The environmental tracer approach in storm runoff studies in forested catchments

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Abstract In small catchments, the response of headwater streams to precipitation is often very rapid but is rarely the same, i.e. the proportion of precipitation which appears quickly as streamflow under the storm hydrograph differs from storm to storm. The environmental tracer approach was applied to three rainfall events in 1991 in the forested Rudbäck catchment (4.20 km$^2$), an upstream sub-catchment (1.42 km$^2$) and a sub-catchment within (0.18 km$^2$), in Siuntio, in southern Finland. Isotope techniques were applied to separate event and pre-event fractions of discharge on a rainfall event and an annual basis. Only in response to very intense storms were streams dominated by "new" rainwater. The percentage of event water amounted to 50-70% of the runoff during the largest event (80 mm day$^{-1}$). During the second largest rainfall event in August this fraction stayed below 25% in all the catchments. The event water fraction was positively correlated to rainfall volume and the maximum hourly runoff of the event. The areal extent of discharge increased in Rudbäck catchments with increasing maximum intensity of runoff, the highest (10%) during the largest event (80 mm day$^{-1}$). The annual event water fraction corresponded to 20-25% of total runoff in these forested catchments with shallow soil depths and relatively high percentages of open bedrock.

INTRODUCTION

Water quality in streams depends on the origin of stream water, flow paths of the water particles, the time water particles have resided in different zones in the soil, and specifically, the soil and vegetation type and the quality of precipitation. Solutions to hydrochemical problems in a stream, such as acidification and non-point source pollution in general, often involve models of runoff generation in the catchment. Unfortunately, modelling studies, based only on hydrometric data from the hillslope and hydrochemical data from the stream, have not been totally successful in explaining the hydrochemical behaviour of streams during high-runoff events. One of the major reasons for this failure is that the models often incorrectly estimate the residence time of water in the catchment, that is, the flow paths assumed in the models are often not correct. Tracer studies can improve runoff apportioning by tracing the movement of water through the various pathways in a catchment (Sklash, 1990). In small catchments,
the response of headwater streams to precipitation is often very rapid but is rarely the same, i.e. the proportion of precipitation which appears quickly as streamflow under the storm hydrograph differs from storm to storm. During the last 10-15 years it has been pointed out in many isotope studies that subsurface runoff is an important component even during the high flow period (e.g. Fritz et al., 1976; Herrmann & Stichler, 1980, 1982; Bottomley et al., 1984; Rodhe, 1987; Bengtsson et al., 1989; Lepistö & Seuna, 1990; Bengtsson et al., 1991). In Sweden, Rodhe (1987) observed that in 14 rainfall generated events studied in 7 basins, the fraction of baseflow or groundwater varied between 68 to 99% of the stream discharge, with a median value of 86%.

The purpose of the present project, which is one sub-project in the comprehensive Finnish Research Programme on Climate Change (SILMU), is to study the impacts of possible climate change on the material fluxes in forested catchments. It has two objectives. First the hydrological processes in the catchments, the age and flow paths of runoff, the interrelationships between flow patterns and water quality are studied, as well as mass balances in the catchments. Secondly, a mathematical simulation model will be developed incorporating quantification of the most important hydrological and chemical processes (Kämäri et al., 1992).

The main purpose of this paper is to evaluate the role of "old" and "new" water in storm runoff generation. The environmental tracer approach was applied to three rainfall events in 1991 in the forested Rudbäck catchment (6), an upstream sub-catchment (7), and a first-order sub-catchment (8) within sub-catchment 7. Isotope techniques were applied to separate event and pre-event fractions of discharge on a rainfall event and an annual basis. Contributing areas (discharge areas) were estimated to enable spatial interpretation of hydrograph separation.

SITE DESCRIPTION, FIELD MEASUREMENTS AND METHODS

The Rudbäck catchments are located in Siuntio, southern Finland, about 40 km northwest of Helsinki (Fig. 1). From the whole catchment (6 Rudbäck; 4.20 km²), a sub-catchment (7 Rudbäck; 1.42 km²) has been separated, of which a smaller first-order catchment (8 Rudbäck; 0.18 km²) was separated. The area is underlain by Precambrian granite bedrock, composed of quartz, K-feldspar, plagioclase and biotite. The dominating soil types are relatively thin layers of silty and sandy moraines (about 0.5-5 m). Clay deposits are found in the brook valleys of catchments 6 and 7. The catchments are mostly covered by forests dominated by Norway spruce (Picea abies).

The whole Rudbäck catchment (6) consists of about 7% arable land, which is mostly situated near the main stream close to the catchment outlet. Catchments 7 and 8 are totally forested and partly covered by peatlands (7% at 7 and 6% at 8). A considerable part (29% of 7 Rudbäck and 41% of 8 Rudbäck) of the catchments is composed of exposed bedrock areas. Moraine depths in the smallest catchment (8 Rudbäck) vary between 0.5 and 5 m, with an average of about 2 m, based on seismic refraction data.

The year under study, 1991, was a rainy one: annual noncorrected precipitation at Siuntio was 802 mm of which 424 mm appeared as runoff (6 Rudbäck); rainfall was 30% higher than the long-term average.

Catchment 6 was established in the mid-1970s, and 7 and 8 in early 1991. Runoff monitoring began in March 1991 at 7 Rudbäck, and in early June at 8 Rudbäck. When
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Calculating annual patterns, runoff at the outlet of the whole catchment (6 Rudbäck), was assumed to adequately represent runoff in the sub-catchments during the first months of the year 1991. Rainfall quantity was registered every 10 minutes during the summer season with a tipping bucket rain gauge. Also daily precipitation was recorded in close proximity to the catchment. A detailed description of hydrochemical monitoring of the catchment (throughfall, melt-, ground- and stream water chemistry) is given by Kämäri et al. (1992).

The oxygen-18 content of stream water was intensively monitored in 1991. Stream water samples for isotope analysis were collected from measuring weirs 6, 7 and 8 (Fig. 1) by automatic samplers (ISCO) controlled by time or flow. Annual stream water samples totalled 112 (8 Rudbäck), 246 (7 Rudbäck) and 183 (6 Rudbäck). Sampling concentrated on snowmelt period and rainfall events. Daily precipitation samples (totalling 117) were taken at the meteorological station of Vihti, 25 km from the catchments, from most events in 1991. Also monthly accumulated samples were collected. Some rainfall samples were taken at the outlet of catchment 7. Meltwater samples were taken from the outflow of a 1 m² snow lysimeter in open and forested areas inside catchment 7 for the

Fig. 1 Location of the Rudbäck catchments 6, 7 and 8 in Siuntio, southern Finland.
The oxygen-18 content of a water sample was determined by a ratio mass spectrometer at the University of Copenhagen, Denmark. The O-18 content of a water sample is expressed as the relative deviation of the isotopic ratio of the sample from that of a reference water, which is Vienna SMOW (Standard Mean Ocean Water) in our case. The accuracy of the measurements is about 0.1‰. The basic principle of the isotopic method for stream hydrograph separation is that stream flow is assumed to be derived from two sources i.e. precipitation (as rain or snowmelt) and groundwater. From the mass and isotope balance in the steady state, the fraction of groundwater contribution in the stream is expressed as:

\[ X_g = \frac{(\delta_s - \delta_p)}{(\delta_s - \delta_p)} \]  

where \( \delta_s, \delta_p \) and \( \delta_g \) are the isotopic compositions of stream water, precipitation and groundwater respectively. Whenever water input occurs in the form of meltwater or rain, having considerably different \( \delta \) values in comparison to stream water, it becomes possible to compute the contribution of the pre-event groundwater and the event water to the stream flow, provided that the inputs are of considerable magnitude. In the above equation it is assumed that all precipitation on the recharge areas infiltrates, while in discharge areas it reaches the stream mostly as saturated overland flow. In general, the isotopic composition of groundwater in a region is more or less similar to the annual weighted mean isotopic content of the precipitation.

**RAINFALL EVENTS**

**Rainfall event I, 9-11 August**

Prior to the first event there was a very dry period with over one month of runoff less than 0.15 mm day\(^{-1}\) and 13 days with no flow. Prior to the event on 9 August 0800 h, the \( \delta^{18}O \) of stream water was -9.38‰, which was assumed to be the same for 8 and 6 Rudbäck, and to remain constant over the event. The relative contribution to streamflow from various sub-reservoirs within the catchments was not known, and baseflow stream values were considered to adequately represent groundwater. Considering catchment 7, the sampler with flow-weighting sampling strategy became full before the flow peak, inhibiting hydrograph separation.

Precipitation input during 9 August was as high as 81 mm, with a maximum hourly intensity of 23.8 mm, and a return period of about 100 years. The average daily isotopic input, measured at Vihti station, was -11.24‰ until 0800 h on 9 August and -11.64‰ during the next 24 hours.

The \( \delta^{18}O \) of stream water at 8 Rudbäck reached its lowest value (-11.46‰) during the evening of 11 August with no return to baseflow values during the next three days. In the whole catchment of 6 Rudbäck, the \( \delta^{18}O \) of stream water reached its lowest measured value (-10.75‰) during the afternoon of 10 August after which there is a break in observations, but the total volume of event water and the fraction during the flow peak could be estimated.

The total runoff during the rainfall event was 13 mm at 8 Rudbäck (Table 1). The average computed fraction of event water in the stream was up to 72% (9.2 mm) in
catchment 8, and 51% (7.8 mm) in catchment 6, respectively. The peak flow corresponded to 0.51-0.56 mm h\(^{-1}\), of which 0.26-0.35 mm h\(^{-1}\) was "new" rainwater.

**Event II, 18-23 August**

In the beginning of the 18 August event, the \(\delta^{18}O\) of stream water was \(-10.07\%o\) (7 Rudbäck) (Fig. 2). For catchments 6 and 8, the \(\delta^{18}O\) of stream water was estimated to recover 0.4-0.5\%o after the last measured value of the previous week (event I), in the same way as for catchment 7. Estimated values were \(-10.2\%o\) for catchment 6 and \(-11.0\%o\) for catchment 8. Precipitation input during the event was 34 mm, with a maximum hourly intensity of 5.6 mm (Table 1). The average daily isotopic input, measured at Siuntio, near the catchments, was \(-13.65\%o\) on 18 August 8 a.m.-19 August 8 a.m. The \(\delta^{18}O\) of stream water of catchment 7 reached its lowest value \(-10.92\%o\) on 20 August 0300 h (Fig. 2) after which it slowly recovered to \(-10.34\%o\) on 23 August, which is close to the baseflow value. In catchment 8 Rudbäck, the \(\delta^{18}O\) of stream water reached its lowest measured value \(-11.63\%o\) on the evening of 20 August. During this period there was no recovery to the baseflow values.

The total runoff during the rainfall event was 11-13 mm (Table 1). The average computed fraction of event water in the stream was 17-23%. The peak flow corresponded to 0.20-0.29 mm h\(^{-1}\), of which 0.05-0.08 mm h\(^{-1}\) was "new" rainwater. For catchment 8, the problem is that the exact groundwater value before the event is not known. This means that there is clearly a higher uncertainty with this event. It can be assumed that the \(\delta^{18}O\) of stream-water has recovered approximately to those values of larger catchments, e.g. to \(-10.4\%o\), after the event I. In that case the event water fraction goes up to 33% (compared to 18%).

**Event III, 8-10 November**

Event III was analysed in the same manner as previously described. The total runoff of 10-13 mm (Table 1) during the rainfall event was of the same order as the second event during August. The average computed fraction of event water in the stream was only 2-8%. Peak flow corresponded to 0.20-0.26 mm h\(^{-1}\), of which 0.03-0.04 mm h\(^{-1}\) was "new" rainwater.

**Event water fraction compared to rainfall volume and runoff intensity**

The total volume fraction of event water was compared to rainfall volume and maximum hourly runoff (mm h\(^{-1}\)) during three studied rainfall events at three catchments (Fig. 3). The event water fraction increased with increasing rainfall volume and maximum runoff. Limited data (only 8 cases) provides, however, no evidence of the type of relationship between those variables.

**Event water contributing area**

Event water contributing areas (discharge areas) (Table 1) were estimated by dividing
Fig. 2 Hourly rainfall; $\delta^{18}O$ content of runoff and rainfall; and total runoff (solid line) and pre-event water fraction (broken line) in the catchments 6 and 7 Rudbäck, during the event II, 18-23 August 1991.
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Table 1 Total rainfall and maximum intensity, total runoff and maximum intensity, event water fraction (highest and total), and event water contributing area (%) during the events I, II and III in the three studied catchments.

<table>
<thead>
<tr>
<th>Event</th>
<th>Total rainfall (mm)</th>
<th>Rainfall maximum intensity (mm h⁻¹)</th>
<th>Total runoff (mm)</th>
<th>Runoff maximum intensity (mm h⁻¹)</th>
<th>Event water fraction highest (%)</th>
<th>Event water fraction total (mm)</th>
<th>Contributing area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6</td>
<td>87.9</td>
<td>23.8</td>
<td>15.2</td>
<td>0.51</td>
<td>61</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>87.9</td>
<td>23.8</td>
<td>11.4</td>
<td>0.39</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>87.9</td>
<td>23.8</td>
<td>12.8</td>
<td>0.56</td>
<td>92</td>
<td>9.2</td>
</tr>
<tr>
<td>II</td>
<td>6</td>
<td>33.6</td>
<td>5.6</td>
<td>13.0</td>
<td>0.29</td>
<td>26</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>33.6</td>
<td>5.6</td>
<td>11.0</td>
<td>0.20</td>
<td>24</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>33.6</td>
<td>5.6</td>
<td>12.7</td>
<td>0.23</td>
<td>23</td>
<td>2.3</td>
</tr>
<tr>
<td>III</td>
<td>6</td>
<td>16.4</td>
<td>2.2</td>
<td>13.6</td>
<td>0.26</td>
<td>14</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>16.4</td>
<td>2.2</td>
<td>11.3</td>
<td>0.22</td>
<td>11</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>16.4</td>
<td>2.2</td>
<td>10.1</td>
<td>0.20</td>
<td>10</td>
<td>0.3</td>
</tr>
</tbody>
</table>

the specific discharge (mm day⁻¹) by the rate of precipitation (mm day⁻¹) and multiplying by the event water fraction (e.g. Rodhe, 1987). All precipitation on recharge areas is assumed to infiltrate, while all such water on discharge areas is assumed to generate saturated overland flow. Event water contributing area is considered to be defined in the same way as Bengtsson et al. (1991).

Contributing area percentages range between 1 and 11% of the catchment areas, with higher values in the smallest catchment (average 6.5% at 8 Rudbäck) compared to the mid-catchment (average 3.3% at 7 Rudbäck). For catchment 6, arable land areas near the catchment outlet and main stream have an increasing effect on contributing area percentage (average 8.1%). Fractions during the event III (16.4 mm) in November are of the same order as that calculated for the forested Teeressuonoja catchment (4%) during 15 mm of rain (Bengtsson et al., 1991). However, the autumn rainfall event (III) was rather small, and cannot fully represent the conditions of a rainy November.

This method roughly attempts to spatially interpret the results of hydrograph separation. The estimates provide, however, a means for a field check of the hydrograph separation results. They also offer a possibility of verifying the modelled variation of fraction of discharge area, when using semi-physical topographic models such as TOPMODEL (Beven & Wood, 1983, Sivaplan et al., 1987) and to study the relations between the dynamics of saturated areas and nutrient loading (Andersson et al., 1993).

ANNUAL PATTERN OF EVENT WATER FRACTION OF TOTAL RUNOFF

An estimate of the annual pattern (year 1991) of event water fraction was made for catchment 7 (1.42 km²) and sub-catchment 8 (0.18 km²). Monthly average precipitation
contents of oxygen-18 as INPUT and monthly volume-weighted average contents of stream water oxygen-18 as OUTPUT (Table 2) were used in the analysis. The groundwater monthly average was estimated by assuming the stream water oxygen-18 content, measured during the low flow (0.1-1 mm day\(^{-1}\)) to represent groundwater during the same month. Monthly event water fractions (Table 2) varied between 2 and 35\%, with a high (30\%) in August due to 180 mm of rainfall (Fig. 4). (In July the fraction was high, but there was practically no runoff). In October, precipitation and stream water concentrations were within the analysis accuracy of 0.1\%, with groundwater concentration also being very close to those values, thus preventing this type of analysis. If the event water fraction is assumed to have been about 25\% during the relatively rainy months of January and December, an annual "new" water runoff (quick flow) of about 80 mm is obtained, corresponding to 20\% of annual runoff of 400 mm.

For the smallest catchment (8 Rudbäck), the fraction varied between 0 and 66\%, with the highest in August (180 mm of rainfall) (Table 2, Fig. 4). Assuming an event water fraction of about 30\% for the average rainy months of January and December, annual "new" water runoff (quick flow) was about 95 mm (25\% of annual runoff).

Also, monthly average fractions of event water contributing area (discharge area) were estimated by dividing the specific discharge (mm month\(^{-1}\)) by the rate of precipitation (mm month\(^{-1}\)) and multiplying by the event water fraction. This method was used

![Graph](image_url)  
Fig. 3 Event water percentage of the total runoff vs. volume of rainfall and maximum hourly runoff of 8 studied rainfall events.
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Table 2 Monthly precipitation; runoff; δ\(^{18}\)O of precipitation, runoff and groundwater; event water fractions (% and mm); and event water contributing area (%) for the catchments 7 and 8 Rudbäck, year 1991.

<table>
<thead>
<tr>
<th></th>
<th>7 Rudbäck</th>
<th></th>
<th></th>
<th>8 Rudbäck</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(q) mm</td>
<td>(\delta^{18})O</td>
<td>Event water</td>
<td>(q) mm</td>
<td>(\delta^{18})O</td>
<td>Event water</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td></td>
<td>% mm</td>
<td>mm</td>
<td></td>
<td>% mm</td>
</tr>
<tr>
<td>rain</td>
<td>mm</td>
<td></td>
<td>mm rain</td>
<td>mm</td>
<td></td>
<td>mm rain</td>
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<tr>
<td>stream</td>
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<tr>
<td>ground</td>
<td>mm</td>
<td></td>
<td>mm ground</td>
<td>mm</td>
<td></td>
<td>mm ground</td>
</tr>
<tr>
<td>Jan.</td>
<td>79.3</td>
<td>55.5(^1)</td>
<td>-13.72</td>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>Feb.</td>
<td>20.3</td>
<td>11.7(^1)</td>
<td>-16.46</td>
<td>-12.44</td>
<td>-11.93</td>
<td>11.3</td>
</tr>
<tr>
<td>Mar.</td>
<td>41.6</td>
<td>37.0</td>
<td>-13.56</td>
<td>-12.43</td>
<td>-11.93</td>
<td>30.7</td>
</tr>
<tr>
<td>Apr.</td>
<td>21.9</td>
<td>58.9</td>
<td>-10.35</td>
<td>-12.35</td>
<td>-12.57</td>
<td>9.9</td>
</tr>
<tr>
<td>May</td>
<td>41.1</td>
<td>17.8</td>
<td>-10.12</td>
<td>-11.59</td>
<td>-11.88</td>
<td>16.5</td>
</tr>
<tr>
<td>Jun.</td>
<td>69.9</td>
<td>11.0</td>
<td>-7.72</td>
<td>-10.91</td>
<td>-10.98</td>
<td>2.2</td>
</tr>
<tr>
<td>Jul.</td>
<td>59.9</td>
<td>3.0</td>
<td>-10.35</td>
<td>-10.00</td>
<td>-9.81</td>
<td>35.2</td>
</tr>
<tr>
<td>Aug.</td>
<td>179.5</td>
<td>33.3</td>
<td>-11.75</td>
<td>-10.36</td>
<td>-9.75</td>
<td>30.5</td>
</tr>
<tr>
<td>Sep.</td>
<td>64.8</td>
<td>7.6</td>
<td>-9.10</td>
<td>-9.86</td>
<td>-10.00</td>
<td>15.6</td>
</tr>
<tr>
<td>Oct.</td>
<td>46.7</td>
<td>30.9</td>
<td>-10.31</td>
<td>-10.22</td>
<td>-9.89</td>
<td>.</td>
</tr>
<tr>
<td>Nov.</td>
<td>114.0</td>
<td>89.8</td>
<td>-14.73</td>
<td>-10.95</td>
<td>-10.43</td>
<td>12.1</td>
</tr>
<tr>
<td>Dec.</td>
<td>62.8</td>
<td>46.0</td>
<td>-12.31</td>
<td>.</td>
<td>.</td>
<td>48.6</td>
</tr>
<tr>
<td>Total</td>
<td>801.8</td>
<td>402.5</td>
<td>45.0</td>
<td>376.9</td>
<td>63.6</td>
<td>.</td>
</tr>
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</tbody>
</table>

\(^1\) runoff measured at 6 Rudbäck.

during the snow-free period with no soil frost disturbance. The fraction varied between 0 and 16%, with the highest fraction in a rainy November (Table 2).

CONCLUDING REMARKS

Streamflow consists of two main parts, those being a mixture of: (a) surface runoff plus some shallow groundwater flow with a very short transit time (event water) and (b) base-flow composed of shallow to intermediate groundwater flow (pre-event water). The percentage of event water amounted to 50-70% of the runoff during the largest event (80 mm day\(^{-1}\)). According to this data, only in response to a very intense storm, were streams dominated by "new" rainwater. During the second largest rainfall event in August this fraction remained lower than 25% in all the catchments. In November, in the case of smaller rainfall (maximum intensity 2.2 mm h\(^{-1}\), the fraction was unexpectedly low, 2-8%, and is not fully representative of the rainy November. The event water fraction increased together with increasing rainfall volume and runoff intensity. The annual event water fraction corresponded to 20-25% of total runoff in those forested catchments with low soil depths and relatively high percentages of open bedrock. A
more profound analysis of the differences between the catchments will be one of the next phases of the project.

The degree of uncertainty in calculating the "old" and "new" water contributions is inversely related to the difference in isotopic concentrations of the two components. During some events or months, the "old" and "new" water isotopic contents may be too similar for meaningful hydrograph separations, for example in October at 7 Rudbäck. The degree of uncertainty in our calculations is ±10%, except for the event II in the smallest catchment, where the error may be larger due to limited knowledge of pre-event groundwater level.

Increase in the size of the discharge area (event water contributing area) seems to be essential in producing both large pre-event and event water contributions to the stream. The new rainwater flow in the stream, at a certain rainfall rate, should increase with increased ground water level, since the extent of overland flow producing (saturated) areas then increases. The extent of discharge area increased in Rudbäck catchments with increasing maximum intensity of runoff, being highest (10%) during
the first event of August (88 mm rainfall), when rainfall intensity was over 23 mm h$^{-1}$.
The rough estimates of discharge area provide a means for a field check of the hydro-
graph separation results. Also, they offer a possibility to verify the modelled variation
of discharge area fraction calculated by semi-physical topographic models, and to study
the linkage between surface-saturated areas and nutrient loading.

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