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Groundwater hydrology of boreal peatlands above a bedrock tunnel – Drainage impacts and surface water groundwater interactions

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SUMMARY

Little attention has been given to the pattern of hydrological connectivity between peatlands and water bearing fracture zones in crystalline bedrock. The construction of the railway tunnel Romeriksporten provided an opportunity for studying impacts of bedrock tunnelling on peatland hydrology and the hydraulic connectivity between peat deposits and deeper layers in an area with fractured Precambrian gneisses, exposed bedrock, and surficial covers of thin till deposits and peatsoils. Above the tunnel the water level in peat wells fluctuated with maximum depths up to 3 m, and water that otherwise would have generated surface runoff infiltrated in the peat. Drawdowns of the groundwater table in peatlands were observed as far as 340 m away from the tunnel trace. The deep drainage base provided prolonged water table drawdowns in peatlands in dry periods, and differential settlements in drained peatsoils resulted in secondary changes in patterns of surface water storage and flow. The groundwater drawdowns were influenced by the balance between tunnel leakage and water supplies from catchments and the wetland position within the groundwater flow system. Deep and simultaneous lowering and fluctuations of hydraulic heads in wells in the peat, the subpeat sediments and the bedrock above the tunnel demonstrated hydraulic connectivity between the peat layers and the bedrock, and revealed vertical flow even through highly humified peat layers in the catotelm. This shows that in peatlands with a subsurface of a relatively thin till cover above fractured crystalline bedrock, favourable conditions for groundwater flow from peatsoils to rock are not always restricted to a few specific sites, and indicates that attention should be given to the influence of peat water–bedrock water connectivity on impacts of groundwater exploitation, droughts and climate changes in such areas.

1. Introduction

The increasing recognition of the importance of wetlands and the human exploitation of groundwater resources during the last decades have brought drainage impacts on wetlands and interactions between ecosystems and deeper aquifers into focus. In Europe, the new EU Water Frame Directive (European Commission, 2000) emphasizes the importance of considering these aspects in future groundwater management. Peatlands are the most widespread wetland type on earth, are found in all continents, and cover about 3 per cent of the earth's terrestrial and freshwater surface (Joosten, 2004; Environment and Heritage Service Belfast, 2010). These areas are important for landscape and biological diversity (Korpela, 1998) and can also be important for regulations of catchment runoff (Kværner and Kløve, 2008). Peatlands are physically and ecologically adapted to stable water tables fluctuating near the surface. The water table levels in peatlands are crucial for the ecological niches of plant species (Malmer, 1962; Økland, 1989; Rydin and Jeglum, 2006) and thus even for peat development (Ingram, 1983). Alterations in wetland hydrology and water table levels can have large effects on water quality, as wetlands can be transformers and sinks of different elements such as sulphate (Devito, 1995; Devito and Hill, 1997), nitrogen, phosphorous (Devito and Dillon, 1993) and methylmercury (Branfireun et al., 1996). In dry periods sulphides can be oxidised to sulphate, and 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). Moreover, alterations of water tables in peatlands might have important consequences on the release of greenhouse gases (Glaser et al., 2004; Strack et al., 2004; Strack and Waddington, 2007).

The acrotelm–catotelm model of the structure of peatlands (Ingram, 1978, 1983) has gained wide acceptance and use. The model assumes that peatlands consist of two main layers, a surface layer (acrotelm) with thickness up to 0.5 m characterised by relatively undecomposed peat and high hydraulic conductivity, and the deeper peat (catotelm) with higher degree of peat decomposition and lower hydraulic conductivity. At present two

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alternative models of groundwater hydrology of peatlands (Reeve et al., 2000) implying different vulnerability to underground drainage exist. The shallow flow model is based on the acrotelm–catotelm concept and assumes that groundwater flow in peatlands is restricted to the acrotelm due to low permeability in deeper peat layers (Reeve et al., 2000; Siegel and Glaser, 2006). Since 1980s flow systems have been observed in deeper peat layers in several studies (Glaser et al., 2006), and an alternative model has been proposed, the groundwater flow model, which assumes that the extent of vertical groundwater flow in peatlands is primarily not controlled by the permeability of humified peat layers, but by the permeability of the underlying mineral soil (Reeve et al., 2000). Recent studies have shown that the type and extent of groundwater interaction can influence the amplitude and duration of water-level fluctuations in undisturbed peatlands, and that the hydrogeological settings, landscape position and climatic conditions may be important for the extent and role of groundwater–wetland interactions (Ferone and Devito, 2004; Vidon and Hill, 2004; Price et al., 2005). Although several peatland studies have examined relationships between groundwater and surface water in different hydrogeological settings (Vidon and Hill, 2004; Price et al., 2005), the research has mainly focused on interactions with surficial deposits and surrounding catchments. Little attention has been given to the pattern of hydrological connectivity between peatlands and water bearing fractures zones in crystalline bedrock. The issue of groundwater flow from soil to bedrock has been addressed only in a limited number of studies, and is still poorly understood (Rohde and Bockgård, 2006; Praamsma et al., 2009).

Numerous tunnels and other underground constructions are being built in bedrock for different purposes such as roads, railways, water supply, sewage transport, mining, and hydropower development. Tunnel studies have usually focused on inflow and engineering aspects, whereas environmental impacts have received less attention. Groundwater decrease and inleakage of surface water have been described from several tunnels (Olofsson, 1993; Statens Offentliga Utredningar, 1998; Cesano et al., 2000; Mabee et al., 2002; Kim and Lee, 2003; Vincenzi et al., 2009). Although water contributions from peatland water storage to tunnels have been reported (Skjeseth, 1982; Olofsson, 1991), the spatial and temporal effects of tunnelling on peatland hydrology are seldom described. Studies of drainage impacts on peatland hydrology have traditionally been restricted to surficial drainage, as surface ditches for forestry, agricultural or peat mining purposes. Exploring the hydrological impacts of tunnel drainage on peatlands may improve the understanding of the hydrogeology and vulnerability of peatlands, and thus improve the basis for management of such ecosystems and adjacent deposits and bedrock.

The construction of the railway tunnel Romeriksporten provided an opportunity for studying impacts of bedrock tunnelling on peatland hydrology and hydraulic connectivity between peat deposits and deeper layers. During the construction of the tunnel subsidence of the peat surface, slides, cracks, and dry holes in the peat deposits around Lake Northern Puttjern indicated that peatland hydrology was affected by tunnel leakage (Kværner and Snilsberg, 2008), and it was decided to monitor the groundwater tables in the peatlands. This paper presents the results from the geohydrological investigations carried out in the peatlands around Lake Northern Puttjern and adjacent areas. The objectives of the study were: (1) to reveal the spatial and temporal effects of tunnel leakage on water levels and hydrology of peatlands in a catchment with crystalline bedrock and thin till deposits, (2) to relate the hydrological effects on peatlands to catchment hydrology and wetland position, (3) to provide insight into leakage processes and hydrological connectivity between peatlands and bedrock.

2. Site description

The study has been conducted in the Lake Northern Puttjern area above the Romeriksporten railway tunnel and nearby catchments in Østmarka, northeast of Oslo in Southern Norway (Fig. 1). The investigation comprises five peatland areas, the peatlands around Lake Northern Puttjern and Lake Southern Puttjern (70–350 m south-east of the tunnel trace), the mire Kjerringmyr north of Lake Northern Puttjern (100–250 m north-west of the tunnel trace), the peatlands 350–590 m south of Lake Southern Puttjern in the Lake Northern Puttjern valley (580–770 m south-east of the tunnel trace) and two reference peatlands situated west of Lake Lauvtjern and around Lake Rundtjern, respectively (Fig. 1b). The construction of the 13.7 km long tunnel between Oslo and Lillestrøm was commenced in 1994. Tunnelling under the Lake Northern Puttjern area started in autumn 1996 and excavation was finished September 4, 1997. The railway tunnel was officially opened August 21, 1999.

A decline of the water level was discovered in Lake Northern Puttjern in February 1997 (Aars, 1998). During November 1997, 560 L min^{-1} of leakage was measured over a 600 m long section of the tunnel in this area (A–B Fig. 1b) (NSB Gardermobanen AS, 1998a). After the excavation was finished until February 1999, the tunnel was tightened by grouting. The grouting reduced the leakage in this section to 146 L min^{-1} in November 1999 (NSB Gardermobanen AS, 1999b). Between August 14, 1997 and September 8, 1998, water was periodically transferred to Lake Southern Puttjern from Lake Kroktjern in the neighbouring catchment to compensate for the leakage to the tunnel (Fig. 2f). In 1999 eighteen injection wells were drilled from the tunnel in the sections with most fractures (Kitterød et al., 2000). The wells were arranged in a fan-shape with the orientation ranging from almost parallel to the axis of the tunnel to an angle of 45°. During 1999 and 2000 water was injected in the bedrock from these wells in dry periods to counteract drawdown of groundwater and surface water tables (Fig. 2f).

The climate in this area is suboceanic. Annual mean temperature is about 4.0 °C and annual mean precipitation is around 850 mm (Bendiksen et al., 2005). In 1997, 1998 and 1999 the annual precipitation was 587, 784 and 944 mm, respectively, at the nearby meteorological station at Blindern, whereas the annual mean precipitation at this station was 763 mm (The Norwegian Meteorological Institute, 2009). Average annual runoff for the normal period 1961–1990 is approximately 700 mm (Beldring et al., 2002). Precipitation normally falls as snow in December–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 in autumn due to reduced evapotranspiration.

The elevation of the study area around Lake Northern Puttjern is about 265 m above sea level, approximately 180 m above the Romeriksporten railway tunnel. The reference areas at Lake Lauvtjern and Lake Rundtjern are situated ca. 325 and 225 m above sea level, respectively. The catchments of Lake Northern Puttjern and the mire Kjerringmyr comprise 33.2 and 5.5 ha, respectively, whereas the catchments of the reference fields in the Lake Lauvtjern and the Lake Rundtjern areas cover 9.2 and 32.2 ha.

The bedrock mainly consists of Precambrian gneisses (Berthelsen et al., 1996), belonging to the southeastern Norwegian basement, generated approximately 1.5–1.6 $*$ 10^9 year BP (Graversen, 1984). The supracrustal gneiss is the oldest unit in the area, and is intruded by several generations of granitic and basic plutonic rocks. The intrusive events were separated by major deformation episodes. Four fold episodes of regional importance have been distinguished (Graversen, 1984). This has resulted in varying bedrock, with alternating rocks