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Process-based estimation of suspended-sediment concentration during the thaw season in a small headwater basin

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Abstract The time variation of suspended-sediment concentration (SSC) in the thaw season obtained in the Hiyamizusawa Brook, Hokkaido, Japan, was simulated by the process-based grain lift model. The grain-size distributions of suspended sediment have indicated that the suspended sediment was mainly supplied from sand bed sediment. Thus the model calculated the amount of fine grains stirred up from sand bed sediment. All the fine grains in the tractive layer were assumed to be suspended during a certain time. The thickness of the tractive layer was calculated from the hydraulic condition at the time, and the maximum grain size possible to be stirred up (d_{max}) was calculated by the pressure difference on the river bed surface. By dividing the amount of fine grains finer than d_{max} by the discharge at the time, the SSC was calculated. From the tractive layer where fine grains were already stirred up by previous discharge conditions, only the grains coarser than d_{max} were set to be stirred up the next time. Only the amount and grain-size distribution of sand bed sediment were set as initial conditions, and the SSC was calculated from time to time. The model explained well both the time and amount of peak SSC throughout the thaw season.

INTRODUCTION

The suspended-sediment concentration (SSC) has rarely been predicted from the actual process of suspended-sediment supply. In many studies, the SSC was predicted from the sediment-rating curve, but the prediction produces substantial errors in the resulting estimates (e.g. Olive *et al.*, 1980; Walling & Webb, 1981). Other researchers have considered using numerical models to improve the low accuracy of the estimation using the sediment-rating curve (e.g. VanSickle & Beschta, 1983; Lemke, 1990). These methods, however, have not been based on the actual process of suspended-sediment supply to rivers.

Meanwhile, Kurashige (1993) obtained the hysteresis function in which the peak of SSC appeared earlier than the peak discharge in the thaw season in the Hiyamizusawa Brook basin, Hokkaido, Japan. The grain-size distribution of suspended sediment indicated that the suspended sediment was mainly supplied from the sand bed sediment. Further, Kurashige (1996) considered the physical process of the suspended-sediment supply, and simulated the time variation of SSC with his original "grain-lift model". Kurashige (1996) obtained good results, but the time-variation simulation was for one complete day only. In this study, the time variations of SSC during the thaw season of 1990 and 1993 in the Hiyamizusawa Brook were again simulated by the grain-lift model.

FIELD STUDY

The Hiyamizusawa Brook basin, with an area of 0.93 km^2, is located in a mountainous region southwest of Sapporo City, Hokkaido, Japan. The slope is vegetated by fir, birch and maple forest. The period from late October to late March is the snowy season, and snow mantles the basin from December to April to a depth of several metres. The thaw season of the basin is from early April to mid-May. The total precipitation in the snowy season is *c.* 800 mm, which is about 60% of the total annual precipitation (*c.* 1400 mm).

An unpaved road was constructed in 1989, and further selective logging was carried out from May to June 1992 during which time a bulldozer cut part of the slope in order to construct a path to remove the logs. During this operation, the sediment cut from the slope was deposited on the slope, and this sediment is here called the deposited sediment.

The river bed of the Hiyamizusawa Brook was originally a gravel bed. However, new sandy material, which was most likely derived from the unpaved road, was deposited in several locations on the bed surface in September 1989, and in October 1989 this new sandy bed sediment comprised about 10% of the bed surface (Kurashige, 1993, 1996). In October 1992 the sandy bed sediment also existed in several locations, but its amount and distribution were not examined. More details of the basin are given by Kurashige (1993) and Kurashige & Fusejima (in press).

River discharge and SSC were obtained 800 m downstream of the headwater spring in 1990 and 1200 m downstream in 1993. The river discharge during the thaw season was calculated from the stage–discharge curve obtained at each site. The SSC was determined by manually sampling one litre of river water in 1990, and sampled by an automatic water sampler in 1993. Further, the water sample was vacuum filtered through pre-weighed cellulose nitrate filter paper (0.45 μm) to calculate the SSC. The results are shown in Fig. 1. On 8 April 1990, 16 April and 23 April 1993, the peak SSC appeared earlier than the peak discharge. In contrast, on other sampling days, a clear peak of SSC was not obtained, even when the discharge was relatively high.

Kurashige (1993, 1996) measured the grain-size distribution of suspended sediment on 8 April 1990, and compared it to the grain-size distributions of regolith, road-bank sediment, river-bank sediment and river-bed sediment to determine the origin of suspended sediment. Each grain-size distribution was divided into several lognormal subpopulations by the method of Inokuchi & Mezaki (1974). Some representative subpopulations are shown in Table 1. Since the suspended sediment was mainly composed of two subpopulations (population 1 and 2), Kurashige (1993, 1996) concluded that the suspended sediment on this day was mainly supplied from the sand bed sediment.

In contrast, from the grain-size distributions of suspended sediment in April 1993, we could not determine the origin with confidence. The suspended sediment was composed of two subpopulations (populations 2 and 3), and all sediment sources have these two subpopulations (Table 1). The grain-size distribution could not be used as an effective tracer in this case. However, the entire hillslope and the unpaved road were covered with snow until late April, and accordingly an active sediment supply from the regolith, deposited sediment and the unpaved road could not have

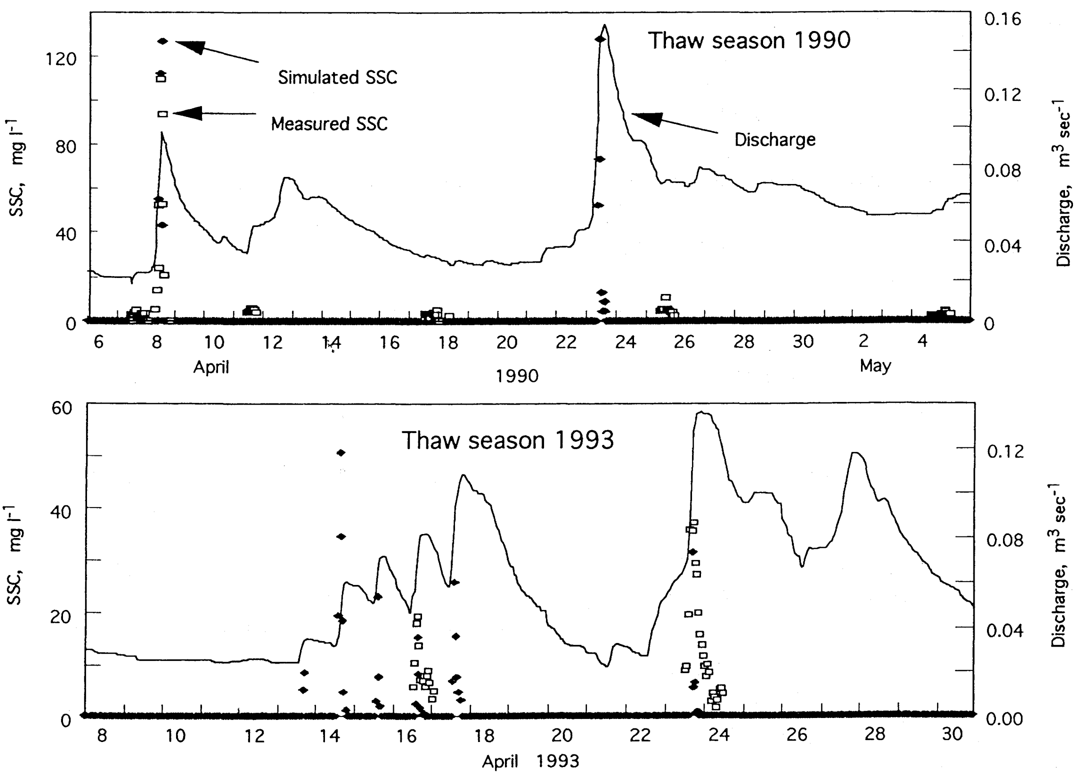

Fig. 1 The time variation of actual river discharge and SSC (solid line and open squares, respectively) and the calculated result of SSC (hatched squares.

occurred in this season. Thus, the suspended sediment in the thaw season of 1993 was also considered to be supplied mainly from the sand-bed sediment.

OUTLINE OF THE GRAIN LIFT MODEL ON SAND BED SEDIMENT

The grain lift model for sand bed sediment was originally proposed by Kurashige (1996). In the first stage, the bed surface is covered with sand, and only sand grains on the bed surface are moved by the tractive force τ acting on the surface. The stirring up of fine grains does not occur at this stage. When τ increases, the tractive layer thickens. Fine grains buried in the tractive layer are consequently stirred up in the river water through gaps between sand grains. These gaps are probably produced between sand grains while they are transported by the process of traction (the second stage). This stirring-up process continues while fine grains remain available in the tractive layer. After all the fine grains have been removed, no more stirring up occurs from the tractive layer (the third stage). If a greater τ acts on the bed surface, the tractive layer extends downward, and another progression from the second to the third stage occurs. Since the coarse of the fines, which were not able to be stirred up in the previous sequence, remained in the previous tractive layer, the stirring up of the remaining fine grains from that layer also occurs in the new sequence.

Table 1 Mean sizes (Mϕ), standard deviation (σϕ) and percentages of subpopulations of fine portion of each sediment sample in the Hiyamizusawa Brook basin.

	1		2		3	
	Mϕ	σϕ	Mϕ	σϕ	Mϕ	σϕ
Suspended sediment 11:00, 8 April 1990*	5.6 (4%)	0.7	7.7 (37%)	0.7	10.6 (14%)	1.2
Sand bed sediment October 1989*	4.6 (72%)	0.9	7.9 (28%)	1.3		
Suspended sediment 16:00 23 April 1993			6.6 (60%)	1.3	10.3 (40%)	1.6
Sand bed sediment June 1993			6.2 (95%)	1.1	9.6 (5%)	0.6
Deposited sediment			6.2 (85%)	0.8	8.9 (15%)	1.8
Regolith			6.7 (72%)	1.3	9.9 (28%)	1.2

* Data after Kurashige (1993, 1996).

In this model, the fine grains in the tractive layer are stirred up by the pressure difference (Δp) between the bottom and the top of the tractive layer. Einstein (1950) proposed that the maximum diameter (d_{max}) of grains stirred up by Δp be expressed as:

$$\Delta p = \frac{2}{3}(\sigma - \rho)\, g\, d_{max} \tag{1}$$

where σ is the density of grains, ρ is the density of river water, and g is the acceleration due to gravity. Meanwhile, the relationship between τ and Δp, introduced theoretically by Christensen (1971), is written as:

$$\frac{\Delta p}{\tau} = 0.556 \left\{ \ln\left(\frac{10.4\, D_{65}}{k_s} + 1 \right) \right\}^2 \tag{2}$$

where k_s is the equivalent roughness height of the bed, and D_{65} is the diameter of the 65th percentile of the bed-sediment distribution. Since τ at a given time can be calculated by $\tau = \rho\, g\, R\, I$, where R is the hydraulic radius, and I is the slope gradient of the river bed, and both k_s and D_{65} can be obtained from the river bed condition, equations (1) and (2) show that d_{max} can be calculated from the hydraulic conditions at the time. Consequently, in the grain-lift model, all of the grains finer than d_{max} in the tractive layer were set to be stirred up into the river water within a certain time. For this calculation, the grain-size distribution of the river bed sediment should be measured first, and then the thickness of the tractive layer should be estimated.

Assuming that all the sandy grains in the tractive layer are moving at the velocity U_b, the thickness of the tractive layer δ can be expressed as:

$$\delta = \frac{q_b}{(1-\varepsilon)\sigma U_b} \tag{3}$$

where q_b is the bed-load mass flux per unit width, and ε is the porosity of sandy-bed sediment. In addition, Sato *et al.* (1956) obtained q_b as:

$$q_b = \frac{\Phi(n)\ \rho}{(\sigma - \rho)} u_*^3\ \mathrm{F}\left(\frac{\tau}{\tau_c}\right) \tag{4}$$

where u_{**} is the shear velocity, n is the roughness coefficient of Manning's equation, τ_c is the critical shear stress, and $\Phi(n)$ and $\mathrm{F}(\tau/\tau_c)$ are functions of n and τ, respectively. They assumed that $\Phi(n)$ and $\mathrm{F}(\tau/\tau_c)$ are constant at 0.62 and 1.0, respectively, while $n \geq 0.025$. These values are comparable to conditions on the sand bed in Hiyamizusawa Brook (n = 0.04).

Bagnold (1966) carried out an experiment on bed-load transport, and obtained $U_b 0.13V$, where V is the mean velocity of river flow. Introducing this equation and equation (4) into equation (3), we get:

$$\delta = 4.77 \frac{\rho\ u_*^3}{\sigma(\sigma - \rho)(1 - \varepsilon)V} \tag{5}$$

On the other hand, V can be expressed by Manning's formula, and u_* is defined as $u_* = \sqrt{\tau / \rho}$. Consequently, δ can be calculated from the hydraulic condition at the time. Moreover, if the grain-size distribution of river-bed sediment is known, the weight of grains finer than d_{max} in δ can be estimated, and this weight will be the total amount of suspended sediment stirred up from river-bed sediment within a certain time.

CALCULATION OF SSC

In this study, the SSCs in the thaw seasons of 1990 and 1993 were simulated by the grain-lift model. The distance from the sampling site to the headwater spring is only about 1 km, consequently water originating from the spring reaches the sampling site within 30 minutes during a flood event. Thus, as an approximation by Kurashige (1996), the average shear stress acting on the river bed between the sampling site and the headwater spring was assumed to stir up fine grains in the section. The brook was therefore not divided into several subsections in the calculation.

The average discharge Q_{ave} was calculated by the regression equation between the river discharge and the distance from the spring. Further, to calculate the average shear stress τ_{ave}, the average depth h_{ave} is solved from Manning's equation by a bisection method, assuming that the section is rectangular. Then the average hydraulic radius R_{ave} is calculated, and τ_{ave} is derived with the average slope of the sand bed I_{ave}.

Next, we consider the mass of suspended sediment supplied from a sand bed of unit width, length L and height δ in a unit time. The sand grains move a distance equivalent to U_b in a unit time, thus $L = U_b$. Further, from R_{avei} at time T_i, we can obtain U_{bi} and δ_i. Fine grains are stored in pore spaces between sand grains in the sand bed materials which have the volume $L_i\ \delta_i$, thus the bulk volume of fine grains in this sand material can be approximated to be $L_i\ \delta_i$,. Assuming that the porosity of fine grains is equivalent to that of sand grains, the potential mass of fine grains W_i

can be written as $W_i = L_i\delta_i\varepsilon(1 - \varepsilon)\sigma$.

On the other hand, $d_{\max i}$ is calculated by equations (1) and (2), and the cumulative weight percent of fine grains with the diameter $d_{\max i,}$ which is counted from the coarser fraction, is here written as P_i. The mass of fine grains stirred up from L_i δ_i during the time between $T_{i\text{-}1}$ and T_i is then given by:

$$S_i = \frac{\delta_i - \delta_{i\text{-}1}}{\delta_i}\frac{100 - P_i}{100}W_i + \frac{\delta_{i\text{-}1}}{\delta_i}\frac{P_i - P_{i\text{-}1}}{100}W_i \tag{6}$$

assuming that all the fine grains finer than $d_{\max i}$ are stirred up within the unit time. In this equation the first term indicates the mass of grains stirred up from the layer between $\delta_{i\text{-}1}$ and δ_i, and the second term indicates the mass from the layer shallower than $\delta_{i\text{-}1}$. Then, the total amount of fine grains stirred up from the sand bed S_{Ti} can be expressed as $\underline{S_{Ti}}$, $= S_iX/L_i$, where X is the total distance over which sand bed sediment is deposited. The SSC C_i at time T_i is thus written as $C_i = S_{Ti}/\{q_{\text{ave}i}(T_i - T_{i\text{-}1})$, where $q_{\text{ave}i}$ is the average river discharge for a unit width of the brook at time T_i.

The slope angle of the sand bed was set to be 1°. To calculate V from Manning's formula, $n = 0.2$ was used, which is the average roughness coefficient of the brooks in the vicinity of the study area. The calculation periods were from 13:00 on 5 April to 23:00 on 8 May 1990 and from 0:00 on 8 April to 23:00 on 30 April 1993. The time step was 1 h.

As for the initial conditions of the calculation, the grain-size distribution of sand-bed sediment in September 1989 was used. A total distance of 70 m from the spring to the measuring site was set to be covered with sand bed in 1990, according to the result of a field survey. In contrast, in 1993, the distance of 20 m was assumed to be covered with sand bed by the trial-and-error method. The fines in the sand bed at 13:00 on 5 April 1990 and those at 0:00 on 8 April 1993 were set to be already exhausted by $Q = 0.06$ m^3 s^{-1} and $Q = 0.036$ m^3 s^{-1}, respectively, which are the previous maximum discharges before the calculation period. The calculation results are shown in Fig. 1. The simulation explained well both the time and amount of actual peak SSC throughout the thaw season.

DISCUSSION AND CONCLUDING REMARKS

The model underestimated the rising stage and the falling stage of the time variation of SSC (Fig. 1). This underestimation was probably caused by the current simplicity of the model. The stirring up of fines was assumed to be generated by the average shear stress acting on the section of the river bed under discussion, and the section was not divided into several subsections. However, in an actual event, the shear stress varies with distance along the section, and the amount of stirred-up grains also varies accordingly with distance. Moreover, at the site near the headwater spring, sand from the river bed is transported downstream, so the layer from which fine grains can be stirred up may deepen considerably. The subdivision may improve the simulation's accuracy in predicting the rising and falling stages (Kurashige, 1996).

Nevertheless, the trend of SSC was estimated with fair accuracy in this calculation. In particular, on 25 April and 5 May 1990, very low SSCs (less than

5 mg l^{-1}) were obtained even when the discharge was relatively high (about 0.05 m^3 s^{-1} or more), and the model estimated the SSC of these days to be 0 mg l^{-1}. Such low SSCs under high discharge conditions cannot be estimated by a model based on the sediment-rating curve.

The grain-lift model calculates the high SSC only when the discharge exceeds the previous maximum and the increased rate of discharge is high, because the tractive layer can deepen rapidly to the layer still filled with fines only under this condition. Thus, even if the discharge is relatively high, a new stirring up of fines does not occur when the discharge does not exceed the previous maximum. Both on 25 April and 5 May 1990, the discharge did not exceed the previous maximum (0.154 m^3 s^{-1} on 23 April), thus the model calculated the SSC to be zero.

Moreover, the peak SSC usually appears earlier than the peak discharge in thaw season at small basins in Hokkaido (Kurashige, 1993). On the rising stage of the hydrograph in thaw season, the maximum increase in the rate of discharge appears at the middle of the rising stage. Since the grain-lifting model calculates the maximum SSC at the time when the increased rate of discharge is maximum, the peak of SSC before the time of peak discharge can be explained by the model.

In the Hiyamizusawa Brook, the SSC during the low-water season usually varies from 3 to 10 mg l^{-1}. This suggests that this value is a base level of SSC for the brook. In the model, the base level of SSC was not given, thus SSC = 0 mg l^{-1} is calculated when the stirring-up of fines does not occur. The inclusion of the base level in the calculation will improve the modelling of low SSC.

The grain-lifting model requires data for the amount and grain-size distribution of sandy sediment at the beginning of the thaw season, and it simulates well the time variation of SSC through a thaw season. A precise field study of the river bed sediment is necessary to simulate SSC by this model.

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