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The role of catchment scale and landscape characteristics for runoff generation of boreal streams

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Summary The effect of catchment scale and the influence of landscape characteristics on runoff generation were investigated during snow melt in 15 nested boreal streams within the Krycklan catchment in northern Sweden. We used detailed oxygen-18 analyses of soils from two characteristic landscape types, snow melt samples and water samples from 15 streams with subcatchments ranging in size from 0.03 to 67 km^2. The detailed process understanding that was derived from isotopic and hydrometric measurements at a wetland and a forest site, in combination with the stream monitoring, enabled the development of a conceptual framework that could explain the variability in hydrological pathways over a range of catchment scales. While the proportion of new or event water was over 50% in wetland dominated catchments, the event water contribution in forested catchments was between 10% and 30%. The results suggest a large degree of scale-independence of hydrological flow pathways during the snow melt period, controlled by the proportion of wetland and median subcatchment area, across three orders of magnitude in spatial scale. The results from this study highlighted the importance of different runoff generation processes in different landscape elements, an understanding that can be useful in disentangling the temporal dynamics in hydrology and biogeochemistry during snow melt episodes when moving from small headwater streams to catchment outlets.

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Introduction

The effect of catchment scale and the influence of landscape characteristics on runoff generation are still not fully understood because of a complex multi-scale dynamics with numerous processes operating concurrently (Blöschl, 2001; Gergel et al., 1999; McGlynn et al., 2004). Evidence from hydrometric as well as isotopic and chemical tracer studies has been used to infer how the partitioning of event and pre-event water during episodes (Brown et al., 1999; Shanley et al., 2002) and mean transit time (McGuire et al., 2005; Shaman et al., 2004) are affected by catchment scale. Although some evidence of self-similarity of hydrological pathways and transit times across scales has been presented, the construction of hydrological models and river management tools that operate at different spatial and temporal scales remains a challenging task.

One of the most widely recognized methodologies for understanding and quantifying hydrological pathways in catchments is the use of natural stable isotopes as environmental tracers for isotopic hydrograph separation (IHS). The use of IHS has provided important understanding for questions related to water resource management, transport of contaminants and biogeochemical cycling. Its use dates back to the pioneering work by Dinçer et al. (1970) and has since been used in various environments around the world (Laudon and Slaymaker, 1997; Rodgers et al., 2005; Sklash et al., 1986; Stadnyk et al., 2005; Uhlenbrook et al., 2002). The general finding from these studies has been that so-called old, or pre-event, water dominates the hydrograph during events, whereas contribution from new, or event, water during rain storms and snow melt events remains generally small.

As valuable as IHS is, it only provides an answer to the question of the relative contribution of two sources, event and pre-event water, leaving many questions about the specific flow pathways and runoff mechanisms unanswered. Most previous IHS work has been based on isotopic information of inputs and outputs (i.e., precipitation and stream water) only, relying on assumptions about what occurs in the catchment soils. Using internal isotopic information and by combining isotopic and hydrometric information, new process understanding can be acquired that can help decipher the dominant runoff generation mechanisms during hydrological episodes in ways that are otherwise not possible (Burns, 2002).

As with most other process-oriented hydrological investigations, previous IHS studies are mainly based on small individual catchments or hillslopes. The few multi-scale IHS studies that have been conducted provide inconclusive results (Buttle, 2005). For example, Rhode (1987) compared the pre-event fraction for a number of runoff events from different small catchments. He found a decrease of pre-event water fraction for larger events, but no relation to catchment area. Brown et al. (1999) showed that catchment size was negatively correlated with event water contribution during heavy summer rain storms, whereas Shanley et al. (2002) found a positive correlation during snow melt episodes (i.e., the amount of event water increased with catchment size).

Although there is an unavoidable loss of mechanistic understanding when moving from hillslopes or small catchments to larger watersheds, this can be compensated by a more integrated understanding of catchment processes (Soulsby et al., 2006a). Large scale catchment investigations are also needed to improve our ability to understand and predict hydrologic and biogeochemical responses to natural disturbance and human activity over a wide range of climatic and geographic conditions. Furthermore, as there is an urgent need to support decision making at scales where water resource management most often occurs, a more advanced scientific understanding of the hydrological functioning of larger catchments is required (Kirchner, 2006).

In the boreal region, stream networks drain landscapes comprised of a mosaic of forest, wetlands and lakes. This varying landscape organization results in a complex and dynamic hydrology that can vary with stream size, flow and season (Spence and Woo, 2006). Another defining feature of the boreal landscapes is that the hydrology is dominated by snow melt during spring and early summer, often making up 50% of the total annual water yield (Barnett et al., 2005).

At present, little is known about how the pattern in event/pre-event water contribution is affected by major landscape elements or catchment scale in the boreal region. The purpose of this study was therefore to investigate (1) whether similar processes are important for runoff generation in forested and wetland catchments during the spring flood and (2) whether scale (e.g., catchment size) influences the relative contribution of event and pre-event water to spring runoff. Stream water isotopic data from 15 nested streams draining catchments ranging in size from 0.03 to 67 km^2 were used in combination with detailed soil isotopic data from two contrasting catchments (representing peat wetlands and coniferous forest underlain by till, respectively) to answer these questions.

Study area

The study was performed as a part of the multidisciplinary Krycklan Catchment Study at Vindeln Experimental Forests (64°14′N, 10°46′E), approximately 50 km northwest of Umeå, Sweden (Fig. 1). Within this catchment 15 partly nested subcatchments were instrumented for continuous discharge measurements and stream water sampling. The upper part of the catchment, including the two experimental catchments used in this study (Västrabäcken, catchment 2 (C2) and Kallkälsmyren, catchment 4 (C4)), is well documented, as both climatic and hydrological studies have been performed in the area for nearly three decades (Bishop et al., 1990; Folster et al., 2003). Short summers and long winters characterize the climate in the region. Snow covers the ground on average for 171 days, from the end of October to the beginning of May (Ottosson-Löfvenius et al., 2003). The mean annual precipitation and temperature are 600 mm and 0 °C, respectively. Approximately 50% of the annual precipitation falls as snow and the average January temperature is −10 °C. The upland parts of the catchment are mainly forested with Norway spruce (*Picea abies*) in low-lying areas and Scots pine (*Pinus sylvestris*) in upslope areas. There are also large patches of mires predominantly in the upper part of catchment. Further downstream, Nor-