Cold Regions Science and Technology 71 (2012) 118–128

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

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

Assessment of temporal and spatial variation in chemical composition of groundwater in an unconfined esker aquifer in the cold temperate climate of Northern Finland

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ARTICLE INFO

Article history:
Received 4 April 2011
Accepted 11 October 2011

Keywords:
Cold region
Snowmelt recharge
Groundwater quality
Statistical analysis
Groundwater–surface water interaction

ABSTRACT

Samples of groundwater, surface water, snow and precipitation were collected to identify potential end-members for aquifer recharge in an unconfined esker aquifer connected to nearby surface waters. Concentrations of Ca^{2+}, Cl^{-}, NO_3–N and SiO_2 and electrical conductivity were determined in these water samples. Time series, ANOVA followed by HSD test and biplots were used to investigate temporal and spatial variations in surface water and groundwater chemistry. Examination of the spatial and temporal variations in groundwater solutes revealed that water quality was similar in perched groundwater and the main aquifer. The exception was NO_3–N concentration, which increased in the perched groundwater with rising groundwater level, indicating a nitrogen source from the overlying airport. In the main aquifer, solute concentrations generally decreased during and immediately after snowmelt periods, indicating the importance of snowmelt input for groundwater quality. Groundwater solute concentrations generally decreased with declining groundwater level. During the spring melt period, the surface water level rise higher than groundwater level and the Cl^{-} concentration in groundwater decreased showing a seasonal surface water intrusion. During the anomalously warm period in winter ($T > 0$ °C) the solute concentration decreased, implying that groundwater quality may be sensitive to future warming.

1. Introduction

Groundwater is an important freshwater source in the world, as it provides almost 40% of the world's potable water (Morris et al., 2003). Groundwater requires less chemical treatment owing to its good quality and it is better protected against pollution than surface waters. In Finland, nearly 60% of municipal water supply is groundwater and its usage is expected to increase in the future (Finnish Environmental Institute, 2011). Most aquifers used for water supply in Finland are glaciofluvial deposits, i.e. eskers or ice-marginal end moraines (Mälkki, 1999). Eskers are typically well-sorted gravel and sand deposits and represent the most common aquifer on the Fenno-Scandian shield. The watertable usually lies between 2 and 4 m below the ground surface, but can reach as much as 30 m in some regions in southern Finland (Korkka-Niemi and Salonen, 1996). Unconfined esker aquifers are often located next to surface water bodies, i.e. lakes, ponds, rivers and wetlands, and are affected by human activities (Mälkki, 1999).

The quality of Finnish groundwater is generally good by EU standards (EC, 2006). Cumulative factors affecting groundwater quality in Finnish esker aquifers can be roughly classified into two scale-dependent categories (Korkka-Niemi, 2001): regional effects and site-specific effects. Regional effects depend on the aquifer type, i.e. the hydraulic properties of the aquifer that affect the flow conditions, residence time, rock–water interaction, the thickness of the vadose zone and proximity to lakes, rivers and wetlands. Well structure and pollution are considered site-specific factors (Korkka-Niemi, 2001). In shallow parts of unconfined esker aquifers, groundwater chemistry is also affected by the composition of rainwater (Lahermo et al., 1990) and snowmelt water (Soveri et al., 2001). Groundwater chemistry can also change with time and respond quickly to precipitation or snowmelt events (Soveri et al., 2001), with concentration minima occurring in spring and autumn and concentration maxima in winter and summer. During the spring melt periods, minimum values for alkalininity, electrical conductivity and hardness can also be found. However, the water quality in general may decline due to surface water intrusion increasing bacterial counts and $KMnO_4$ consumption (Korkka-Niemi, 2001). In coastal aquifers, relict seawater trapped in silt and clay pores and rainfall containing a variable amount of sea salt components can increase the SO_4, Cl^{-} and Na concentrations in groundwater.

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0165-232X/$ – see front matter
doi:10.1016/j.coldregions.2011.10.003

Extreme variability in climate and future climate change may also change groundwater quality in the vadose zone (Gurdak et al., 2007). Recent studies of chalk aquifers in the UK (Bloomfield et al., 2006; Gooddy et al., 2001; Johnson et al., 2001) and laboratory experiments (Sugita and Nakane, 2007) showed that increased recharge can increase solute leaching, capture pesticides and other pollutants in the unsaturated zone and reduce groundwater quality. As a consequence of global warming, the amount and timing of recharge are expected to change in snow-dominated regions (Jyrkama and Sykes, 2007). The rise in winter temperature will change the form of precipitation from snow to rain, reduce ice in seasonally frozen ground and significantly increase winter recharge rates, shifting the spring melt period to earlier in the year and decreasing the snowmelt peak (Okkonen et al., 2010). Changes in recharge will eventually lower the amplitude of fluctuations in the water table and the minimum and maximum water levels (Okkonen and Kløve, 2010). Recent studies in Finland suggest that anomalously warm periods during winter ($T > 0$ °C), snowmelt infiltration in sandy soils increases the soil moisture content below the partially frozen soil and may increase aquifer recharge (Sutinen et al., 2007). Runoff is generally expected to decrease and infiltration to increase as a result of the decrease in ice in seasonally frozen ground and increase in snowmelt (Eckhardt and Ulbrich, 2003; Jyrkama and Sykes, 2007). In cold regions, ice in seasonally frozen ground and snow cover will play an important role for variations in groundwater quantity and possibly also its quality (Silander et al., 2006). Identification of these risks and threats is most valuable in areas where groundwater is used, or will be used, for public consumption.

Previous studies in snow-dominated esker aquifers in Finland have pointed out the seasonal trends in groundwater quality (Hatakka and Väisänen, 2007; Soveri et al., 2001), and the cumulative impact of extra-regional, regional and site-specific effects (Korkka-Niemi, 2001). However, there is still relatively little research into temporal variations in groundwater-surface water interactions in cold, snow-dominated regions (Korkka-Niemi et al., 2011; Rautio and Korkka-Niemi, 2011; Scibek et al., 2007). Such temporal variations, especially on the local scale, account for the response of the hydrogeochemical constituents to snowmelt and rainfall, which may give an indication of groundwater recharge periods, the spatial variability of the recharge (Cherry, 2000), potential surface water–groundwater interactions (Rautio and Korkka-Niemi, 2011) and groundwater flow paths in the aquifer. The assumption is usually made that a single point represents the water quality in the whole aquifer, although the water quality in different units may change depending on the mineralogy and groundwater residence time within the aquifer (Kortelainen and Karhu, 2009). In addition, seasonal changes in solute concentrations may indicate the sensitivity of the groundwater to any action that occurs on the land surface. Such knowledge is important in assessing aquifer vulnerability to pollution and climate change and in developing good monitoring strategies.

In this study, we examined the temporal and spatial variability in groundwater and surface water hydrogeochemistry in a seasonally snow-covered unconfined esker aquifer (Pudasjärvi) in northern Finland. The concentrations of Ca^{2+}, Cl^-, NO_3–N and SiO_2 and electrical conductivity were determined in a number of water samples. These chemical constituents represent the weathering of the mineral soil (Ca^2, SiO_2) and possible sources of pollution (Cl^- from road salt and NO_3–N from agriculture). SiO_2 has also been used as an indicator of groundwater age (Burns et al., 2003). Monthly groundwater and surface water samples were collected over a one-year period. Groundwater samples were collected near the groundwater level except in one well, in which the deeper groundwater was sampled. One of the sampling wells represented the perched groundwater. Monthly water samples were studied by biplots based on the principal components, obtained through principal component analysis (PCA). Spearman rank correlation between variables was also studied. Multiple comparisons were made by the one-way analysis of variance (ANOVA) approach followed by the Tukey's multiple-comparison post-hoc test (Tukey Honestly Significant Difference, HSD) in order to study the differences in concentrations in group means across site types. The main objective of this study was to investigate the monthly changes in the groundwater solution across the aquifer and to differentiate groundwater recharge periods, recharge sources, potential pollution sources and groundwater–surface water interactions in the Pudasjärvi aquifer.

2. Study site description

The Pudasjärvi aquifer is a small, shallow, unconfined esker aquifer (Fig. 1). The study site is classified as having a mid-boreal climate and typically snow cover from November to April (Finnish Meteorological Institute, 2010). The mean winter temperature varies between −6 and −4 °C and the mean summer temperature between 14 and 16 °C. Precipitation is highest in summer (June to August), varying between 181 and 200 mm, and lowest in spring (March to May), varying between 81 and 100 mm. Within the Iijoki watershed, the snow pack grows from November to April and melts in April–May. The snow depth usually varies between 50 and 75 cm and the snow water equivalent varies between 30 and 260 mm from February to April.

2.1. Anthropogenic risks to groundwater quality in the Pudasjärvi aquifer

Since 1981, the groundwater in Pudasjärvi municipality has been pumped for domestic use, at an average pumping rate of 750 m^3/day, which is 40% of the annual estimated recharge. Seasonal variations in the water level in Lake Pudasjärvi and in the groundwater level have been observed every year since 1981. Because surface water intrusion is likely to occur during and just after the spring snowmelt period, when the surface water elevation reaches the groundwater elevation, pumping of groundwater is halted in May and June. Besides adjoining Lake Pudasjärvi, the Pudasjärvi aquifer is also located next to Lake Kivarijärvi and the Kivarijoki river (Fig. 1).

In the Pudasjärvi aquifer, the potential anthropogenic factors affecting groundwater quality are a gravel pit, an airport, roads, oil tanks, industries, farming, an abattoir and a landfill site (PSV-Maa ja Vesi, 2001) (Fig. 1). Surface water intrusion can also potentially change the groundwater quality (PSV-Maa ja Vesi, 2001). The airport is located in the north-west part of the aquifer and is only used in summertime. The wastewater from the airport is drained to the Kivarijoki river and Lake Pudasjärvi (PSV-Maa ja Vesi, 2003). The main road cuts the aquifer at 1.6 km length and the de-icing salt that is used to prevent ice on this road poses a risk to groundwater by increasing the Cl^- and Na concentrations (PSV-Maa ja Vesi, 2001). Pastures are located in the east and east-south of the aquifer. Fertiliser, manure and urine may leak into the soil and percolate to the groundwater, potentially increasing the NO_3–N concentration in the groundwater. An abattoir is located 1.1 km east of the pumping well and may also threaten groundwater quality by increasing the Cl^-, bacteria levels and NO_3–N concentration due to animal waste. An old landfill site that was in use during the period 1950–1969, which is located 1.5 km to the north-east of the pumping well and 400 m from the Kivarijoki river, also poses a risk to groundwater quality (PSV-Maa ja Vesi, 2001). The final surface area of the landfill at closure was 0.8 ha and the volume of the waste was 10,000 m^3. Nitrogen typically leaches out as NH_4^+ from landfills in Finland. In 1970, the contaminated soil below the landfill was removed and replaced with new soil (PSV-Maa ja Vesi, 2001). Today, the area is used as grassland and pasture for horses.

The main industries operating in the Pudasjärvi aquifer area are a construction industry (since 2000), a sawmill (1970–1980), and a clamp store for impregnated wood (1980–1990) (PSV-Maa ja Vesi, 2002). The sawmill is located 650 m south-west of the pumping well and in 1970 small amounts of chloride phenol were observed in the groundwater, probably originating from the sawmill. In 1990, the polluted soil was removed and replaced. The clamp store for impregnated wood is located 1.2 km north-east of the pumping well.