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Effects of clear-cutting on annual and seasonal runoff from a boreal forest catchment in eastern Finland

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ABSTRACT

To examine the effects of clear-cutting on annual and seasonal runoff from a boreal headwater catchment, a paired-catchment study was conducted in Norway spruce- (*Picea abies* (L.) Karsten) and Scots pine- (*Pinus sylvestris* L.) dominated forest catchments in eastern Finland. Long-term hydrological data were obtained for 5 years before and 18 years after clear-cutting, during which the clear-cut area was ploughed in the 4th year and planted with Scots pine seedlings in the 5th year. Calibration equations for annual and seasonal runoff were developed between the paired (i.e. treatment and control) catchments during the pre-treatment period and after clear-cutting, the treatment effect (*TE*) was calculated as the difference between the measured and predicted runoff in the treatment catchment. The annual *TE* was highest in the 1st year after the clear-cutting and tended to decrease with time, gradually diminishing from the 8th year after the clear-cutting. The seasonal *TE* had different temporal variations from the annual *TE*. The spring *TE* continued to be positive until the end of the observation period. On the other hand, the summer *TE* continued to be negative from the 8th year to the end of the observation period. The autumn *TE* was positive until the 6th year, but subsequently became negative. The winter *TE* was almost zero throughout the observation period. The decreasing trend in annual *TE* therefore resulted from the fact that the persistent positive spring *TE*s were offset by the negative summer and autumn *TE*s from the 8th year. These results demonstrate that seasonal *TE*s, i.e. spring and summer *TE*s, more clearly represent the persistence of changes in runoff after clear-cutting than does the annual *TE*. We thus conclude that the effects of clear-cutting on runoff continued for at least 18 years in our catchment. Our study emphasizes the importance of investigating seasonal runoff together with annual runoff to enable a better understanding of clear-cutting effects on runoff from forest catchments.

1. Introduction

Runoff from forest-dominated headwater catchments typically increases in the short term after forest clear-cutting (Bosch and Hewlett, 1982; Harr, 1983; Stednick, 1996). Such increases in runoff can cause higher turbidity and nutrient loads, resulting in degradation of water quality and eutrophication in downstream rivers and waters (Carpenter et al., 1998; Nisbet, 2001; Ahtiainen and Huttunen, 1999; Gomi et al., 2005; Laurén et al., 2009; Webb et al., 2012). In the long term, clear-cutting can lead to reductions in runoff due to increases in evapotranspiration by regenerating young-growth tree stands (Hornbeck et al., 1993; Andréassian, 2004), possibly limiting water use in downstream areas. Therefore, to conduct appropriate forestry operations that consider the conservation of water resources and the water environment, knowledge of the magnitude and duration of clear-cutting effects on runoff from forest headwater catchments is needed.

Paired-catchment methods have been often used to examine temporal variations in runoff from forest catchments after forestry operations such as clear-cutting (Hibbert, 1967; Hornbeck et al., 1993; Stednick, 1996; Swank et al., 2001; Andréassian, 2004). This is because those methods allow climate variability and inter-catchment variability to be accounted for in the analysis, especially in the case where the paired catchments are located adjacent to each other (Andréassian, 2004). Over the last few decades, several paired-catchment studies have focused on the return of changes in annual runoff to the pre-treatment levels, i.e. hydrologic recovery (Stednick, 1996, 2008). The question is how long hydrologic recovery takes after forestry operations. However, the concept of hydrologic recovery is complex. Stednick (1996) reported that changes in streamflow generation and routing mechanisms had not returned to pre-treatment levels 28 years after harvesting in the Alsea watershed of Coastal Oregon, although the annual runoff was within pre-treatment levels. This suggests the possibility that changes in high flows, including peak runoff, and low flows still

Abbreviations: TE, treatment effect; CTE, cumulative treatment effect.

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persist after changes in annual runoff have diminished. High flows and low flows are reflected in seasonal runoff because the frequencies of their occurrences vary depending on season. Therefore, to better understand the duration of clear-cutting effects on runoff, a paired-catchment method should be applied to seasonal runoff together with annual runoff.

In Finland, about three-quarters of the land area is classified as forest and 88% of that is available for wood production (METLA, 2012). The forested areas are located in regions that are likely to be most influenced by climate change (e.g., Kauppi and Posch, 1985; Kellomäki and Kolström, 1994; Carter et al., 1995; Kellomäki et al., 2001). It is predicted that climate change will affect runoff from boreal forest catchments in Finland. Climate change may alter the seasonality of runoff: snow accumulation will decrease and winter floods will increase whereas runoff will decrease during late spring and summer (Vehviläinen and Huttunen, 1997; Silander et al., 2006; Bates et al., 2008; Veijalainen et al., 2010). Also, clear-cutting can strongly affect seasonality of runoff (Jones and Post, 2004; Moore and Wondzell, 2005). Jones and Post (2004) showed that daily runoff increased by up to several hundred percent in late summer and early autumn during the years immediately after clear-cutting in the conifer and deciduous forest catchments in the northwest and eastern United States. Schelker et al. (2013) conducted a paired-catchment study in northern Sweden and specified that clear-cutting of a boreal coniferous forest altered snow accumulation, runoff responses to spring snowmelt and the amount of snowmelt runoff. Therefore, if an increase in runoff after clear-cutting coincides with a season of increased runoff caused by climate change, the seasonal runoff may increase at a rate much greater than that caused by clear-cutting alone. However, little information is available on long-term seasonal runoff changes after clear-cutting in boreal forest catchments, although changes in annual runoff have been extensively monitored (e.g., Rosén et al., 1996; Sørensen et al., 2009).

The objective of this study was to examine the magnitude and duration of clear-cutting effects on annual and seasonal runoff from a boreal forest headwater catchment. For this, we used hydrological data collected for 23 years in paired catchments in eastern Finland. Our main interest was to analyze whether the clear-cutting effects on runoff are different between annual and seasonal runoff.

2. Materials and methods

2.1. Site description

This study was conducted in the Kivipuro (treatment) and Välipuro (control) catchments located in Sotkamo, eastern Finland (63°52′ N, 28°39′ E; Fig. 1). The areas of the Kivipuro and Välipuro catchments are 54 and 86 ha, respectively. Both catchments have a perennial brook, with a length of 960 m in Kivipuro and 1470 m in Välipuro. The altitude of the catchments ranges from 200 to 220 m above sea level. The mean slope gradient of the catchments is 5.3% in Kivipuro and 4.4% in Välipuro. From 1971 to 2000, the mean annual air temperature for these catchment areas was +1.9 °C and precipitation 564 mm, of which about 200 mm (35%) was snowfall (Drebs et al. 2002).

The main soil types of both catchments are iron podzols and histosols (peat), which have developed on stony till material. The proportion of peatlands is 32% of the catchment area in Kivipuro and 56% in Välipuro, and the depth of the peat layer ranges from 40 to 160 cm. The underlying bedrock consists of gneiss granite and granodiorite.

The dominant tree species in both the Kivipuro and Välipuro catchments were Norway spruce (*Picea abies* (L.) Karsten) and Scots pine (*Pinus sylvestris* L.). According to Kortelainen et al. (2006) and

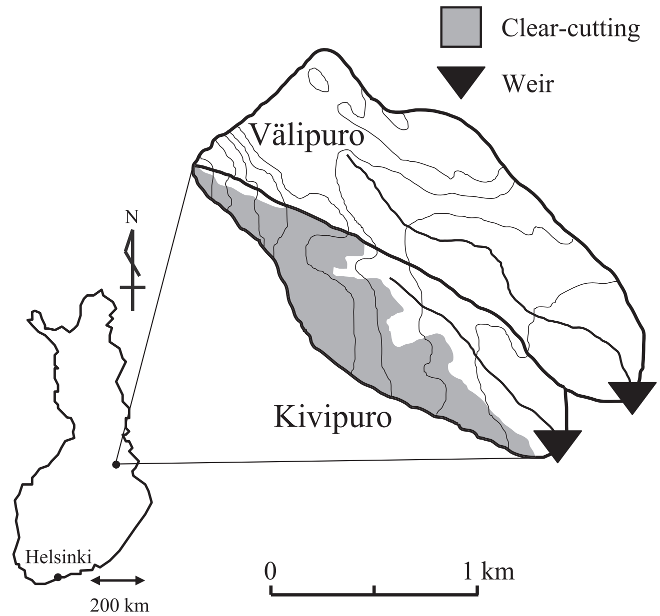

Fig. 1. Location and map of the Kivipuro (treatment) and Välipuro (control) catchments.

Laurén et al. (2009), forest cover in the Kivipuro catchment area prior to the clear-cutting was 65% Norway spruce and 21% Scots pine, with the stand age ranging up to 150 years, whereas in the Välipuro catchment area it was 73% Norway spruce and 25% Scots pine, which were old-growth stands. Before the clear-cutting in 1983, the mean volume of the growing stock was 126 m^3 ha^{-1} in Kivipuro and 84 m^3 ha^{-1} in Välipuro.

In Kivipuro, 30 ha of mature stands (56% of the catchment area) were clear-cut from January to April in 1983 using a combination of harvester and manual cutting (Ahtiainen et al., 1988). The average removal volume of the growing stock was 177 m^3 ha^{-1} (Laurén et al., 2009). An uncut, 30–50 m wide buffer zone was left between the clear-cut area and the brook (Fig. 1). The clear-cut area was ploughed in summer 1986 and planted with Scots pine seedlings in spring 1987 (Ahtiainen et al., 1988). In Välipuro, approximately 8 ha of stands (9% of the catchment area) were clear-cut in 2001 (Sarkkola et al., 2009) and therefore this study was ended in 2000.

2.2. Hydrological measurements

Daily precipitation data were obtained from the Finnish Meteorological Institute weather stations at Valtimo (63°40′N, 28°49′E), located approximately 24 km from the catchments. There might be some spatial variability in the precipitation intensity and frequency between Valtimo and our study catchments, but on annual and seasonal time scales, this is assumed to be small, as indicated by Venäläinen et al. (2005). Weirs were built at the outlet of both catchments, and float type water gauges were installed and calibrated weekly for continuous measurement of water levels. Daily runoff was calculated using the stage-discharge relationships based on the theoretical weir formula (Mustonen, 1986), which had been calibrated by the hydraulic laboratory experiment. In our calculations, the water year (WY) begins on 1 November and ends on 31 October. The spring season refers to March–May, summer to June–August, autumn to September–November, and winter to December–February. During winter, vegetable oil was applied to the flow gauges to prevent them from being frozen. During the period after the clear-cutting, some data gaps (<1.3%) occurred in the Välipuro catchment when the water level dropped below the over-