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Article

Effect of Hydrograph Separation on Suspended Sediment Concentration Predictions in a Forested Headwater with Thick Soil and Weathered Gneiss Layers

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Abstract: Two-component hydrograph separation using oxygen-18 concentrations was conducted at a sediment runoff observation weir installed in a small subcatchment of a forested gneiss catchment in Japan. The mean soil thickness of this catchment is 7.27 m, which comprises 3.29 m of brown forest soil (A and B layers) and a 3.98-m layer of heavily weathered gneiss. Data were collected for a storm on 20–21 May 2003, and the percentage of event water separated by the stable isotope ratio in comparison with the total rainfall amount was about 1%. This value is within the ratio of a riparian zone in a drainage area. Temporal variation of suspended sediment concentration exhibited higher correlation with the event water component than with the total runoff or pre-event water component. This shows that the riparian zone causes rainwater to flow out quickly during a rain event, and that this is an important area of sediment production and transportation in a forested headwater with thick soil and weathered gneiss layers.

Keywords: event and pre-event waters; hydrograph separation; subsurface stormflow; suspended sediment; riparian zone

1. Introduction

Soil sediment discharge from a forested catchment has been studied for over 60 years [1–3]. These studies have shown that soil sediment discharge is related to drainage area, rainfall intensity, and vegetation type and density. Recently, the relationship between suspended sediment (SS) concentration and runoff amount has been observed in small, forested catchments in various parts of the world [4–7].

In Japan, attention to research on runoff and SS concentration from forested catchments has increased remarkably following the Great East Japan Earthquake on 11 March 2011. Radioactive material, such as Cs, was released because of the accident at the Fukushima Daiichi nuclear power plant. Although forest ecosystems are thought to exhibit a tendency to retain radioactive Cs, there is concern that radioactive Cs might flow out from forest ecosystems in steep areas when subject to considerable rainfall—environments and weather conditions that are common in Japan [8]. Shinomiya *et al.* [8] observed that radioactive Cs in a small, forested catchment in Fukushima Prefecture mainly flowed out as suspended matter.

Over the past several decades, research into the rainfall-runoff process for small catchments has been progressed via the use of tracer information [9–12]. A small, forested headwater is the beginning of a river and serves as the minimum unit of the water budget and nutrient cycles in a forest ecosystem [13]. Moreover, as the objective area is relatively small, detailed observations of geographical features and of the situation generating storm runoff, both in and around a stream channel, are also possible. However, few reports of work exist in which the variations of component separation by stable isotope ratio and SS concentration have been observed simultaneously by such research.

Measurement of water and sediment discharge from a headwater catchment is the most elementary study for soil and water conservation. Williams [14] suggested that there is hysteresis between SS concentration and runoff from a catchment. This hysteresis has been an obstacle when the temporal variations of SS concentration and discharge have been modeled simultaneously, and much research relevant to this topic has been performed [15,16]. To improve the predictive accuracy of models forecasting SS runoff from a catchment, it is thought necessary to promote the understanding of both the streamflow mechanism and the SS transport process within a catchment.

Research clarifying the streamflow mechanism from a catchment using a stable isotope tracer is progressing steadily. For example, by measuring the stable isotope ratio, runoff water and event rainwater can be separated into two components: pre-event water and event water [17–19]. Many reports describe the simultaneous observations of dissolved ion concentration and stable isotope ratio in runoff water [20,21]; however, only a few studies report simultaneous observations of SS concentration and stable isotope ratio in runoff water.

This research simultaneously observed the temporal change of the stable isotope ratio of stream water and SS concentration during storm runoff in a small, forested catchment. By performing hydrograph separation using a stable isotope tracer, the relation between each component of runoff and SS concentration was investigated. The runoff mechanism and the SS transport process were considered by comparing these results with information relating to geographical features, especially the riparian zone. The riparian zone refers to the area relating to the stream bank, and the function of this zone has been studied recently with respect to both ecological and hydrological aspects [22].

In this research, a riparian zone is defined as the area that is constantly in a state of wet condition around a spring point and a stream channel between stream banks. Strictly, the spring point and stream channel are not classified as the riparian zone, but such areas are relatively small and thus, they are also included within the definition in this paper. On the other hand, the field of hillslope hydrology provides a related technical term, "source area". This is defined by the "variable source area concept" of Kirkby [23], and it means an area within a catchment that contributes to storm runoff. This paper also follows this definition.

Research is progressing with regard to the function of the riparian zone as a site for the generation of soil and water movement. The results of this research could be expected to be useful in clarifying the function of water and soil movement in a riparian zone of a small, headwater catchment with thick soil and weathered gneiss layers.

2. Experimental

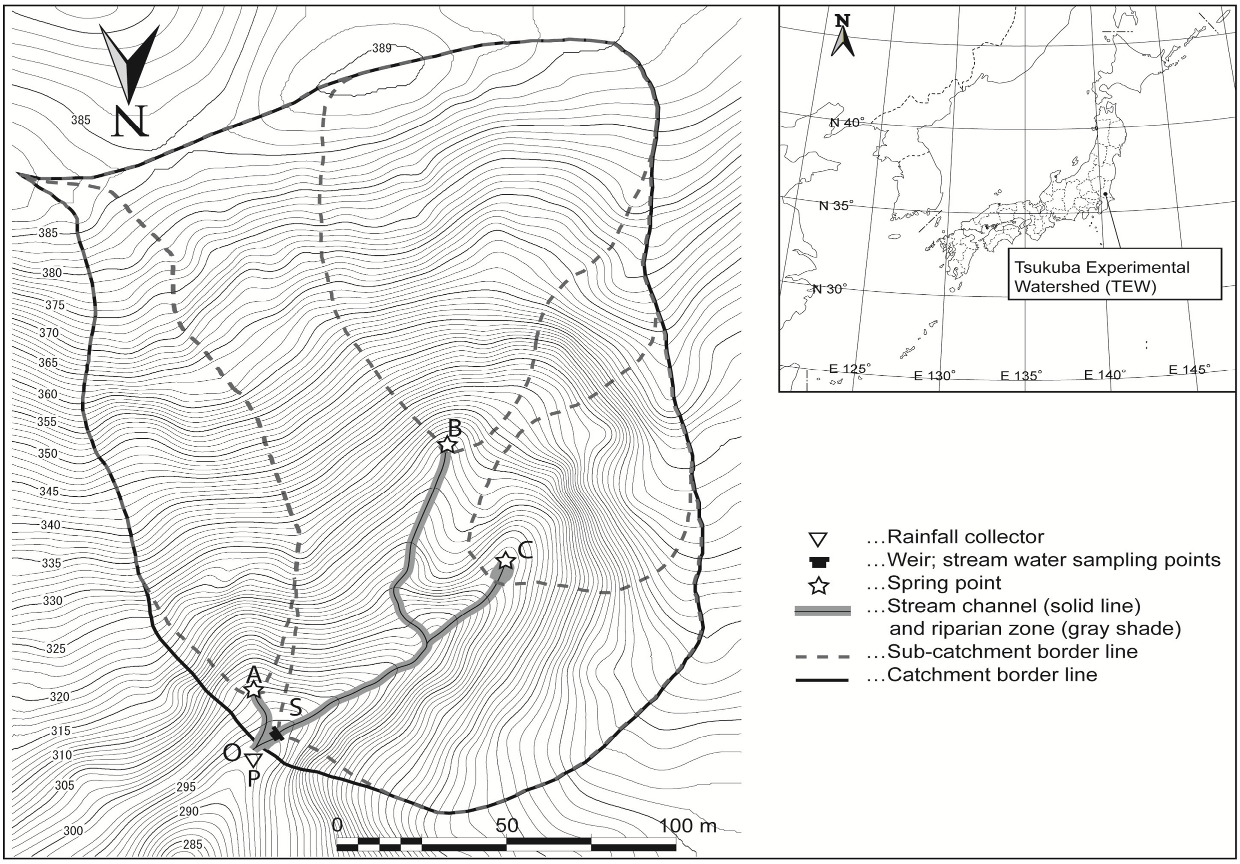
2.1. Study Area

The research was conducted in the Tsukuba Experimental Watershed (TEW), located in southern Ibaraki Prefecture, Japan (36°20' N, 140°18' E; Figure 1). In 1978, this watershed was established as an experimental study site for investigations of hydrological processes in a forested mountainous area [24]. The watershed drains 3.79 ha. The main slope direction is to the north and the mean slope is 25°. In the 10-year period from 1972 to 1981, the average annual air temperature was 14.1 °C at Kakioka, which is the nearest weather station (36°14' N, 140°12' E; altitude 27.7 m). The annual rainfall and discharge from 1979 to 1990 (excluding 1988 when data were lacking) were 1429.1 and 641.6 mm, respectively. Although the TEW experiences several snowfalls per year, snow depths greater than 20 cm are rare and most precipitation is rainfall. Geologically, the watershed is composed mainly of biotite gneiss overlain by weathered volcanic ash; the soil in this area is brown forest soil, or Cambisol in the FAO classification [25]. Plantations of *Cryptomeria japonica* (common name "sugi" or Japanese cedar) and *Chamaecyparis obtusa* ("hinoki" or Japanese cypress) are the main types of vegetation. *Pleioblastus chino*, a type of bamboo grass, and *Aucuba japonica*, an evergreen shrub, both grow on the forest floor. The mean soil thickness is 7.27 m, which comprises 3.29 m of brown forest soil (A and B layers) and a 3.98 m layer of heavily weathered gneiss [26,27].

The stream channel in the TEW originates from three springs (Figure 1) and is one of the headwaters of the Koise River that flows into Lake Kasumigaura as part of the Tone River system. To observe the discharge from the three spring subcatchments, 60° V-notch flow-gauging weirs are operated at the three springs (referred to as A, B, and C). The drainage areas of subcatchments A, B, and C are 0.60, 0.93, and 0.36 ha, respectively. The discharge amount from the entire TEW is observed by a 45° V-notch flow-gauging weir at point O (Figure 1). Based on the results of a drilling investigation, an impermeable wall structure was constructed through the subsurface at point O and attached to the base rock (6.0 m depth); the weir was then built to measure the amount of watershed outflow [24]. In contrast, the impermeable walls of weirs A, B, and C are only 1.2 m deep and are not attached to the rock. In addition to these weirs, a temporary flow-gauging weir was placed at point S in the TEW to observe flow and to investigate sediment production in the forested catchment;

observations were conducted at this weir for about two years from May 2003, to May 2005. The S subcatchment drains an area of 2.97 ha. Zhang *et al.* [28] reported that for the S subcatchment, the discharge amount of SS was determined mainly by the maximum 10-minute precipitation. Each rainfall event also greatly contributed to SS discharge. The SS discharge from one storm accounted for about 5% of the total annual sediment discharge and that from a few storms contributed about 30% of the yearly SS discharge. In addition, the observation of annual sediment discharge and the application of a 5-m meshed distributed type sediment discharge model have been conducted within this catchment [29]. Shimizu *et al.* [29] showed that the annual sediment discharge of the S subcatchment was 0.372 t/year. They applied the distributed type sediment yield model to this catchment and concluded that the area of high sediment production was restricted to the riparian zone near the stream channel in the catchment.

Figure 1. Topography and observation points in the Tsukuba Experimental Watershed.



At spring points A and B, the flat valley bottoms are very narrow (only 0.5 m^2), whereas the valley bottom at spring C is 31.2 m^2. The S and O watersheds contain parts of the stream channel (Figure 1), and the area of the riparian zone of the S subcatchment was calculated by detailed survey as 492.0 m^2. This included the riparian area along the stream channel (stream length (153.4 m) × riparian width (3.0 m) = 460.3 m^2) and the total flat valley bottom area (flat valley bottom of B catchment (0.5 m^2) + flat valley bottom of C catchment (31.2 m^2) = 31.7 m^2) of the wet zones of the B and C catchments. Therefore, the percentage of the drainage area occupied by the riparian zone in the S subcatchment is 1.7%. This riparian zone is including stream channel. In this study, the SS and stable isotope of the runoff were assessed at the V-notch in the S subcatchment of the Tsukuba Experimental Watershed

(Figure 1). Precipitation was observed by a tipping bucket rain gauge (1 tip = 0.1 mm; Ikeda Keiki Co., Tokyo, Japan) installed on the roof of the catchment gauging station at O (Figure 1). In addition, because event water sampling was performed every hour from 17:15 on 17 May 2003, the precipitation and runoff data were also arranged as hourly values at corresponding times, *i.e.*, commencing at 15 min past the hour.

2.2. Storm Runoff Observation and SS Concentration Analysis

The collection of stream water was performed using automatic water sampling equipment (model 6700; Teledyne Isco, Lincoln, NE, USA), and the SS concentration and stable isotope ratios of the sampling water were analyzed in the laboratory. Water sampling was set up to obtain samples every hour when the rainfall intensity was 1.5 mm/h or more. Thus, the rain event from 20 to 21 May 2003, was applicable to this research. This 19 h rainfall event produced 52.1 mm of total rainfall with a peak hourly intensity of 24.6 mm/h (Table 1).

Table 1. Characteristics of the observed rainfall event.

Rainfall characteristic	**Amount or Time**
Total rainfall amount (Σ P) (mm)	52.1
Start time of the rainfall event	16:15 on 20 May 2003
End time of the rainfall event	11:15 on 21 May 2003
Duration of rainfall (hours)	19
A maximum 1-hour rainfall intensity (mm)	24.6
The time of a maximum 1hour rainfall intensity	18:15 on 20 May 2003

After passing a water sample through a 106-μm-mesh sieve at the laboratory, 20 cc were isolated in an airtight, screw-top vial for the stable isotope analysis. Next, it was filtered using the suction filtration machine equipped with glass filter paper, which was weighed after drying at 105 °C for 3 h. The GF/F filter (d = 0.47 μm; Whatman, UK) was used for suction filtration. After filtration, the glass filter paper was placed in the drier and dried at 80 °C for 48 h, and then weighed with an electronic balance. The difference in weight before and after drying at 80 °C serves as a measurement of the amount of SS contained in the sample.

Rainwater was gathered in a 20 L plastic bottle, which was attached to a 21 cm-diameter funnel installed on the roof of the water level gauging house at O (Figure 1). To prevent the evaporation of rainwater saved in the bottle and causing a change in the stable isotope ratio, silicone oil was added to the bottle at the time of commencement of sampling, which made a film on the water's surface. Subsequently, the bottle was returned to the laboratory and the oil was removed using a separation funnel. The rainwater obtained in this way was saved in airtight 20 cc screw-top glass vials.

2.3. Stable Isotope Analysis

A mass spectrometer (MAT252; Thermo Scientific, Waltham, MA, USA) was used for the oxygen stable isotope analysis of the water samples. The CO_2–H_2O equilibrium method was used to measure the hydrogen and oxygen stable isotope ratios. The isotope ratio was expressed as the δ value with respect to that of the Vienna Standard Mean Ocean Water (V-SMOW), which is given as:

$$\delta^{18}\mathrm{O}_{sa} = \left(\frac{(^{18}\mathrm{O}/^{16}\mathrm{O})_{sa}}{(^{18}\mathrm{O}/^{16}\mathrm{O})_{re}} - 1 \right) \times 1000\,‰\ \mathrm{V\text{-}SMOW} \tag{1}$$

where *sa* and *re* refer to the sample and standard reference, respectively. V-SMOW is a standard reference material for measuring stable isotope ratios in water. The standard uncertainties of the $\delta^{18}O$ measurements were ±0.02%.

2.4. Storm Runoff Hydrograph Separation Using Tracer Information

The runoff component of the stream water is divided into the "event water" (event rainwater) newly added to the catchment in connection with the rain, and the "pre-event water" (precedent moisture) already stored in the catchment before the onset of the rain. The contribution of each runoff component to the rate of total runoff can be calculated using the hydrograph separation method with a tracer. If it is assumed that a chemical reaction does not arise between the event and pre-event waters during the observation time, then the following two equations can be formed for an observed section of a catchment [9]:

$$Q_t = Q_{evt} + Q_{pre} \tag{2}$$

$$C_t\,Q_t = C_{evt}\,Q_{evt} + C_{pre}\,Q_{pre} \tag{3}$$

Here, Q is the discharge; C is the tracer concentration; and subscripts t, evt, and pre express the total runoff, event water, and pre-event water, respectively. The contribution of the pre-event water to the total runoff, derived from Equations (2) and (3), is given by the following Equation:

$$Q_{pre} = [(C_t - C_{evt})/(C_{pre} - C_{evt})]\,Q_t \tag{4}$$

In Equation (4), Q_{evt} and Q_{pre} are unknowns, whereas Q_t could be surveyed as a streamflow rate and used as the observed runoff from the S subcatchment.

3. Results and Discussion

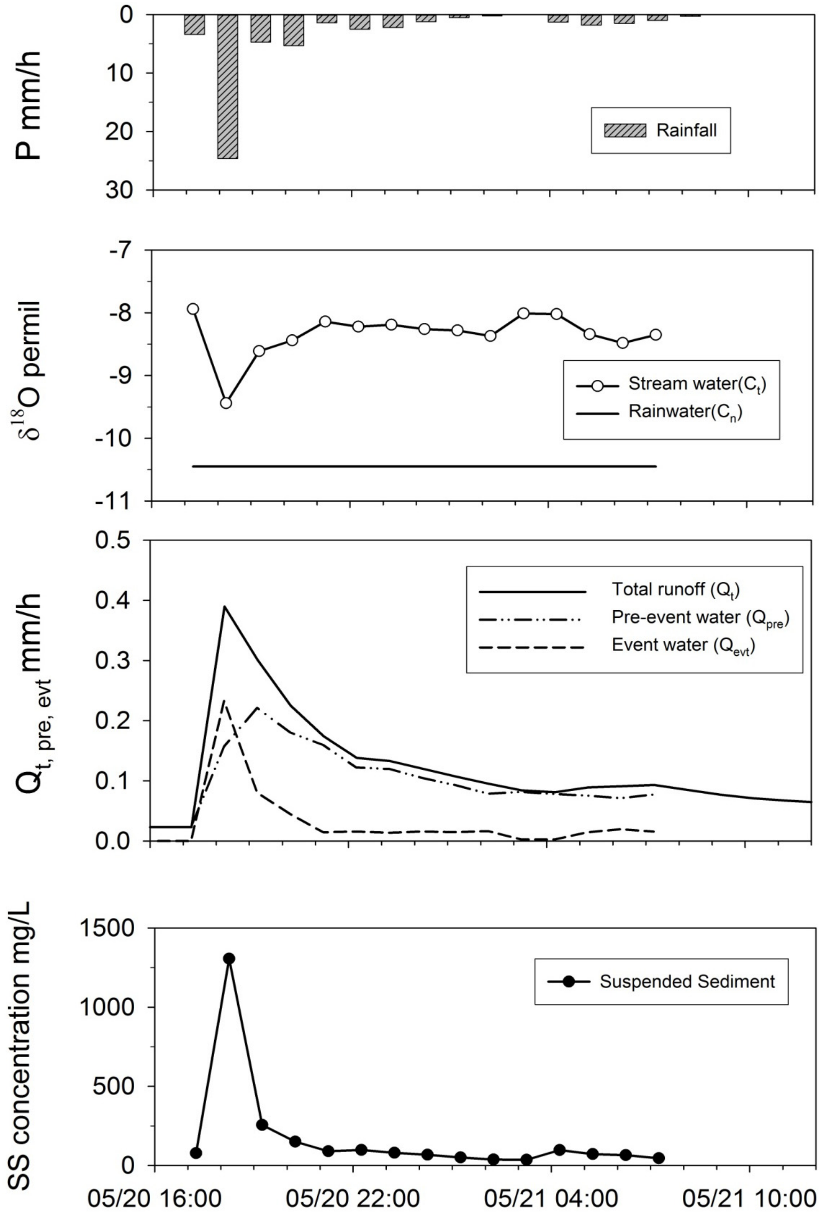
3.1. Hydrograph Separation by Stable Isotope Ratio

The timing of peak runoff was coincident with the peak of precipitation. Moreover, the peak of SS concentration was also coincident with the peaks of precipitation and runoff (Figure 2). These findings were similar to previous researches conducted within this catchment [28,29].

The $\delta^{18}O$ value of the stream water immediately after the start of the event (17:15 on 20 May 2003) was −7.94%. Two weeks after the end of the rain event, the streamflow had returned to the baseflow state. The $\delta^{18}O$ value of the stream water sampled in the baseflow state was the same as that of the stream water at the onset of the rainfall event. Therefore, the $\delta^{18}O$ value of the pre-event water was assumed fixed at −7.94% during the rainfall event.

Thus, the $\delta^{18}O$ value of the pre-event water (C_{pre}) during the event period was set as −7.94%. The measured value of the isotopic ratio of the rain during the event period was −10.45%. This value was set as the $\delta^{18}O$ value of the event water (C_{evt}). By setting the $\delta^{18}O$ value of the hourly sampled stream water to C_t, Equation (3) was used and the runoff at each interval was separated into two components: event water and pre-event water. Thus, when precipitation and runoff simultaneously reached their peaks, the contribution rate of the event water was the highest, which was determined as 60% (Figure 2). The temporal variation of the event water component exhibited a similar pattern to that of SS concentration. The peak of the pre-event water component was 1 h after the peak of the event water component and SS concentration.

Figure 2. Temporal variations in rainfall, runoff, suspended sediment (SS) concentration, and oxygen-18 concentration, and the result of hydrograph separation using oxygen-18 concentration.



The result of hydrograph separation using the stable isotope tracer is shown in Table 2. The ratio of the runoff component of event water to the total rainfall is 1.0%. This is within the value of 1.7% for the ratio of the riparian zone to the drainage area, based on a survey result of the S subcatchment when the riparian zone width was 3.0 m.

Table 2. Storm runoff amounts separated by stable isotope tracer information.

Runoff component	Symbol	Runoff Amount (mm)	Percentage (%)
Total runoff amount	ΣQ_t	2.17	
The pre-event component water	ΣQ_{pre}	1.66	
The event component water	ΣQ_{evt}	0.50	
The ratio of pre-event component water to total runoff amount	$\Sigma Q_{pre}/\Sigma Q_t$		77
The ratio of event component water to total runoff amount	$\Sigma Q_{evt}/\Sigma Q_t$		23
The ratio of total runoff amount to total rainfall amount	$\Sigma Q_t/\Sigma P$		4.2
The ratio of pre-event component water to total rainfall amount	$\Sigma Q_{pre}/\Sigma P$		3.2
The ratio of event component water to total rainfall amount	$\Sigma Q_{evt}/\Sigma P$		1.0

The stream and hillslope conditions were checked several times during rainfall events, and no overland runoff on the hillslope was observed; *i.e.*, the streamflow was flowing only within the stream channel.

The ratio of event water to total runoff was 23%, and that of pre-event water to total runoff was 77%. The generation of most of the event component of the water was restricted to a few hours with strong intensity rainfall. Most of the recession period of the hydrograph comprised the pre-event component of the water.

3.2. Runoff Generation Mechanism

In the TEW, as in other forested catchments, the infiltration capacity of the soil surface was high and Horton overland flow was not observed during the rainfall events. However, the topographical features and soil structure of this catchment are quite different from other catchments. In this catchment, the watershed has a thick covering of a highly permeable soil layer and a weathered gneiss layer. However, the valleys around the spring points are steep and narrow, and groundwater exists in the weathered gneiss layer rather than the soil. For these reasons, changes of the groundwater level in the source area are small, and a riparian zone can be considered almost the same as the source area. This differs from other forested catchments where the source area expands more significantly than the usual riparian zone, for example, where the saturated throughflow dominates runoff generation in weathered granite catchments [30,31] or in normal vegetated catchments [32]. The spring water is provided by groundwater flow through the weathered gneiss layer [33]. In subcatchments A and B that almost do not have a riparian zone, the runoff hardly increased for small-scale rainfall events of 20 mm or less, and the runoff showed a slow response for large-scale rain events of 100 mm or more [27]. The hydrographs of subcatchments A and B are similar to the upper weir at CB1 of Figure 4, in Anderson *et al.* [34], which represents a steep unchanneled catchment with thick weathered layers. On the other hand, subcatchments C and S and the entire catchment at O, which have riparian zone, respond quickly to small-scale rainfall events in the catchment [27]. When a large-scale rainfall event occurred, the quantity of the baseflow of all subcatchments and the entire catchment rose significantly and the baseflow took seven months to come back to pre-storm conditions after a large event [27].

This implies that the quick runoff component is related to the size of the riparian zone within a catchment and the slow runoff component is related to the groundwater flow through the weathered gneiss layer.

The total rainfall during this study was 52.1 mm, which is a mid-scale rain event for this catchment. However, almost half of the total rain fell during a 1 h period of peak rainfall. In the hydrograph separation of the S subcatchment, the runoff peak comprised 60% event water. The runoff of event water occurred only at the time when rainfall was strong. In this catchment with soils that are deeply weathered and have generally high infiltration capacities, surface runoff is restricted mainly to the stream channels, so the storm runoff production must be controlled by subsurface response. Based on this, it is considered that the runoff component of event water comprised subsurface stormflow from the riparian zone. Although the source area in a riparian zone is changed for every rainfall event, it is probably decided by intensity of rainfall and antecedent moisture conditions.

On the other hand, the peak runoff component of pre-event water was 1 h later than the peak of the event water. Moreover, pre-event water comprised a greater proportion of runoff water at the time of recession, when the rainfall intensity had weakened. Thus, the runoff component of pre-event water is mainly formed by groundwater flow.

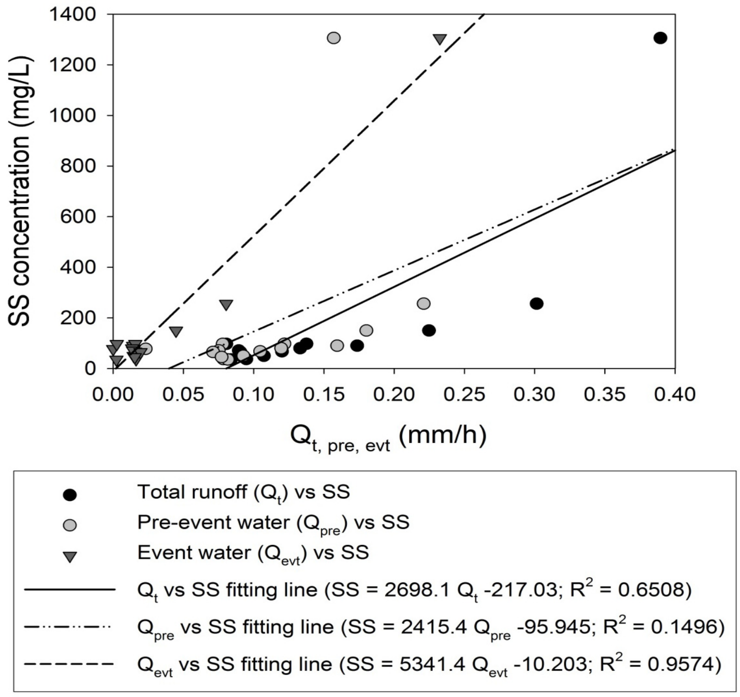
3.3. Runoff Component and SS Concentration

The SS concentration at each interval was compared with the relation between the total runoff (Q_t), runoff (Q_{pre}) of a pre-event water component, and runoff (Q_{evt}) of an event water component, and the regression line between each runoff component and the SS concentration was calculated (Figure 3). The coefficient of determination of the regression line to the SS concentration of Q_t was $R^2 = 0.6508$, the coefficient of determination of the regression line to the SS concentration of Q_{evt} was $R^2 = 0.9574$, and the coefficient of determination of the regression line to the SS concentration of Q_{pre} was $R^2 = 0.1496$. Thus, the highest correlation is seen between SS concentration and the runoff of an event water component. From this, the subsurface stormflow component generated with event rainwater can be said to play an important role in SS concentration formation during the peak hour. The width in a stream channel in this catchment was an average of 0.30 m, and this was not expanded too much even at the time of a heavy rain. Stream bed material was covered with many stones and soil sediment was stored between the stones. In a heavy rainfall intensity, subsurface stormflow is generated in the riparian zone, and it flows into the stream channel. As a result, soil sediment in the stream channel is transported by tractive forces of streamflow.

The event water component is constituted by the subsurface stormflow that occurs in a riparian zone. At this catchment, the temporal variation of SS concentration depended on the intensity of rainfall over a short unit of time (10 min) [28], and soil sediment production is only active in the riparian zone [29].

Thus, the source areas of water runoff and sediment production overlapped in the riparian zone of this catchment, which is why it is thought that the correlation of temporal variation of subsurface stormflow and SS concentration increased.

Figure 3. Relationship between suspended sediment (SS) concentration and total runoff (Q_t), runoff of pre-event water component (Q_{pre}), and runoff of event water component (Q_{evt}).



Lenzi and Marchi [35] investigated the relation between runoff and SS concentration in extremely steep mountainous catchments (mean slope: 52°) of the Dolomites in the Italian Alps. Vegetation cover consisted mainly of herbaceous associations and 14% of the catchment comprised bare land. They reported that the relation varied, but found a case where the SS concentration peak appeared after a runoff peak. Following a particle size analysis, they also reported that the origin of SS was not the stream channel, but the erosion of a slope. Based on their findings and the results of this research, it can be suggested that the difference in the spatial origin of SS within the catchment determines the relation between runoff and SS.

4. Conclusions

This research simultaneously observed the temporal change of the stable isotope ratio of stream water and SS concentration during storm runoff in a small, forested catchment with thick soil and weathered gneiss layers. By performing hydrograph separation using a stable isotope tracer, the relation between each component of runoff and SS concentration was investigated. The runoff and SS concentration during a storm event were shown to peak simultaneously with the maximum intensity of rainfall, which is similar to the findings of previous researches conducted within this catchment [28,29]. The percentage of event water to the total rainfall amount, separated by the stable isotope ratio, was about 1%. This value is within the ratio of a riparian zone within a drainage area. It is considered that the runoff component of event water comprised subsurface stormflow from the riparian zone. Although the source area in a riparian zone is changed for every rainfall event, it is probably decided by intensity of rainfall and antecedent moisture conditions. In a heavy rainfall intensity, subsurface stormflow is generated in the riparian zone, and it flows into the stream channel.

And soil sediment in the stream channel is transported by tractive forces of streamflow. These results suggest that the riparian zone causes rainwater to flow out quickly during a rain event in a forested headwater and that it is an important area for sediment production and transportation.

Temporal variation of SS concentration exhibited higher correlation with the event water component than with total runoff or the pre-event water component. SS discharge correlates well with event-based runoff, and the runoff mechanisms responsible for bringing event-based water to the stream channel during storm events are also likely responsible for increasing the sediment load of the stream channel, thus the runoff mechanism and sources are a critical component to sediment budgets in headwaters.The SS discharge process, based on the runoff mechanism determined by tracer information, was examined and it was established as effective to have used the event water extracted by the stable isotope tracer as a factor of direct SS concentration formation. To reduce the hysteresis between SS concentration and runoff, it was effective to extract the event water component, as a direct driving force for transporting SS, using stable isotope tracer information.

The source areas of water runoff and sediment production overlapped in the riparian zone of this catchment. Such a feature originates in the geographical features and soil structure of this catchment. Thus, in such a case, it is especially important for sediment management to preserve the riparian zone.

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Author Contributions

The study was design and conceived by Naoki Kabeya and Akira Shimizu. Fieldwork was carried out in the Tsukuba Experimental Watershed by Naoki Kabeya, Jian-Jun Zhang and Tastuhiko Nobuhiro under the supervision of Akira Shimizu. Stable isotope analysis was carried out by Naoki Kabeya with the mass spectrometer of Forestry and Forest Products Research Institute. Hydrological analysis was carried out by Tatsuhiko Nobuhiro and Naoki Kabeya under the supervision of Akira Shimizu. Sediment analysis was carried out by Jian-Jun Zhang and Tatsuhiko Nobuhiro under the supervision of Akira Shimizu. The manuscript was largely written by Naoki Kabeya and Akira Shimizu but all authors contributed to the writing and review of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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