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MODELLING OF TURBIDITY CONCENTRATION DISTRIBUTION IN RIVER IN THE UPSTREAM REGION OF THE HITOTSUSE RIVER WATERSHED

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ABSTRACT

The Hitotsuse River watershed, located in the middle of Miyazaki Prefecture, Kyushu, Japan, has recently suffered from the generation of high turbidity in its stored water and river stream. The present study analyzed the turbidity concentration distribution in the river stream to obtain a better understanding of turbidity generation in the upstream region of the watershed. A one dimensional model for sediment transport incorporating sediment advection, deposition, resuspension and lateral sources along the river reach was applied. A series of turbidity observations from July to November 2007 were conducted along the main river and its tributaries. The river channel was divided into upper, middle, and lower reaches for simulation of the turbidity concentration distribution. Model parameter calibration and validation were carried out for each river reach, and the model performance was statistically evaluated. The numerical calculation results revealed that the tributaries in the middle reach provided the largest contribution (55% on average) to the high turbidity in the main river. The modelling approach demonstrated in the study reasonably predicted the turbidity concentration distribution.

Keywords: generation of high turbidity, turbidity concentration distribution, sediment transport, tributary, river reach

1. INTRODUCTION

The generation of high turbidity in stored water and in river streams has recently become a major concern for the Hitotsuse River watershed, which is located in the middle of Miyazaki Prefecture, Kyushu Island, Japan (Harisuseno *et al*., 2007). Several efforts have already been made to reduce the turbidity; however, these efforts only concentrated on reducing turbidity in water outflowing downstream by improving the intake facility. Ideally, overcoming the problem of high turbidity generation should involve the whole watershed, including the upstream region of the watershed. However, there have been few studies on the generation of high turbidity in the upstream region of the Hitotsuse River watershed. In particular, there has been little analysis of the mechanism controlling the transport of sediment in the river stream, including the direct contributions of turbidity by tributaries. Harisuseno *et al.* (2008) have documented that the presence of a collapsed area and heavy rainfall triggered by a typhoon were factors in the generation of high turbidity in river stream in the upstream region of the Hitotsuse River watershed. Sugio *et al.* (2008) have clarified that the most turbid materials in the most upstream part of the Hitotsuse River watershed were

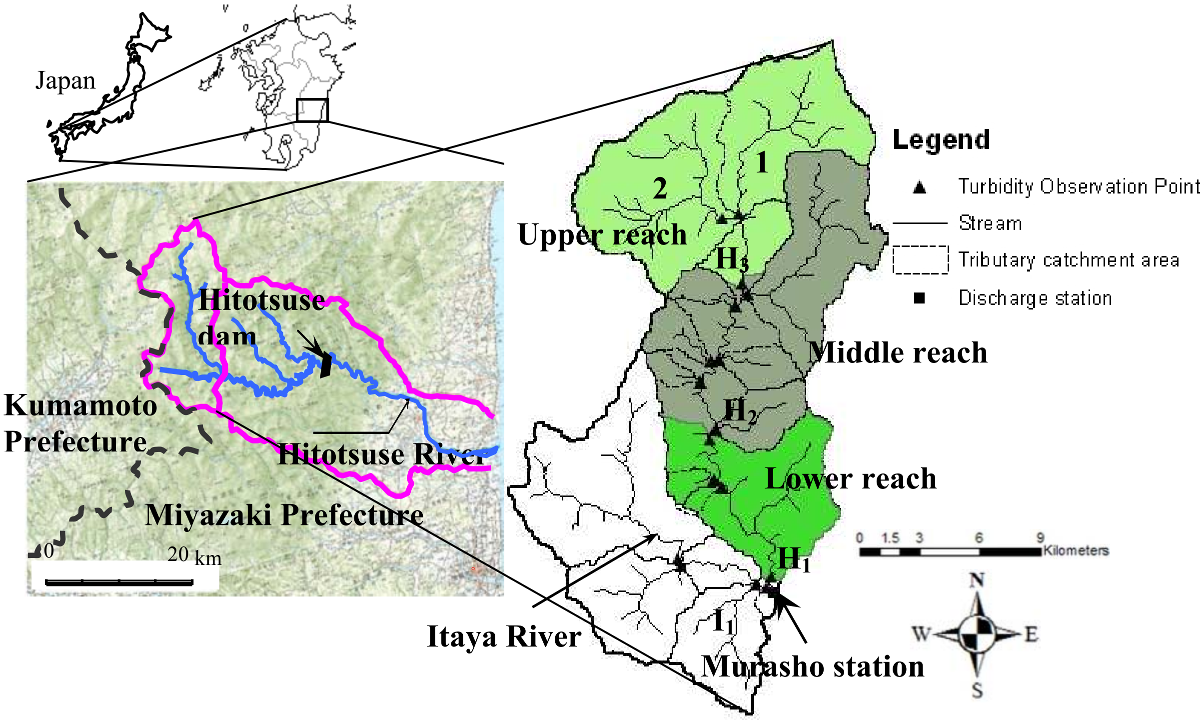


Figure 1 Location of study area

yielded from the erosion on the slope face and waterside erosion at the slope toe of the collapsed slope. However, these studies did not discuss the process of turbidity generation in the river stream.

The present study analyzes the distribution of turbidity concentration in the river stream by applying the one dimensional model of sediment transport to obtain a better understanding of turbidity generation in the river stream, particularly in regard to the identification of tributaries that contribution greatly to turbidity in the upsteam region of the Hitotsuse River watershed. Such analysis could be useful in minimizing high turbidity in the river stream.

2. DESCRIPTION OF THE STUDY AREA

The Hitotsuse River watershed has a drainage area of 852km^2 and a river length of 91.3km. The present study was focussed on the upstream region of the Hitotsuse River watershed, which has a drainage area of 209.3km^2 and a total river length of 24.53km with its lower boundary at the Murasho gauging station (Figure. 1). The topography of the study area is mainly characterized by a steeply incised valley with slopes ranging from 0.20 to 0.71. According to Saito, *et al.* (1996), the dominant geology types are sandstone mudstone (33.4% coverage), mudstone (10.4% coverage), sandstone (6.4% coverage), granodiorite (7.9% coverage) and melange facies (41.9% coverage). The major parts of the study area are mainly dominated by brown forest soil which covers 54.2% of the total study area. Rocks and soils are mainly composed of fine grains and likely to be susceptible to erosion. Discharge was observed at Murasho hydrometric station which was designed under a standard established by Ministry of Economy, Trade, and Industry of Japan in November 1937. In July 1990, the Hokuto-Rikan MA-1601 turbidimeter was installed at the same location to observe turbidity in the river stream. Owing to high turbidity in the river stream, additional instruments to continuously record turbidity along the main river stream and tributaries were installed in

2007.

3 MATERIALS AND METHODS

3.1 River Reach and Turbidity Observations

Simulation of the turbidity concentration distribution was concentrated on the main river stream which is 18.94km in length and has an average bed slope of 0.021. Several observations were carried out from 1 July 2007 to 13 November 2007 comprising turbidity observations at three points along the main river stream and 14 points for tributaries, and discharge observation at the Murasho gauging station (Figure 1). The continuous 10-minute of turbidity observation data were averaged over daily time intervals for analysis. The river channel was divided into three reaches: upper, middle, and lower reaches as the domain analysis according to the locations of the observation stations along the main river stream as shown in the Table 1.

An additional river reach situated along the downstream tributary (the Itaya River) beyond the main river stream was also considered in the turbidity concentration distribution analysis. The observed turbidity concentration in each tributary was considered as a source of the main river turbidity in the model framework. The discharge turbidity relationship during high flow events at the Murasho gauging station in 2006 was used for estimating the discharge at each tributary as shown in Figure 2.

3.2 Instream Sediment Transport

The one dimensional sediment transport model as described by Dietrich *et al.* (1999)

Table 1 Characteristics of the three reaches of the main river stream and Itaya reach

Observation node	River reach	Catchment area (km^2)	Length (km)	River slope	Geology type
H_3	Upper (confluence point of tributaries 1 and 2	61.20	3.20	0.030	Melange facies
H_2	Middle (H_3-H_2)	54.60	8.07	0.021	Melange facies
H_1	Lower (H_2-H_1)	27.30	7.67	0.012	Sandstone
I_1	Itaya River reach	66.24	5.59	0.042	Melange facies

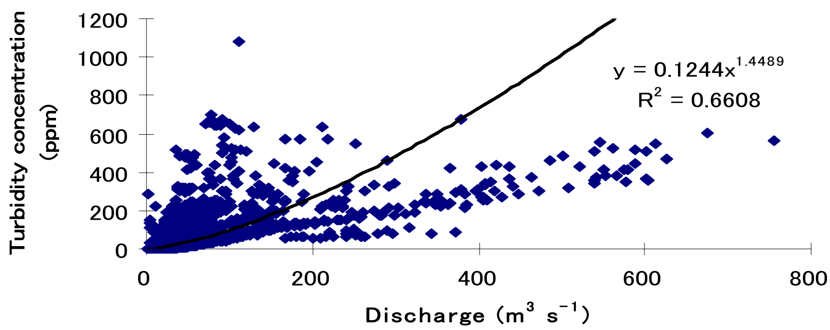


Figure 2 Discharge-turbidity relationship at Murasho in 2006

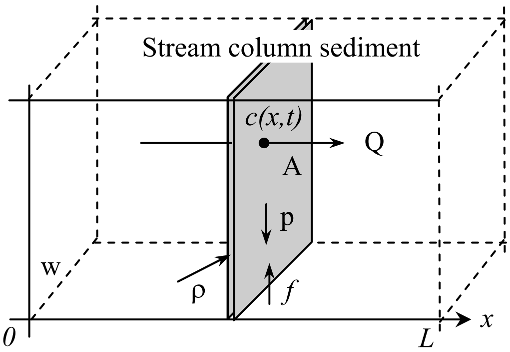


Figure 3 Model scheme of a stream reach

was applied in the present study. The model relies on sediment and water mass conservation principles, where the stream channel is modelled as having rectangular form with a constant width w extending along the positive x-axis, with all stream properties constant over cross-sections. The model scheme is shown in Figure 3. In Figure 3, t is time (days), A is the wetted stream cross section (m^2), Q is the discharge (m^3 day^{-1}), c is the stream sediment concentration (kg m^{-3}), p is the stream sediment settling rate (m s^{-1}), ρ is lateral source per unit length and time (kg m^{-1} day^{-1}), and f is the sediment mass resuspension source per unit length and time (kg m^{-1} day^{-1}).

The model was expanded to include the turbidity observations from tributaries as a concentration loading source in the simulation process. Therefore, the continuity equation gives

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_T \tag{1}$$

where q_T is discharge loading from tributary. If sediments are carried by the stream with advection and resuspension supposed to be the dominant transport processes at play, then Eq. 1 along with a sediment mass balance gives the sediment transport equation:

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+\frac{wp}{A}c=\frac{s}{A}+c_T \tag{2}$$

where $u = Q/A$ is the water velocity, s denotes the total sediment mass source per unit time (composed as f and ρ), w is the channel width, c_T is the turbidity concentration of tributary. Further details on the derivation and definition of model parameters were described in Dietrich *et al.* (1999). Using the method of characteristics to solve the sediment transport equation in Eq. 2, the sediment transport model is derived as

$$c_{sim}(t)=c_0(t-\tau)e^{-\alpha/Q_t}+\left[\frac{\eta\beta\,(Q_1-Q_*)^{\mu}+\gamma}{\alpha}\right](1-e^{-\alpha/Q_t})\;+\;c_T \tag{3}$$

where c_0 is the upstream node concentration, $c_{sim}(t)$ is the simulated downstream concentration at time t, τ is the effective travel time between gauging stations estimated from the data, and c_T is the turbidity concentration from tributary (ppm). From the Eq. 3, the simulated processes encompass five parameters relating to the sediment concentration in the river, namely α is associated with particle settling which control deposition (m^2 day^{-1}), γ is

Table 2 The five parameters in the sediment transport model

Parameter	α	β	γ	Q_*	μ
Dimension	m^2 day^{-1}	Resuspension variable	kg day^{-1}	m^3 day^{-1}	
Physical interpretation	Particle settling		Lateral sources	Resuspension threshold flow rate	Dimensionless resuspension power

associated with the effect of the lateral sources (kg day^{-1}), and β, μ, and Q* simultaneously determine the effect of sediment resuspension. The parameters require calibration before being used in the model equation. Table 2 shows the model parameters with their dimensions and physical interpretations.

3.3 Model Calibration and Validation

For model implementation, the turbidity observation data was split into two time series, 1 July 2007 to 30 September 2007 and 1 October 2007 to 13 November 2007, one for model calibration and the other for model validation. In the case where two tributaries were gauged in parallel at an upstream observation point, e.g. the tributaries in the upper reach of the Hitotsuse River (tributaries 1 and 2 in Figure 1), flow rates were summed and weighted by the ratio of downstream to upstream flow volumes over the period of simulation as described in the following equation (Green *et al.*, 1999).

$$q_0 = \frac{\sum q_L}{\sum \left(q_{0_1} + q_{0_2}\right)} \left(q_{0_1} + q_{0_2}\right) \tag{4}$$

where q is the flow rate (m^3 s^{-1}) , Σq is the cumulative flow over the calibration period and the subscripts denote the gauging station at one downstream (q_L) and two upstream (q_{01} and q_{02}) locations. The turbidity concentration for the upstream observation points which were situated at the confluence point between two tributaries (e.g. tributaries 1 and 2) are estimated by using flow weighted averages of the concentrations at the tributaries:

$$c_0 = \frac{c_{0_1} q_{0_1} + c_{0_2} q_{0_2}}{q_{0_1} + q_{0_2}} \tag{5}$$

where c_0 and q_0 are the turbidity concentration (ppm) and flowrate (m^3 s^{-1}), respectively, while the subscripts denote the tributary 1 and tributary 2 in this example.

The Nash-Sutcliffe efficiency (NSE) (Lian *et al.*, 2007) was computed as a statistical measure of the model calibration and validation performance and is given by

$$NSE = 1 - \frac{\sum_{i-1}^{n} \left(c_{obs_i} - c_{sim_i}\right)^2}{\sum_{i-1}^{n} \left(c_{obs_i} - \overline{c_{obs}}\right)^2} \tag{6}$$

where n is the number of turbidity concentration values of selected time events, c_{sim} and c_{obs} are simulated and observed turbidity concentrations, respectively, and $\overline{c_{obs}}$ is the average observed turbidity concentrations. Moreover, the mean square error (MSE) was calculated to assess the model performance in terms of the prediction errors. The mean square error (MSE) can be computed as (Dogan *et al.*, 2007)

$$MSE = \frac{1}{N}\sum_{p=1}^{n}\left(c_{obs} - c_{sim}\right)^{2} \tag{7}$$

3.4 Assessment of Turbidity Sources from Tributary

The objective of this analysis is to determine which tributaries have large contributions to high turbidity in the main river stream of the Hitotsuse River. The contribution of turbidity from tributaries was measured by calculating the percentage contributions of turbidity from the tributaries in the reaches to high values of turbidity concentration at the Murasho station; i.e., the percentage was only calculated for high turbidity events.

In the present study, the turbid material load derived from the discharge multiplied by the turbidity was used in the calculation of the percentage contribution of turbidity. The turbid material load was calculated for the simulated turbidity results of the reaches, then compared with the turbid material load at the Murasho station. The percentage tributary contribution of turbid material is

$$Trib_{cont} = \frac{\sum_{i=1}^{n}\left(Q_{rc_i} \times c_{rc_i}\right)}{\sum_{i=1}^{n}\left(Q_{ds_i} \times c_{ds_i}\right)} \times 100\% \tag{8}$$

where, $Trib_{cont}$ denotes the tributary contribution (%), $Q * c$ is the turbid material (t s^{-1}), Q_{rc} and Q_{ds} are the discharges in the river reach and at the downstream station (Murasho), respectively, and c_{rc} and c_{ds} are the turbidity concentration in the river reach and at the downstream station (Murasho), respectively.

4. RESULTS AND DISCUSSION

4.1 Model Calibration and Estimation of Parameters

Model calibration was based on the observation period from 1 July 2007 to 30 September 2007 and performed for the three reaches of the main river stream and the Itaya River reach. Table 3 shows the calibrated model parameter values of the sediment transport model for the four reaches.

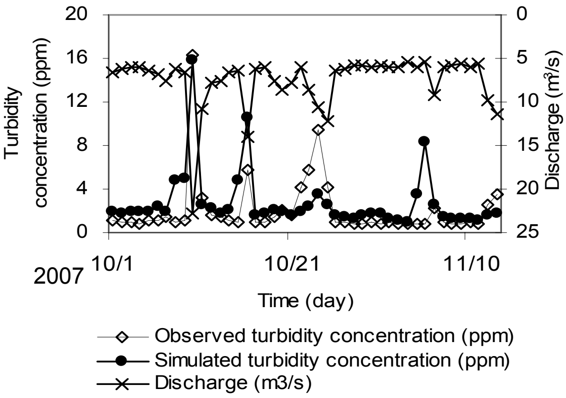
Parameter of α increased significantly from the upper reach to the lower reach indicating particle settling velocities were higher in the middle and lower reaches than in the upper reach. Relatively low values of β, μ, and Q_* indicated the sediment resuspension may not be as a significant process influencing sediment transport in the main river. The middle reach had the largest value of γ (875 kg day^{-1}), which indicated that lateral sources were more active in this reach, whereas for the middle and lower reaches, lateral sources were not significant.

4.2 Model Validation

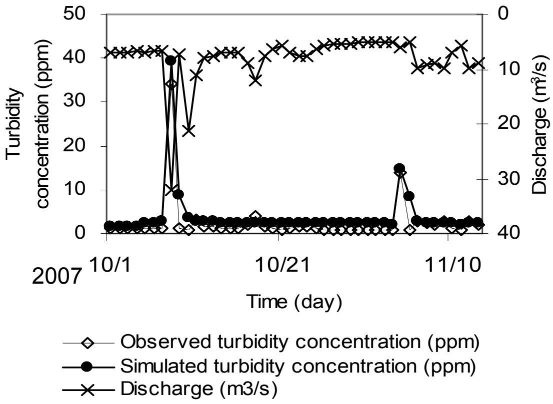
Based on the calibrated parameters shown in Table 3, model validation was performed

Table 3 Calibrated model parameters for reaches in the study area

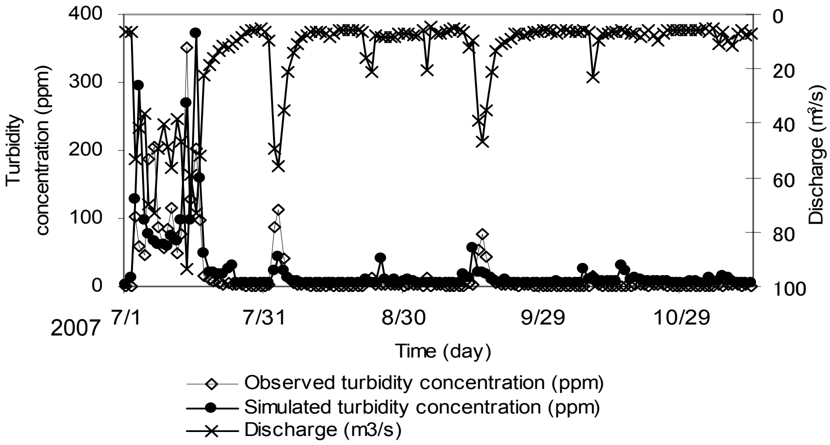
Parameter	Unit	River reach			
		Upper	Middle	Lower	Itaya River
α	$m^2\ day^{-1}$	865	25762	35665	1355
γ	$kg\ day^{-1}$	21.7	875	155	75
β	variable	39	8	7.5	25
Q_*	$m^3\ day^{-1}$	4.3	12	2.95	1.16
μ	-	1	1	1	1



(a) Middle reach



(b) Lower reach



(c) Murasho

Figure 4 Example of model validation : Comparison between simulated and observed turbidity concentration

for the river reaches using turbidity observation data from 1 October 2007 to 13 November 2007. Figure 4 shows an example of model validation results for the middle and lower reaches and the Murasho station.

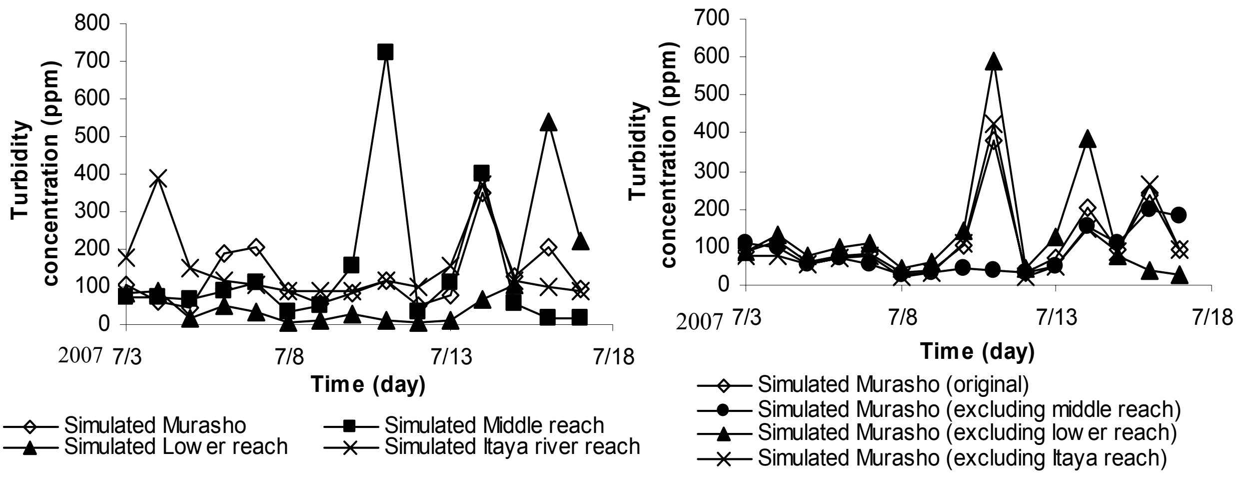
From the figure, it can be seen that the turbidity concentration is well predicted for the middle and lower reaches, and the Murasho station. Table 4 shows the Nash-Sutcliffe (NSE) is generally 0.36 – 0.51 for the upper, middle, lower and Itaya River reaches, which indicates the model is capable of predicting the turbidity concentration distribution in the river. There was poor validation for the Itaya River reach as indicated by MSE and NSE values of 159.86 and 0.36, respectively.

4.3 Assessment of Turbidity Sources from Tributary

Turbidity loading from tributaries was analyzed for high turbidity events from 3 July 2007 to 17 July 2007. Since there are no tributary along the upper reach, the analyses were only conducted for the middle, lower, and Itaya River reaches. The values of model parameter derived from the calibration (Table 3) were used in this analysis. The turbidity at the confluence point of tributaries 1 and 2 estimated from Eq. 5 was used as the initial value in the model, while the downstream boundary condition was the turbidity observation at the Murasho station. Figure 5 (a) shows the simulated turbidity results for the Murasho station, middle reach, lower reach, and Itaya River reach. The middle reach had the highest average turbidity. To examine the effect of each reach in an effort to reduce the high turbidity at the Murasho station, the simulation of turbidity was conducted while excluding particular reaches from the simulation process as shown in the Figure 5 (b). The turbidity loading from the middle reach is excluded when determining its contribution to the turbidity at the Murasho station; hence only the turbidity loading from the lower and Itaya River reaches are considered in this case. The figure shows the middle reach provides the greatest contribution to high turbidity at the Murasho station; high turbidity at the Murasho station is reduced by 26.17% on average if the middle reach is excluded from the simulation. The value was obtained by computing the percentage reduction of high turbidity in each time during high turbidity events, then the average value was calculated.

Table 4 Nash-Sutcliffe efficiency (NSE) and mean square error (MSE) for model performance

Performance	River reach				
	Upper	Middle	Lower	Itaya River	Murasho
NSE	0.45	0.49	0.51	0.36	0.48
MSE	3.98	3.86	5.63	159.86	11.86



(a) Original condition

(b) Simulation condition

Figure 5 Simulated turbidity results at the Murasho station, middle reach, lower reach, and Itaya River reach

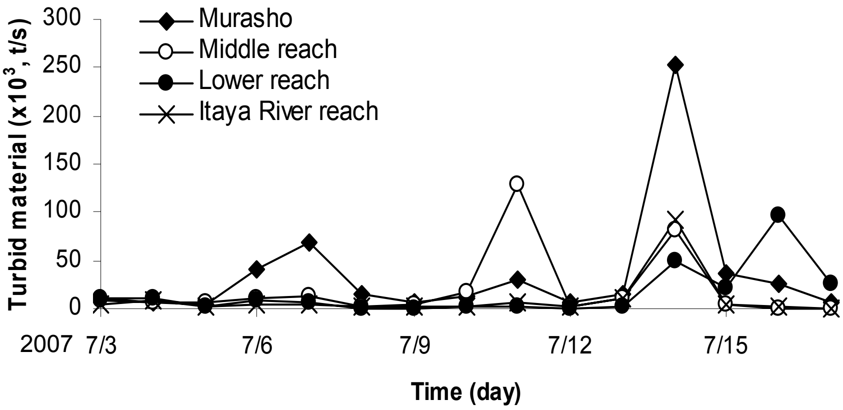


Figure 6 Turbid material at the Murasho station, middle reach, lower reach, and Itaya River reach during high turbidity events

Table 5 The contribution percentage of turbid material for each river to the Murasho station

	River reach			
	Middle	Lower	Itaya River	Murasho
Turbid material (t s^{-1})	296227	101782	146145	538854
Tributary contribution (%)	55	18	27	-

Loading from tributaries was also examined in terms of the turbid material load yielded. The simulated turbidity results in each reach were transformed into turbid material loads and subsequently used in calculating the percentage contribution to turbidity loading of the main river. Figure 6 shows the turbid material loads at the Murasho and in the middle, lower, and Itaya River reaches during high turbidity events.

From the figure, it can be seen that the average turbid material load was very high at Murasho station. Increases in the load were most likely caused by contributions from the tributaries upstream of the Murasho station. This study attempts to identify which tributaries contributed the most to high turbid material loads at the Murasho station. The calculated turbid material loads were summed over period of high turbidity events for each reach. Table 5 displays the percentage contributions of turbid material for reaches obtained using Eq. 8.

The results of numerical analyses showed the tributaries in the middle reach provided the largest turbid material contribution (296227 t s^{-1}) to high turbidity in the main river accounting for 55% of turbid material in high turbidity events at the Murasho station. This result agrees with the result of the calibrated model for which the middle reach had the largest value of γ (875 kg day^{-1}) indicating that lateral sources (turbidity from tributaries) were more active in this reach. This result was also conforms with the result of a geological study that classified the upstream of the Hitotsuse River watershed as having a potentially high level of turbidity based on its characteristic of geology (Examination committee of turbid water mitigation plan, 2008).

5. CONCLUSIONS

Conclusions drawn from this study are as follows.

1. The one dimensional model for sediment transport along river reach in the upstream region of the Hitotsuse River watershed was employed. The model was expanded by

including the turbidity loading from tributaries as sources in the model framework. The analysis results showed the model reasonably predicted turbidity concentrations.

2. From calibration of model parameters, the middle reach was found to have the largest value of γ (875 kg day^{-1}) indicating that lateral sources (turbidity from tributaries) were more active in this reach.
3. The middle reach made the greatest contribution to high turbidity since there was an average 26.17% reduction in high turbidity at the Murasho station when the middle reach was excluded from the simulation process. In terms of turbid material loading from tributaries, the study revealed that the tributaries in the middle reach provided the largest contribution (55%) to the high turbid material loads at the Murasho station.
4. Management of the middle reach is most essential in minimizing the generation of high turbidity in river stream in the upstream region of the Hitotsuse River watershed.

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