

## PARAMETER SENSITIVITY ANALYSIS OF A POLLUTANT PREDICTION MODEL FOR ESTIMATING SOIL SEDIMENT IN RIVERS WITH DIFFERENT SPATIAL SCALE

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### ABSTRACT

Suspended sediment load (SSL) is the main vector for pollutants and nutrients generated from river runoff by affecting the clarity and turbidity of the water and contributing to the distribution of toxic materials. Therefore, estimation of SSL is essential for characterizing water quality and water resources management. The aim of this paper is to propose a method to estimate the total amount of suspended sediment load carried by rivers across Japan. First, based on the analysis of SSL observation data at about 100 agricultural and forest watersheds in Japan, the relationships between SSL and hydrogeography were examined. Suspended sediment transport was found to be importantly affected by changes in river discharge and watershed characteristics. Then, an empirical model was proposed to test the national scale estimation for the indicator of SSL. The resulted estimation of SSL provided simulations in terms of the selected performance criteria comparing with the observed SSL. The  $R^2$  index is 0.717 for the empirical model. Finally, the parameter sensitivity analysis was then conducted for the proposed models for estimating SSL in rivers with different spatial scale. The calibrated model parameters of runoff load factor from soil type and river discharge are found to be the first and second highest among all factors. The impact factors of crop land and forest land are also larger than that of geology, basin area, and average elevation. This study provided a useful base for further investigation of soil sediment in rivers.

### 1 INTRODUCTION

The flux of suspended sediment plays an important role in hydraulics, hydrology, environment and ecology of rivers. High suspended sediment concentrations in rivers usually lead to high turbidity, which is important for aquatic life and contributes to the high cost of water treatment. Suspended sediment concentrations and loads are driven by precipitation and runoff but are influenced by land use and possibly exacerbated by agriculture, construction, as well as industrial and domestic effluent. Sediment transported into the reservoirs due to deforestation, construction and other human activities bring nutrient and toxin bound to them and may retain or release these

compounds when they reach the reservoir. Moreover, deforestation and erosion will cause the extreme cycles of flood and drought, which bring negative effects to humans, plants and animals living in the ecosystem. In addition, sediment is transported as suspended and bed loads by streams and rivers coming into a reservoir (Salas and Shin, 1999). It reduces reservoir storage capacity for flow regulation, water supply, flood control benefits, hydropower, navigation, recreation, and environmental benefit that depend on released from storage. In order to realize the integrated sediment management, it is necessary to know the total sediment load consisting of bed load, suspended load and wash load that is mainly produced and transported from upstream through downstream. Predicting the sediment coming into a reservoir, its deposition and accumulation throughout the years, after construction of the dam, has been important issue in hydraulic engineering. Heavy sedimentation rate shortens the lifetimes of lakes and reservoirs, destroys the aquatic habitats, reduces the reservoir's storage capacity and reduces the flood control capacity of reservoir (Alin et al. 1999). Some previous researches were focused on the relationships among suspended sediment load, channel and land area conditions (Wang et al., 2006), and suspended sediment, rainfall and runoff (Romero et al., 2008). However, reservoir sedimentation is a complex process that varies with watershed sediment production, rate of transportation, and mode of deposition (Sumi, 2000; Salas and Shin, 1999).

Japan is a developed country and has made significant efforts to improve river water quality in recent decades (He et al., 2009a, 2009b, 2010). The rivers in Japan are relatively short and the geography of Japan is generally steep in topography. Heavy rainfall events occur in Japan, especially in the rainy season and summer monsoon season (Saito et al., 2010). During typhoons and others extreme weather events, suspended sediment concentrations are a major concern for citizens, researchers and the government. The objective of this research is to estimate the suspended sediment loads in Japanese rivers for providing a better understanding of suspended sediment conditions in Japan.

## **2 DATA COLLECTION**

Japan is a country comprised of many islands, located in East Asia with 127.7 million inhabitants as of 2008. The total surface area of Japan is 377944 km<sup>2</sup> and 70% to 80% is covered by forest. From the viewpoint of conserving national land and contributing to the national economy, especially important river systems in Japan are called "first-class river systems." By the end of 1998, there were 109 rivers designated first-class. Due to the narrow and mountainous topography, the rivers are short with steep gradients and deep V-shaped valleys in the upper, more mountainous reaches. In this study, we selected a total of 100 rivers on the main islands of Japan. The available annual datasets of suspended sediment (SS) concentration were collected from 100 rivers with water quality observation stations located at the most upstream reservoirs of the selected rivers. The period of the collected data is available from 1964 to 2003 and they are published in the Electric Power Civil Engineering database by Japan Electric Power Civil Engineering Association (JEPOC). As a preliminary study, the river discharge data in 2003 was collected at those selected 100 observation stations in which the river discharge data is available, from the River Bureau of the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT).

National land use map with 100 meter mesh was obtained from the Geospatial

Information Authority of Japan, MLIT. The original types of land use include rice fields, upland fields, forest, waste land, building sites, arterial traffic sites, inland water areas, beach, seawater, and others. We reclassified these 11 types of land use to 5 types which are forest, agriculture, urban, road and other area. The areas of 100 river basins were created by using the “Create basin” tool in the hydrology analysis package of ArcInfo, and 50 meter mesh DEM data from Geospatial Information Authority of Japan, MLIT. Suspended sediment loads, which are used for quantifying the amount of suspended sediment in a river are calculated by using suspended sediment concentrations and river discharge.

The dam reservoirs’ SSL datasets used for model calibration in this study were selected according to the following conditions considering location, basin area and river discharge:

Located in the most upstream of each river and there are no other dams in its upstream watershed;

The calculated reservoir watershed area by GIS software is same to the actual one;

The observed river discharge data is available.

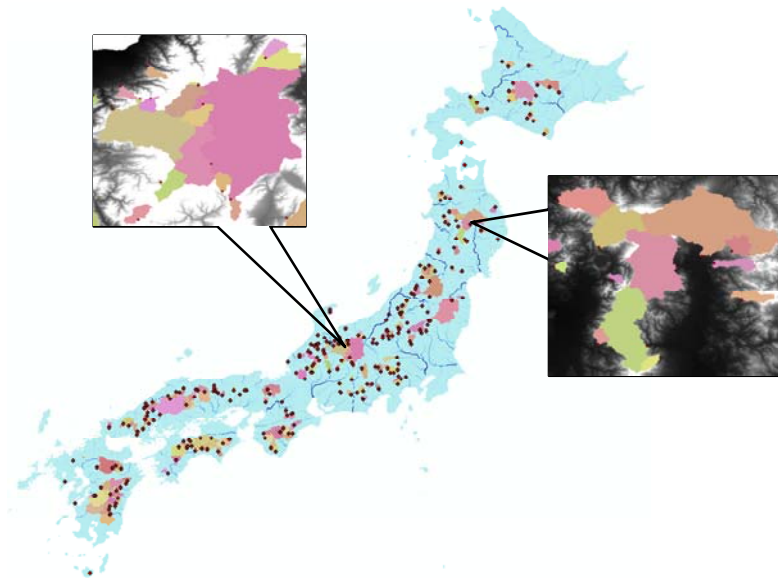


**Figure 1.** Location of the selected river basins with different spatial scales in this study.

**Table I.** All dam basins with available SS data.

| Region        | Numbers of Dam basin | Region   | Numbers of Dam basin |
|---------------|----------------------|----------|----------------------|
| Hokaido       | 33                   | Kitariku | 52                   |
| Tohoku (East) | 18                   | Kinki    | 33                   |
| Tohoku (West) | 80                   | Chugoku  | 43                   |
| Kanto         | 36                   | Shigoku  | 30                   |
| Chubu         | 56                   | Kyusyu   | 40                   |
|               |                      | Total    | 421                  |

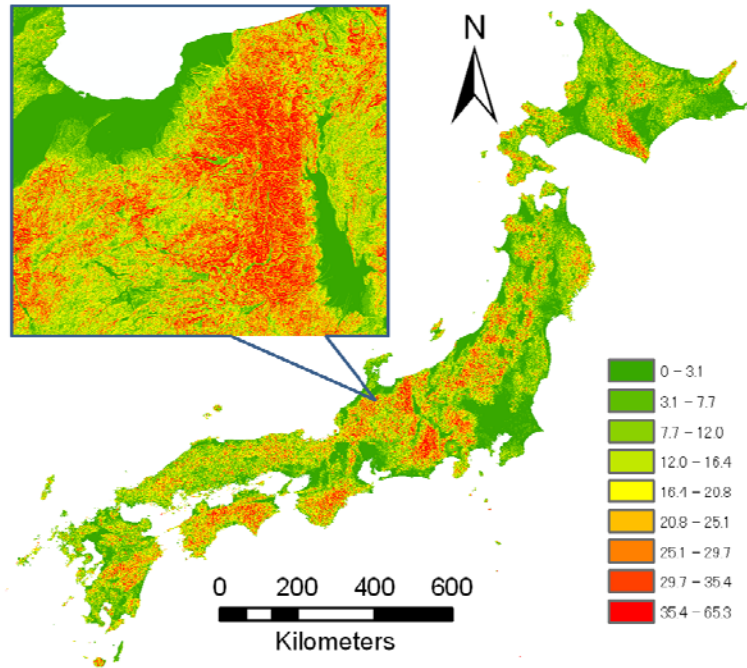


**Figure 2.** Generated slope angles by using GIS.

Thus, 100 reservoirs were selected from the original total 421 reservoirs (Table I) in the Electric Power Civil Engineering database. Figure 1 show the location of these 100 reservoirs across entire Japan. The watersheds of all the dam basins have different spatial scales. Their basin areas range from 6 to 1193 km<sup>2</sup>. For generating the spatial information of geology, soil type, and land use, ArcGIS has been employed in this study. Figure 2 shows an example of the generated slope angles by using ArcGIS software.

### 3 METHODS

Stream water quality is always correlated with stream discharge, especially during storm and snow-melt periods; and the relationship between stream water quality and stream discharge can be presented as below:

$$C = k \cdot Q^n \quad (1)$$

Where,  $C$  (mg/L) is the concentration of the water quality parameter,  $Q$  is river discharge (m<sup>3</sup>/s), and  $k$  and  $n$  are calibrated coefficients.

In the previous study (He et al., 2009a), based on the statistical analysis of the collected database and Equation (1), an optimized model was used to simulate the annual total SS flux by linking it with different environmental variables which account for both anthropogenic and natural variables. The model is shown for each river basin  $i$  as follows:

$$\frac{L_i}{A} = k \cdot \left( \frac{Q_i}{A_i} \right)^n \cdot \left( \frac{S_i}{A_i} \right) \quad (2)$$

Where  $L_i$  (kg/yr) is the annual SS flux discharged from basin  $i$ ;  $A_i$  (km<sup>2</sup>) is the basin area of river  $i$ ;  $Q_i$  (m<sup>3</sup>/yr) is the annual river discharge of a river in basin  $i$ ;  $S_i$  (kg/yr) is the annual SS load accumulating in basin  $i$ ;  $k$  and  $n$  are coefficients. In this equation, the effect of basin area on SS flux is removed with the division by basin area. The annual SS loads in each reservoir were estimated as the product of the annual average SS concentration and the annual discharge.

$$S_i = \sum_{j=1}^{LC} (U_j \cdot A_{ij}') \quad (3)$$

where  $j$  (=1 to  $LC$ ) means each category of class 1 to class  $LC$ ,  $U_j$  (kg/km<sup>2</sup> · yr) is the runoff load factor for each category  $j$ , and  $A_{ij}'$  [km<sup>2</sup>] is the land cover area of each category  $j$  in river basin  $i$ . In this study, we defined the runoff load factor of each category  $j$ .  $U_j$  (kg/km<sup>2</sup> · yr) can be expressed as an average value of the annual SS load accumulating in each category  $j$ .

In addition, sediment yield is the end product of erosion or wearing away of the land surface by the action of water, wind, ice, and gravity. the amount of sediment inflow to a reservoir depends on the sediment yield produced by the upstream watershed. The factors that determine a watershed's sediment yield can be summarized as follows (Strand and Pemberton, 1982):

- Rainfall amount and intensity, runoff
- Soil type and geologic formation
- Ground cover, land use, topography, slope, shape
- Upland erosion rate, drainage network density, size, and alignment of channels
- Sediment characteristics-grain size, mineralogy, etc.
- Channel hydraulic characteristics

Therefore, most of the empirical approaches for the estimation of erosion rate are based on one of the following methods:

- Universal Soil Loss Equation (USLE) or its modified versions
- Sediment yield as a function of drainage area
- Sediment yield as a function of drainage characteristics

In this study, the following model was proposed and tested to estimate the suspended sediments.

$$S_i = k \cdot (Q \cdot k_q + A \cdot k_a + ELV \cdot k_e) \cdot \theta \cdot \left( \sum_{j=1}^m LU_j \cdot k_{mj} + \sum_{j=1}^n SOL_j \cdot k_{nj} + \sum_{j=1}^p GEO_j \cdot k_{pj} \right) \quad (4)$$

where,  $m=8$ ,  $n=13$ ,  $p=20$

Where,  $S_i$  is the annual suspended sediment load (m<sup>3</sup>),  $Q$  is the river discharge (m<sup>3</sup>/s),  $A$  is the area of reservoir watershed (km<sup>2</sup>),  $ELV$  is the average elevation (m),  $\theta$  is the average slope angle (Degree),  $LU_j$  is landuse in each basin,  $SOL$  is soil type in each basin,  $GEO$  is geological type in each basin.  $k$ ,  $k_q$ ,  $k_a$ ,  $k_e$ ,  $k_{mj}$ ,  $k_{nj}$ ,  $k_{pj}$  are coefficients. To estimate these coefficients, minimization of the given criteria is carried out under the constraint of  $k_q$ ,  $k_a$ ,  $k_e$ ,  $k_{mj}$ ,  $k_{nj}$ ,  $k_{pj}$  being nonnegative (Eq. (5)):

$$\sum_{i=1}^{bsn} \left[ S_i - \left( k \cdot (Q \cdot k_q + A \cdot k_a + ELV \cdot k_e) \cdot \theta \cdot \left( \sum_{j=1}^m LU_j \cdot k_{m_j} + \sum_{j=1}^n SOL_j \cdot k_{n_j} + \sum_{j=1}^p GEO_j \cdot k_{p_j} \right) \right) \right] \rightarrow \min. \quad (5)$$

Where,  $bsn$  is the total number of river basins.

## 4 RESULTS AND ANALYSIS

### 4.1 Model results

The suspended sediment loads were estimated using the empirical method which is described in Section 3. As results, Fig. 3 shows an  $R^2$  of 0.717 and the trend line between the logarithm of estimated SS load and logarithm of predicted SS load is less than 45 degrees (1:1 line). This demonstrated the under-estimation of SS load by using the empirical model. The calibrated model parameters of runoff load factor from soil type and river discharge are found to be the first and second highest among all factors. The impact factors of crop land and forest land are also larger than that of geology, basin area, average elevation.

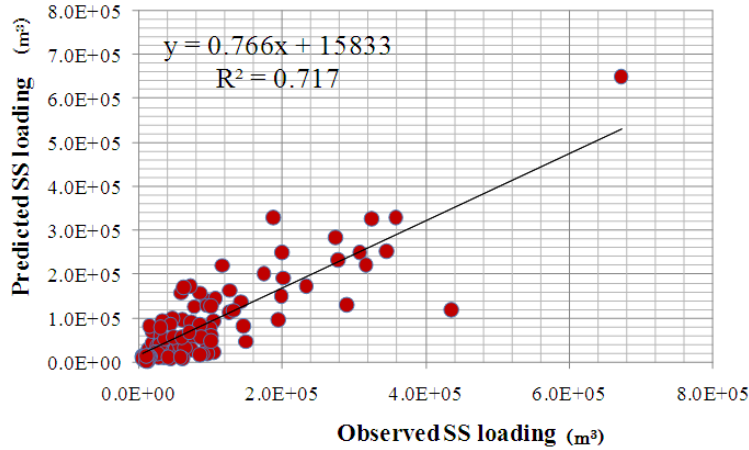


**Figure 3.** Scatter plot of observed and predicted SS loading by using the empirical model in this study (Equation 4-5).

Figure 4 shows the time series plot of observed and predicted SS loading by using the empirical model. From it, we can find that the SSL has been predicted well for most of the rivers. For some specific rivers, the SS loadings were not well predicted.

### 4.2 Uncertainty of model parameters

For estimating the uncertainty of parameters, two scenarios were assumed in this study (Table II). In scenario 1, the area ratio of agricultural land, forest, and river discharge are all increased by 5%. In scenario 2, the area ratio of agricultural land, forest, and river discharge are all increased by 10%.

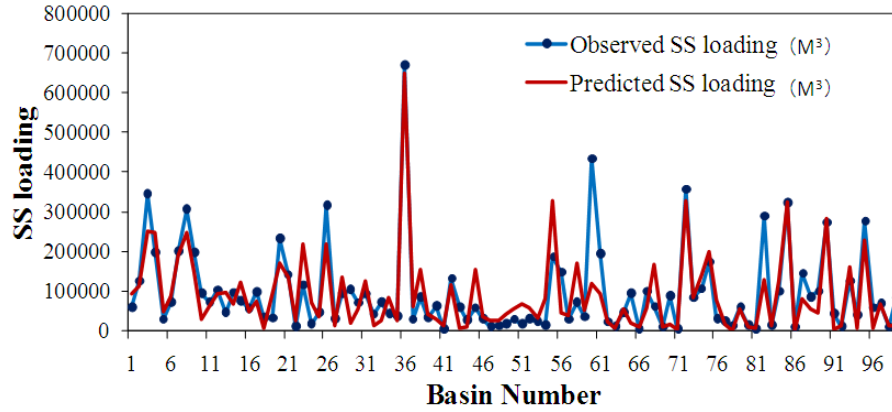


**Figure 4.** Time series plot of observed and predicted SS loading by using the empirical model.

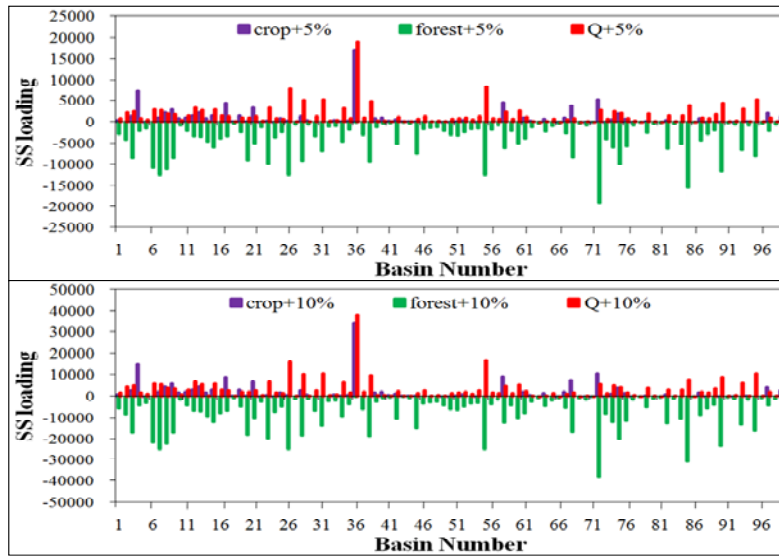


**Figure 5.** Predicted SS loading in different scenarios by using the empirical model.

From Figure 5, it can be found that the annual suspended sediment increased following to the increasement of agricultural land area and river dishcharge. The annual suspended sediment decreased following to the increasement of forest land area.

#### 4.3 DISCUSSION

Human activities such as land use change, dam construction and timber harvesting are likely major factors affecting suspended sediment (SS). Whereas natural erosion is limited to hilly and mountainous areas, the SS in the dams of central Japan is linked to agriculture, construction work and domestic and industrial effluent sources in residential

areas (Siakeu et al., 2004). The scenarios of 1 and 2 both demonstrated that farming activities will increase SS yield. Moreover, timber harvesting in the forested area can result in large sediment inputs into downstream rivers. Japanese cypress plantations under current management practices could yield larger amounts of SS than those from other undisturbed forests (Ide et al., 2009). Thus, forest management practices should consider the contribution on annual SS yield. However, human activities can also reduce the SS yield. For example, dams are artificial reservoirs which trap fluvial sediment and reduce the sediment transporting downstream (Mossa, 1996; Walling, 1997). Our previous study found that the large number of the rivers showing decreasing trends in SS concentration. It is probably caused by increasing dam construction during the last 3 decades. Good watershed management including sustainable management of land use and improvements in effluent treatment could reduce SS flux to the rivers (O'Hara et al., 1993; Tiffen et al., 1994).

Moreover, the increasing typhoon events and heavy rainfall events could directly increase SS concentration in Japanese rivers. Even though there is forest covering almost 80% of the Japanese land, the SS concentration is closely correlated with rainfall. Sediment flux is found to be sensitivity to climate change which showed higher sediment flux under wetter and warmer climate conditions. The simulation of the sediment transport regime driven by climate change in the Waipaoa River showed that suspended sediment flux may be expected to respond to longer-term variations in temperature and precipitation, and may also be connected to land management activities (Gomez et al., 2009). In this study, the empirical equations are tested using data collected from specific geographical areas across Japan. However, application of these equations should be limited to areas represented in this study.

## **5 CONCLUSIONS**

This study proposed a method to estimate the total amount of suspended sediment load carried by rivers across Japan. Based on the analysis of SSL observation data at about 100 agricultural and forest watersheds in Japan, the relationships between SSL and hydrogeography were examined. Suspended sediment transport was found to be importantly affected by changes in river discharge and watershed characteristics. The empirical model was proposed to test the national scale estimation for the indicator of SSL. The resulted estimation of SSL provided simulations in terms of the selected performance criteria comparing with the observed SSL. The  $R^2$  index is 0.717 for the empirical model. The calibrated model parameters of runoff load factor from soil type and river discharge are found to be the first and second highest among all factors. The impact factors of crop land and forest land are also larger than that of geology, basin area, and average elevation. This study provided a useful base for further investigation of soil sediment in rivers.

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