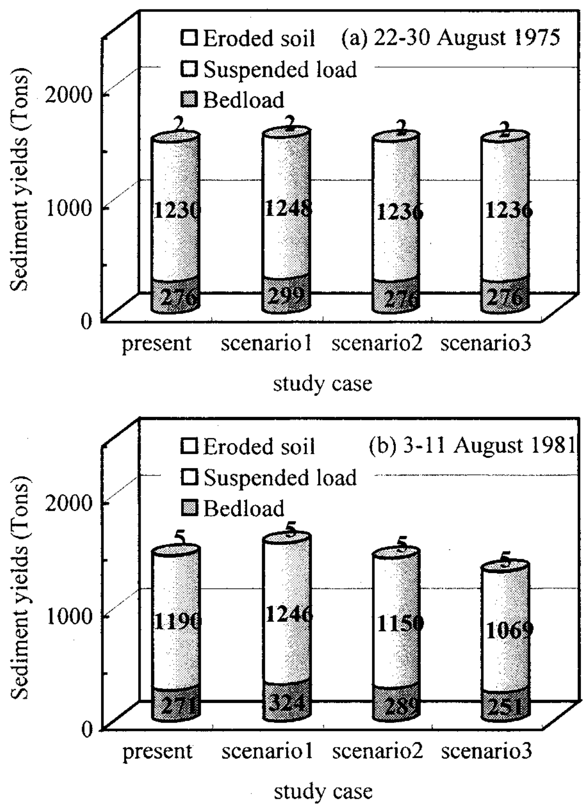

Fig.10 Simulated results of sediment yield.

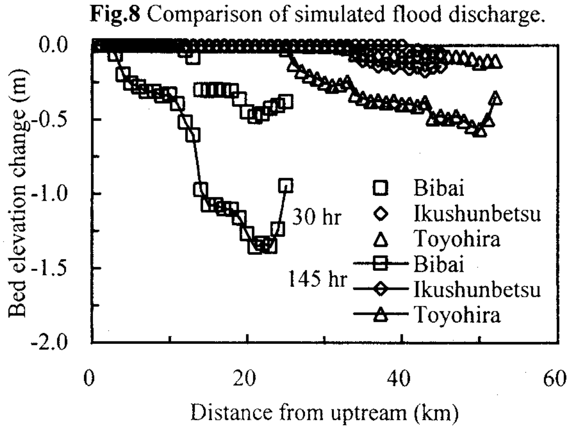

Fig.9 Change of river bed in main sub-basin river.

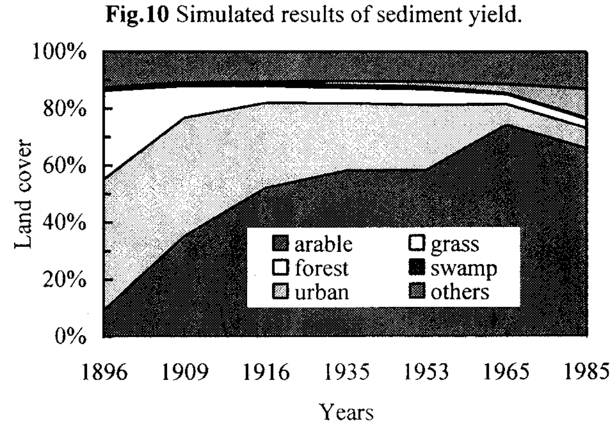

Fig.11 Land use change of Ishikari river basin.

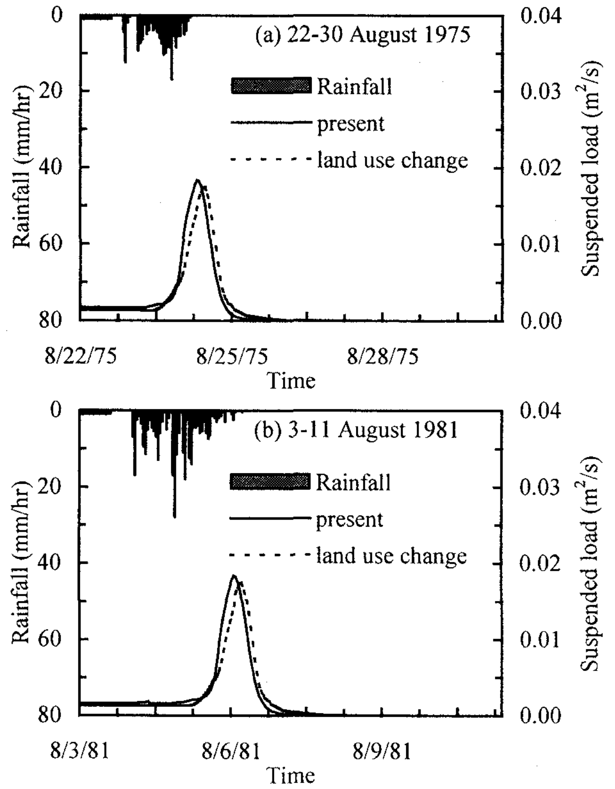

Fig.12 Comparison of simulated suspended load.

increasing of suspended load can be ignored. However, the effect of land use change within the Ishikari river basin 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 indicates that the proposed model might be expected to give accurate results for unsteady flow problems. As a consequence, it is difficult to accurately quantify the sediment yield of bedload, and to make a comparison with measured data by the absence of eroded soil from hillslope and bedload in channel measured data during major flood events. Furthermore, the manner in which an alluvial river responds to the pre-channelization will be important in controlling the connectivity between tributaries and main rivers, which connecting points have been changed after short-cut and flood protection work. In such case, sub-catchment areas and river network system should also be altered.

6. 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. Two flood events in 1975 and 1981 of Ishikari river basin were used to verify the proposed numerical model. This proposed model satisfactorily predicted the flood discharge and sediment yield with good agreement. 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 and land use change from forest to arable land or vice versa, has a significant impact on regional flood, but no significant effect on sediment yield of Ishikari river basin. However, the results as such cannot represent the effect of inundated and return flow from floodplain/swamp area. The simulation should be extended by considering 2-dimensional model or special 1-dimensional floodplain model. Such developments are in progress.

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