Precipitation Pattern and Intensity Control on the Sediment and Large Wood Discharges from River Catchments in the Japanese Archipelago

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1. Introduction

Water, sediment, and large wood (LW) are the three key components that provide templates for stream and riparian ecosystems. Stream flow carries sediment and LW pieces and determines landscape patterns of bars, floodplains, and LW distributions. Additionally, floods and stream flows supply moisture for riparian forests to grow, may destroy riparian forest patches, and can recruit LW pieces into streams. In turn, variations in flow depth, velocity, channel unit (e.g., pool, riffle, and slide), and the extent of the hyporheic zone are largely determined by sediment and LW accumulations.

Although these components has received high attention by ecologists and/or geomorphologists as a scientific theme, most of those studies has dealt with a single disturbance event at the reach scale, rather than the flow regime at the watershed scale. On the watershed-scale perspective, we therefore examined variations in sediment and LW discharges with respect to precipitation patterns and intensity using a nationwide database of monitoring results at dam sites.

2. Methods

2.1. Selection of the study watersheds

To examine sediment and LW discharges, we respectively selected 154 and 104 watersheds with (i) no upstream reservoirs, (ii) ratio of forest area to riparian zone area >0.85, corresponding to quasi-natural conditions of riparian zone, and (iii) with monitoring periods of at least 5 years to ensure that we could examine temporal trends in sediment and LW discharges.

We classified the selected watersheds by area into three categories to examine the size effect on sediment and LW discharges: small watersheds (<20 km^2), intermediate watersheds (20–100 km^2), and large watersheds (>100 km^2), based on the results from Seo et al. (2008) and Seo et al. (2012).

2.2. Estimation of sediment and LW discharges

The volumes of sediment and LW accumulated in dam reservoirs were monitored on a yearly basis by local reservoir management offices. Sediment accumulation was usually surveyed using the weight drop method or a single/multi-beam echo sounder, and sediment discharge (m^3 yr^{-1}) was calculated by net changes in volume between two consecutive years. LW accumulation was estimated from a survey of water surface area occupied by driftwood pieces or was calculated by counting the number of trucks filled with the removed driftwood pieces after their removal from each reservoir.

To remove the area-proportional effect of the watershed on sediment and LW discharges, sediment volume and LW data were transformed to express the sediment and LW discharge per unit watershed area (unit SED discharge, m^3 km^2 yr^{-1}; unit LW discharge, kg km^2 yr^{-1}).

2.3. Analysis of sediment and LW discharges with precipitation pattern and intensity

We compiled daily precipitation (DP) data, which were collected from the meteorological station closest to each study watershed and were monitored by the local reservoir management offices. From the DP data, we also calculated effective precipitation (EP), which is calculated by current and antecedent precipitation and is often used to predict the occurrence of sediment-related disasters:

$$EP_t = DP_t + \sum_{i=1}^{x} (0.5^{i/T_h}) \cdot DP_i$$

Here, EP_t (mm) is the EP of day t; DP_t (mm) is the DP of day t; DP_i (mm) is the DP of i day(s) before day t; T_h is the assumed period of time for precipitation to decrease its contribution to mass movement initiation by one-half (3 days in this study).

To include variation in the precipitation parameters (i.e., pattern and intensity), the latitude (LAT) of each reservoir site was evaluated using the channel network data.

To reveal explanatory variables that had the greatest influence on unit SED and LW discharges, we used a generalized linear mixed model (GLMM) with Gaussian error distribution and identity link function. The response variables were unit SED and LW discharges. The explanatory variables were (i) precipitation parameter, expressed as the cumulative DP or EP greater than a (0, 10, 20, ⋯, 130, 140, and 150 mm) or b (0, 10, 20, ⋯, 280, 290, and 300 mm) (DPc$\geq a$ or EPc$\geq b$), (ii) LAT category, classified into the lower- and higher-LAT zones with a threshold of 36° N, and (iii) interaction between variables (i) and (ii). In addition, to avoid pseudo-replication from the multiple annual measurement at each reservoir site, we considered “reservoir site” to be a random effect.

3. Results

3.1. LW discharge with respect to precipitation

In small watersheds, unit LW discharge did not vary with LAT, and EP was a strong predictor of LW discharge. By contrast, unit LW discharge in intermediate and large watersheds varied with LAT, and cumulative DP was the strongest predictor for unit LW discharge. Moreover, in intermediate and large watersheds, unit LW discharge was greater in the high-LAT zone than in the low-LAT zone in the range of comparable precipitation intensities. This can be interpreted as reflecting a supply-limited situation in southern Japan (low-LAT) and a transport-limited in northern Japan (high-LAT).

3.2. Sediment discharge with respect to precipitation

The same analysis conducted for sediment discharge revealed trends similar to those of LW discharge. Unit SED discharge was greater in the high-LAT zone than in the low-LAT zone, and EP was a significant, strong predictor in small watersheds. However, several differences were found. Unit SED discharge exhibited larger variation than does unit LW discharge along the precipitation gradient. Unit SED discharge varied between high- and low-LAT in all sizes of watersheds, including small watersheds, but corresponding slopes of the regression models were similar between the two latitudinal zones. However, the regression slopes for unit LW discharge differed substantially in intermediate and large watersheds. Moreover, the daily precipitation intensities most related to the unit SED discharge in intermediate and large watersheds were ≥20 and ≥30 mm, respectively; whereas those for unit LW discharge were ≥40 and ≥60 mm, requiring greater precipitation for transport.

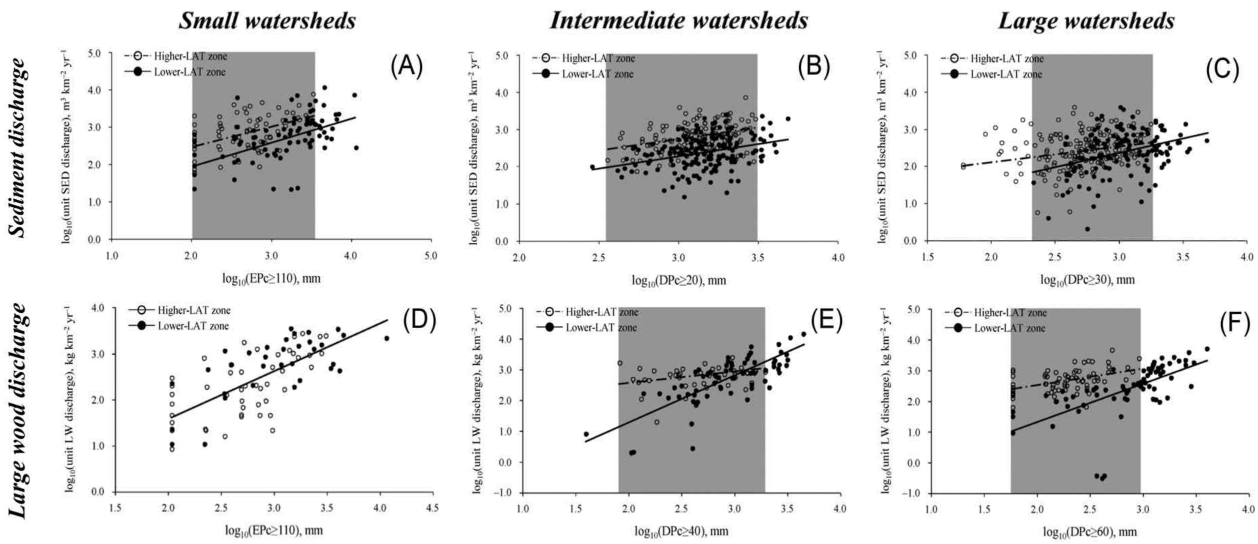

Figure 1. Changes in sediment (A, B, and C) and LW (D, E, and F) discharges per unit watershed area in relation to precipitation and latitude in small, intermediate, and large watersheds.

4. Discussion

In small watersheds with narrow valley floors and low water discharges, the effective precipitation required to initiate mass movements, such as landslides and debris flows, regulated the sediment and LW discharges. However, sediment discharge differed with the latitude unlike LW discharge, and this should be because, whereas tree biomass on hillslopes does not differ much between southern and northern Japan, less precipitation in northern Japan may allow sediment to be retained on hillslopes.

In intermediate and large watersheds with wide channel widths and high water discharges, heavy rainfall and subsequent floods, caused by the daily precipitation, achieved the shear stress to transport sediment and the buoyant depth to initiate LW movement. In southern Japan, heavy rainfall accompanying typhoons and torrential downpours frequently scour sediment and transport LW pieces from valley floors; their discharge are supply-limited. Conversely, in northern Japan, where typhoons and major seasonal rain fronts are rare, sediment and LW can be stored on wide valley floors and their movement is transport-limited. Only difference in sediment and LW discharges was found in the intensity of precipitation, and this should be due to the differences in particle shapes (small spherical sediment vs. large cylindrical LW forms) and the related transport mechanism to channel size (width and/or depth).

These flow regimes may continue or reach another dynamic state of quasi-equilibrium in the future, and thus the continued monitoring is critical to anticipating future change in stream ecosystems.

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