Runoff characteristics of major ionic species during rain events in forested watershed

A.Y. Komai*, S. Umemoto* and T. Inoue**

*Hyogo Prefectural Institute of Environmental Science, 3-1-27 Yukihiracho Suma Kobe, 654-0037, Japan
**Department of Civil Engineering, Gifu Univ., 1-1 Yanagido Gifu, 501-1193, Japan

Abstract The runoff characteristics of major ionic species from a stream in a forested watershed were investigated during two rain events. The values of EC and the concentrations of alkalinity, anions and cations, except for NO$_3^-$, decreased according to the increase of discharge, and showed a sharp lower peak. On the other hand, the concentrations of NO$_3^-$ and K$^+$ indicated an opposite change. The amount of output of anions and cations was also larger than that of the input, especially in a storm event. During a storm event, the NO$_3^-$ concentrations in soil water 20 cm deep taken by a tension lysimeter were not detected, even though the surface soil of 0–5 cm deep included 20 to 50 mg/kg of NO$_3^-$. The direct contribution for NO$_3^-$ concentrations by suspended solids in water was estimated through three percentages of the stream water output. Surface runoff was also not observed. These results suggest that the prompt subsurface runoff off the direct runoff from surface layer of soil may be predominant during rainfall in the forested area, and the increase of NO$_3^-$ concentrations in the stream may be caused through the process.

Keywords Forested watershed; major ionic species; rain event; runoff characteristics; runoff components; stream water

Introduction

Approximately 70% of the surface area of Japan is forested, serving the important function of recharging water sources and maintaining the water quality of streams. Generally, water quality and discharge in a forested watershed are stable in dry weather. The rapid changes in these factors, largely during rain events, however, would cause an increase in the loadings of major ionic species. It is significant to study their behavior in regard to watershed management. Kunimatsu and Sudo (1997), Ebise (1984), and Hirata and Muraoka (1988) studied the runoff characteristics from streams in Japanese forested watershed and pointed out that water quality and loadings changed largely during storm events. Kunimatsu and Sudo (1997) also emphasized that the runoff characteristics from streams were largely different depending on each field, and that it was important to take many samples for several years in each fields. The changes of water quality and pollutant loadings during rain events may be effected by the runoff process in addition to precipitation, rainfall intensity, or the characteristics of the forested watershed. Thus, we investigated the runoff characteristics of major ionic species during two rain events in order to study certain factors related to the changes of water quality and loadings.

Methods

Study sites

A stream in a forested watershed located in the middle of Hyogo prefecture in Japan was chosen. The sampling site is shown in Figure 1. The stream flows into an artificial lake constructed in 1973 called Lake Ginzan. There is no human population in the forested watershed. The area of the watershed is 5.8 km$^2$ and it faces west. Its altitude ranges from 350 m to 800 m. This area is covered by rhyolitic faces named the Ikuno Group, and its soils are of the brown forest type which is common in Japan. The vegetation is mainly planted Japanese
cedar, Japanese cypress and red pine with deciduous stands. The precipitation was observed at the Ikuno dam office which is located 3 km west of the sampling site. An average annual precipitation in three water years between August 1995 and July 1998 was 1720 mm. Although there is snowfall in the winter, it is usually not very heavy.

Sampling and analytical methods
Water samples were taken at least once a week since August 1997 at the end point of a stream in the watershed. The hourly change of water quality for each season was also surveyed. The investigations for two rain events were carried out on 16-18 July 1997 (event A) and on 21-23 September 1998 (event B). Total precipitation of events A and B were 28 mm and 117 mm, respectively. Water samples were taken every hour, or every 30 minutes, at the end point of the stream. Flowrates were calculated using a flowrate meter for event A and using HQ equation (Umemoto and Komai, 1999) for event B. A bulk precipitation and throughfall were collected by a simple collector (Kobayashi et al., 1993) once a week. Soil water at 20 cm depth was taken by a tension lysimeter (Nagafuchi, 1997) once a week. Suspended solids were filtered using a glass fiber filter and weighed after being dried. The hydrograph during event B and the following period was observed using an automatic water level meter. NO₃⁻ in surface soils of 0-1 cm, 1-3 cm and 3-5 cm was extracted by using distilled water. Electric conductivity (EC) and pH were measured using an EC meter and pH meter, respectively. Alkalinity at pH 4.3 was measured by means of the titration method of 0.01 mol/l sulfuric acid. Cl⁻, NO₃⁻, SO₄²⁻, Na⁺, K⁺, Mg²⁺, and Ca²⁺ analyzed using the ion-chromatography method for stream water, was filtered through a membrane of 0.2 μm pore size.

Results and discussion

Change of stream water quality during a year and a day
Weekly changes of flowrate, alkalinity, anions, and cations in the stream from July 1997 to December 1998 are shown in Figure 2. These values fluctuated greatly each sampling week. For example, the concentrations of alkalinity, Cl⁻, SO₄²⁻, Na⁺, K⁺, Mg²⁺, and Ca²⁺ increased gradually from September to November 1997 and then decreased. These changes corresponded to the non-precipitation period and a later storm event. The water quality fluctuated greatly during this, as well as during other seasons, when it rained within several days before sampling in winter when little precipitation is usually experienced around the investigation area. These results showed that precipitation is one of the significant factors related to the change of water quality.

The daily precipitation from July 1995 to June 1999 is shown in Figure 3. The average number of days of precipitation producing more than 1 mm per day were 139 days per year.
in the watershed. The average number of days precipitation producing more than 10 mm a day, which causes an increase of flowrates, were 50 days, constituting 13.6% per year. The hydrograph produced by an automatic water level meter during the period between September 1998 and June 1999 is shown in Figure 4. These results suggest that the changes of flowrate and stream water quality shown in Figure 2 would become larger, if water samples were to be taken during all rain events.

Hourly changes in the stream water quality in March, July, September, and November are shown in Figure 5. Three cases, except for case-IV in July 1998, which experienced 39 mm of rainfall for a few days, were taken during the periods of ordinary water levels. The concentrations of major ionic species were different due to the differences in sampling months. For example, the concentrations of Ca\(^{2+}\) were the highest in November 1997 (case-II) and the lowest in March 1998 (case-III) and in the case-IV. Although the flowrates in September 1997 (case-I) and case-IV were similar, the concentrations of Ca\(^{2+}\) in case-II were higher than those in case-I. It was difficult to evaluate seasonal variation and rainfall influence separately, but it appeared that the concentrations of Ca\(^{2+}\) in case-II, which were the highest, and those in case-IV, which were the lowest, were related to each of the flowrates. Small changes in the concentrations of major ionic species except for NO\(_3\)^{−} and alkalinity were seen during daytime in each case. The concentrations of NO\(_3\)^{−} increased at night. Alkalinity also showed a similar tendency, which was slight. This suggests that biological activities such as photosynthesis and respiration by algae in stream water may cause a change in these concentrations during the daytime.
Change of stream water quality during rain events

The changes of water quality during event A and event B are shown in Figures 6 and 7, respectively. The discharges increased after a slight time lag in each rain event, and decreased rapidly after the rain stopped. The response of flow rate for rainfall was very rapid, even though the precipitation differed greatly in each rainfall event. The concentrations of alkalinity, anions, and cations, except for NO$_3^-$ and K$^+$, decreased according to the increase of discharge, and showed a sharp lower peak. On the other hand, the concentrations of NO$_3^-$ and K$^+$ indicated an opposite change, and those of NO$_3^-$ concentrations were larger and clearer than those of K$^+$.

The budget of bulk precipitation inputs and stream water outputs of major ionic species in two rain events during the periods between the start of the rainfall and the day following the rainfall are shown in Table 1. The inputs were calculated based on the amounts and water quality of bulk precipitation taken during the rain event.

Figure 4 Hydrograph by an automatic water level meter: (a) September–November 1998, (b) December 1998–February 1999, (c) March–April 1999 and (d) May–June 1999

Figure 5 Hourly changes of flow rate and water quality. ——, September 1999 (case-I);——, November 1999 (case-II), ——, March 1998 (case-III) and ——, July 1998 (case-IV)

Change of stream water quality during rain events

The changes of water quality during event A and event B are shown in Figures 6 and 7, respectively. The discharges increased after a slight time lag in each rain event, and decreased rapidly after the rain stopped. The response of flow rate for rainfall was very rapid, even though the precipitation differed greatly in each rainfall event. The concentrations of alkalinity, anions, and cations, except for NO$_3^-$ and K$^+$, decreased according to the increase of discharge, and showed a sharp lower peak. On the other hand, the concentrations of NO$_3^-$ and K$^+$ indicated an opposite change, and those of NO$_3^-$ concentrations were larger and clearer than those of K$^+$.

The budget of bulk precipitation inputs and stream water outputs of major ionic species in two rain events during the periods between the start of the rainfall and the day following the rainfall are shown in Table 1. The inputs were calculated based on the amounts and water quality of bulk precipitation taken during the rain event.
About 26% of the precipitation in event A and about 45% of the precipitation in event B apparently run off during the rainfall period. In event A, the stream water outputs of Cl\(^-\), Na\(^+\), K\(^+\), Mg\(^{2+}\), and Ca\(^{2+}\) were larger than those of the precipitation inputs, and the outputs of anions and cations were larger than the input in event B, which produced more than 100 mm of rainfall. These observations suggest that the sources of major ionic species runoff during rain events originate from the forest ecological system.

**Process of runoff during rain event**

The changes of NO\(_3^-\) concentrations in stream water were considerably different compared with other major ionic species during events A and B. NO\(_3^-\) is considered to be an available tracer of the separation of runoff components during a rain period (Ebise, 1984). As the concentrations of NO\(_3^-\) rainfall and throughfall during event B were lower than those in stream water, they were not considered the direct source of NO\(_3^-\) in stream water. Rainfall flows into rivers through paths in the forested watershed, and several runoff components can be separated (Figure 8). Direct runoff that is directly related to rainfall is divided into two processes: surface runoff and prompt subsurface runoff. It seemed that surface runoff might be dominant because the discharge increased rapidly in the two cases.

Surface runoff, however, may not generally happen. Indeed, it was not observed throughout event B or event A. On the other hand, the concentrations of suspended solids in
Table 1 Budget of bulk precipitation inputs and stream water outputs of major ionic species in two rain events

<table>
<thead>
<tr>
<th></th>
<th>Amount of water (m³/ha)</th>
<th>Cl⁻ (g/ha)</th>
<th>NO₃⁻ (g/ha)</th>
<th>SO₄²⁻ (g/ha)</th>
<th>Na⁺ (g/ha)</th>
<th>NH₄⁺ (g/ha)</th>
<th>K⁺ (g/ha)</th>
<th>Mg²⁺ (g/ha)</th>
<th>Ca²⁺ (g/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event A Input</td>
<td>280</td>
<td>30</td>
<td>230</td>
<td>300</td>
<td>12</td>
<td>82</td>
<td>36</td>
<td>13</td>
<td>59</td>
</tr>
<tr>
<td>Output</td>
<td>72</td>
<td>240</td>
<td>65</td>
<td>240</td>
<td>200</td>
<td>0</td>
<td>47</td>
<td>43</td>
<td>260</td>
</tr>
<tr>
<td>Event B Input</td>
<td>1600</td>
<td>52</td>
<td>40</td>
<td>68</td>
<td>74</td>
<td>0</td>
<td>22</td>
<td>6</td>
<td>38</td>
</tr>
<tr>
<td>Output</td>
<td>710</td>
<td>1400</td>
<td>1400</td>
<td>2000</td>
<td>1400</td>
<td>4</td>
<td>430</td>
<td>300</td>
<td>1600</td>
</tr>
</tbody>
</table>

Table 2 Concentrations of major ionic species in surface soil extracted by distilled water

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Water content (%)</th>
<th>Cl⁻ (mg/kg)</th>
<th>NO₃⁻ (mg/kg)</th>
<th>SO₄²⁻ (mg/kg)</th>
<th>Na⁺ (mg/kg)</th>
<th>NH₄⁺ (mg/kg)</th>
<th>K⁺ (mg/kg)</th>
<th>Mg²⁺ (mg/kg)</th>
<th>Ca²⁺ (mg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1 cm</td>
<td>57.5</td>
<td>21.8</td>
<td>534.4</td>
<td>21.2</td>
<td>15.3</td>
<td>10.7</td>
<td>7.0</td>
<td>5.2</td>
<td>32.4</td>
</tr>
<tr>
<td>1–3 cm</td>
<td>46.2</td>
<td>11.3</td>
<td>26.4</td>
<td>16.5</td>
<td>11.4</td>
<td>2.7</td>
<td>3.5</td>
<td>3.2</td>
<td>17.8</td>
</tr>
<tr>
<td>3–5 cm</td>
<td>44.5</td>
<td>6.5</td>
<td>25.4</td>
<td>12.2</td>
<td>6.4</td>
<td>2.7</td>
<td>2.4</td>
<td>2.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>

Table 3 Suspended solids’ (SS) direct contribution to NO₃⁻ concentrations in water during event B

<table>
<thead>
<tr>
<th>Discharge (m³/sec)</th>
<th>SS (mg/l)</th>
<th>NO₃⁻ (mg/l)</th>
<th>Direct contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>26.9</td>
<td>394</td>
<td>3.72</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.046</td>
<td>0.1</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Figure 8 Separation of runoff components (Chow, 1964)
stream water increased from 0.1 mg/l to 394 mg/l during event B; thus, the surface soil might be eroded by surface runoff during event B and contribute as suspended solids. The concentrations of NO\textsubscript{3}\textsuperscript{D} in the surface soil at 0 cm, 1 cm, and 3 cm depth are shown in Table 2. These surface soils included 20 to 50 mg/kg of NO\textsubscript{3}\textsuperscript{D}. So, the amounts of NO\textsubscript{3}\textsuperscript{D} in stream water were estimated by using discharge, the concentrations of suspended solids, and the concentrations of NO\textsubscript{3}\textsuperscript{D} in the surface soil.

The suspended solids direct contribution to NO\textsubscript{3}\textsuperscript{D} concentrations in water was estimated to be between zero and 3% of the stream water output (Table 3). This suggests that the higher concentrations of NO\textsubscript{3}\textsuperscript{D} in stream water during event B mainly originated from other factors besides surface soils eroded by surface runoff.

The vertical distribution of NO\textsubscript{3}\textsuperscript{D} concentrations within 5 cm of the soil surface decreased toward the lower layer. Furthermore, NO\textsubscript{3}\textsuperscript{D} in soil water at 20 cm depth, taken by a tension lysimeter once a week, was detected in very small amounts throughout investigation periods including those during rainfalls. The soil water at 20 cm and 50 cm depth in a neighboring forested watershed was taken since May 1999, using the methods described above. The NO\textsubscript{3}\textsuperscript{D} concentrations in soil water at 50 cm deep were slight as well. Hirata and Muraoka (1988) studied the vertical distribution of NO\textsubscript{3}\textsuperscript{D} concentrations in the forested watershed of Ibaraki prefecture. They reported that NO\textsubscript{3}\textsuperscript{D} showed the highest concentrations in the surface soil layer and decreased toward the lower layers.

These results suggest that NO\textsubscript{3}\textsuperscript{D} accumulated in the surface soil layer, and it may flow into rivers by the prompt subsurface runoff which Ebise (1984) separated using a tank model. It is pointed out that macropores in the soil layer play an important role in runoff during rain events (Kitahara et al., 1994). The pipe flow through macropores may well be able to explain why the discharge during rain events rapidly increased and decreased after rain events in the forested watershed. However, the present study could not determine whether most of the direct runoff consists of old water pushed by seeping water and/or if new water produced by the current rainfall infiltrated the soil.

**Conclusion**

The stream water quality in the forested watershed was closely associated with precipitation. The discharge and water quality increased and decreased rapidly during the two rain events in which the amount of precipitation differed greatly. Most major ionic species were diluted in stream water during rain events. On the other hand, the concentrations of NO\textsubscript{3}\textsuperscript{D} and K\textsuperscript{+} increased in stream water. Although NO\textsubscript{3}\textsuperscript{D} accumulated in the surface layer of soil, NO\textsubscript{3}\textsuperscript{D} in soil water at 20 cm depth was only slightly detected during the investigation period including observations made during rain events. Suspended solids direct contribution to NO\textsubscript{3}\textsuperscript{D} concentrations in water was estimated at less than 3% of the stream water output, if most of the suspended solids originated in the surface soil eroded by rainfall. These results suggest that the prompt subsurface runoff, associated with the direct runoff from the surface layer of soil, may be predominant during rainfall in forested areas, and the increase of NO\textsubscript{3}\textsuperscript{D} concentrations in the stream may be caused by this process.

**Acknowledgements**

The Ikuno Dam Office, Hyogo Prefecture, offered the daily precipitation data. Hyogo Science and Technology Association, Japan sponsored a part of this study. We thank them for their support.
References


