Journal of Hydrology (2006) **331**, 186–204

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Tracing sources of summer streamflow in boreal headwaters using isotopic signatures and water geochemical components

Jens Kværner [a,*], Bjørn Kløve [a,b]

[a] *Bioforsk — Norwegian Institute for Agricultural and Environmental Research, Soil and Environment Division, Frederik A. Dahls vei 20, N-1432 Ås, Norway*
[b] *Water Resources and Environmental Engineering Laboratory, Department of Process and Environmental Engineering, 90014 University of Oulu, Oulu, Finland*

Received 29 April 2005; received in revised form 7 May 2006; accepted 10 May 2006

KEYWORDS
O and H isotopes;
Hydrochemistry;
Stream water;
Peatland;
Tracer hydrology;
Catchment hydrology

Summary Content of ^{18}O, ^{2}H, ^{3}H and geochemical components in rainfall, stream water, peat water and bedrock groundwater in four headwater catchments were compared to reveal differences in sources of runoff and hydrological vulnerability to tunnel drainage during summer. Water previously stored within the catchments was the predominant component of streamflow during small and moderate events. The proportion of event water increased at high discharge in autumn. Neither the isotopic nor the hydrochemical composition of stream water indicated any considerable contribution from old bedrock groundwater. Stream water hydrochemistry revealed clear influence of soil water pathways. The differences in land cover could be seen in water quality and runoff generation. Water storage and mixing in lakes and lowland wetlands reduced fluctuations in runoff and water quality. Runoff retention and the solute trapping effect in peatlands were most efficient in flat areas near the catchment outlet. In lowflow periods fluxes from hillslopes were of minor importance compared to discharges from wetland water storage. Water delivery from hillslopes with thin till cover (<0.6 m, average depth 0.3 m), short slope lengths (<100 m) and steep inclines (17%) was very restricted in drought periods. An increase of slope from 13% to 17% can influence the delivery of water from uplands in lowflow periods.

Introduction

Boreal forested catchments of south-eastern Norway consist mainly of shallow till soil underlined by crystalline bedrocks, exposed bedrocks, peatlands and lakes. Small headwater

* Corresponding author. Tel.: +47 64948148; fax: + 47 64948110.
E-mail address: jens.kvarner@bioforsk.no (J. Kværner).

0022-1694/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2006.05.008

catchments located on drainage divides typically have similar features, but the portion of different land types can vary considerably. Such catchments often discharge to small lakes or mires. Previous studies of wetlands and catchments in forested areas with shallow till soils show that flow rates are tied to shorter-term variation in rainfall and thus susceptible to extended dry periods (Devito and Hill, 1999), and that streamflow generation at the basin scale is dictated by the differential ability of landscape elements to generate runoff and the degree of interaction of these elements (Buttle et al., 2004).

Changes in land use and climate can affect delivery of water and solutes which effect wetland ecological and hydrological functions in many ways. Wetlands are adapted to stable water tables fluctuating near the surface. A permanent change in water inflows can lead to reduced groundwater table resulting in subsidence of peat soils and loss of nutrients and greenhouse gasses. Changes in wetland can have large effects on the catchment water quality as wetlands often trap different elements such as sulphate (Devito, 1995; Devito and Hill, 1997), nitrogen, phosphorous (Devito and Dillon, 1993) and methylmercury (Branfireun et al., 1996). Stream acidification caused by episodic SO_4^{2-} release from wetlands following droughts has been reported in several studies, (Brække, 1981; Wieder, 1985; Bayley et al., 1986; Van Dam, 1986), and acidification of water has also been linked to fish mortality (Gosling and Baker, 1980; Holopainen and Oikari, 1992). Studies have also shown that extended dry periods might have important consequences on the release of greenhouse gases (Roulet et al., 1992).

In small headwater wetlands, potential hydrological changes are often caused by intensive forestry, road construction, groundwater use and climate change. In Norway, environmental impacts of tunnel constructions have recently received considerable attention after severe drawdown of groundwater and notable changes in headwaters were detected in the late 1990s after construction of a rail road tunnel to Oslo airport (Aars, 1998). Environmental effects noted were acidification of surface water (Lund and Straith, 1999), peat settlements and shrinkage and death of Sphagnum mosses in wetlands (Kværner and Snilsberg, 1997). This brought attention to headwater catchment hydrology and the susceptibility of different wetlands to drought and hydrochemical and ecological changes. It also highlighted the importance of understanding wetland—upland interactions and their importance to wetland hydrology and vulnerability in drought periods in landscapes with different topography and soil covers. A better knowledge of headwater and upland—peatland summer hydrology and the role of wetlands in catchment hydrology are needed to assess consequences of different land use and drainage scenarios, to assess the hydrological vulnerability of different basins, and to set limits for groundwater drawdown and leakage to tunnels in order to prevent future damage to ecosystems.

The general theory of runoff generation in headwater boreal catchments dominated by shallow till soils, peatlands and lakes can be formulated based on previous studies of hillslope and wetland hydrology. In till hillslopes, storm water often originates from pre-event water (Genereux and Hooper, 1998). Event water is often generated from saturated areas that grow in time as rainfall continues (Beven, 2001). Also other fast runoff processes through the soil are common, such as interflow in the top soil layer. Base flow is released from saturated storages in deeper soil horizons and fractured rock (groundwater). In boreal catchmets, a large proportion of the water is stored in lakes and peatlands. It is well known that lakes regulate runoff by reducing peak flows and increasing base flow (Kaitera, 1949). The hydrology of mires is rather complex and different theories exist on their role in runoff generation (Kløve and Bengtsson, 1999). Based on the water balance equation, the runoff from mires depending on the rate and magnitude of inputs, and the efficacy of storage, usually involving an interaction of surface and shallow groundwater (Gibson et al., 2000). Depending on external water source being either from rain or also from groundwater, mires are traditionally classified into bogs and fens, respectively. As generally wet areas mires do not store water during rainfall events (Clymo, 1987). But, extensive drought periods can increase the storage which can cause reduction in runoff generation from some mires (Kløve, 1997). It can be assumed that fens are less affected by droughts if the upland area is large with contribution to runoff also in dry periods (Gregory, 1988).

The objective for the present study was to clarify the role of different boreal landscape elements such as peatlands, lakes and forested till soils in catchment hydrology and solute transport with focus on sources of stream water during baseflow and peak flows in the non-frost season. Hypothesis for the present study are: (1) discharge from hillslopes is of minor importance compared to discharge from wetlands and lakes during lowflow periods, (2) location and magnitude of water storage in wetlands and lakes are essential to patterns of water composition and runoff in drought periods, (3) differences in baseflow discharge in neighbouring catchments can be attributed to basin properties and differences in sources which are reflected in water isotopic composition and hydrochemistry, and (4) at storm events a significant portion of event water originates from hillslopes. The main approach was to use hydrological and water quality data from four adjacent catchments with different wetland and upland land cover and topography.

Materials and methods

Study site

The study was carried out in four headwater catchments located 40 km north from Oslo, above the proposed new road RV 35 tunnel between Grua and Bruvoll. Elevation of the study area ranges from 510 to 627 m above sea level. The climate in this region is humid temperate with slight continental characteristics. Annual mean temperature is circa 2.5 °C. Average annual precipitation and runoff are approximately 1100 and 650 mm, respectively. Precipitation normally falls as snow in November—March with snowmelt in April. The hydrological regime has a seasonal cycle with discharge minimums in summer and winter and maximums during spring due to snowmelt runoff and autumn due to reduced evapotranspiration. Evaporation from free water surface around the closest meteorological station Gardermoen has been gauged to be in average 87, 107, 102, 94 and 60 mm in May, June, July, August and September, respectively (Hetager and Lystad, 1974).