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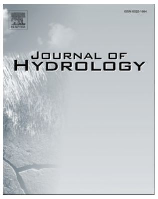

Environmental conditions of boreal springs explained by capture zone characteristics

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SUMMARY

Springs are unique ecosystems, but in many cases they are severely threatened and there is an urgent need for better spring management and conservation. To this end, we studied water quality and quantity in springs in Oulanka National Park, north-east Finland. Multivariate statistical methods were employed to relate spring water quality and quantity to hydrogeology and land use of the spring capture zone. This revealed that most springs studied were affected by locally atypical dolostone–limestone bedrock, resulting in high calcium, pH, and alkalinity values. Using Ward's hierarchical clustering, the springs were grouped into four clusters based on their water chemistry. One cluster consisted of springs affected by past small-scale agriculture, whereas other clusters were affected by the variable bedrock, e.g., springs only 1 km from the dolostone–limestone bedrock area were beyond its calcium-rich impact zone. According to a random forest model, the best predictors of spring water chemistry were spring altitude and the stable hydrogen isotope ratio of the water (δ^2H). Thus stable water isotopes could be widely applicable for boreal spring management. They may also provide a rough estimate of groundwater flow route (i.e., whether it is mainly local or regional), which largely determines the chemical characteristics of spring water. Our approach could be applied in other boreal regions and at larger spatial scales for improved classification of springs and for better targeted spring management.

1. Introduction

Springs are groundwater dependent ecosystems (GDEs) that are unique from an ecological, economic, and cultural perspective (Kløve et al., 2011). Springs harbor highly specialized and regionally restricted flora and fauna, and are thus regarded as hotspots of freshwater biodiversity (Cantonati et al., 2012; Virtanen et al., 2009). The main environmental drivers of spring ecosystems are the quantity and quality of the groundwater inflow. In boreal regions, the ecology of cold springs differs markedly from that of other aquatic environments, because the springs provide a cold, clear-water, and nutrient-poor habitat (Miettinen et al., 2005). Natural variations in groundwater quantity and quality are controlled by a range of hydrogeological factors such as geology, topography, land cover, and recharge (Kresic and Stevanovic, 2009).

Globally, springs suffer from groundwater depletion (Konikow and Kendy, 2005) and contamination by e.g., nitrate or metals (e.g., Laini et al., 2012). Boreal springs are currently facing drastic changes arising from direct anthropogenic disturbance to spring habitats, changes in catchment land use practices, and changes in groundwater quality (Ilmonen et al., 2012). In Finland, many springs are impacted by lowering of the groundwater through intensive peatland drainage (Aapala et al., 2013). Springs have been monitored over time for anthropogenic influences (e.g., salting of roads), but natural variations in spring habitats, their water chemistry, and potential modifying factors such as groundwater flow routes or temperature have gained less attention (Kløve et al., 2011). Despite the importance of springs to regional biodiversity (Cantonati et al., 2012), they gained only minor interest in the scientific literature in terms of their classification (Kresic and Stevanovic, 2009; Springer and Stevens, 2009) and vulnerability for conservation purposes (Barquín and Scarsbrook, 2008). Recently, however, status assessment and protection of springs

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and other GDEs was given high priority in the European Union (EU) Groundwater Directive (European Commission, 2006). In Finland, for instance, more than 6000 individual groundwater areas (Britschgi et al., 2009) and their GDEs must be classified by 2019 (Government of Finland, 2014). To accomplish these targets, new information from different types of GDEs on their functioning and current status is required. More local-scale data and cost-efficient tools for monitoring and management are also urgently needed.

Previous studies have used self-organization maps (Żelazny et al., 2011), principal component analysis (Kreamer et al., 1996; Moore et al., 2009), and other classification tools (Jang, 2010; Matić et al., 2013) to identify the main environmental factors affecting spring water quality. Although most of these studies have included a relatively large number of springs, they are typically based on a single sample per site, as springs are usually defined as rather static systems (Gibert et al., 2009), or lack information on spring capture zone properties and/or a hydrological perspective. In addition, most previous studies have been made in karst regions (Matić et al., 2013; Toth and Katz, 2006), agriculture dominated regions (Elhatip et al., 2003), temperate environments (Levison et al., 2014; Michalik and Migaszewski, 2012), and mountainous areas (Jeelani et al., 2010, 2014; Kanduč et al., 2012), where climate, land use, geology, and many other factors differ from boreal conditions. Furthermore, boreal springs are in many cases associated with near-surface groundwater sources (e.g., springs connected to unconfined glaciofluvial formations). For this reason, boreal springs may face more risks from changes in land use and groundwater recharge patterns than springs originating from deeper, regional groundwater flow systems with longer residence times.

In this study, we examined the hydrology, hydrogeology, capture zone land use, water chemistry, and stable water isotopes (^{18}O and ^{2}H) of springs in Oulanka National Park and its surroundings in north-east Finland. Only a handful of previous studies have examined springs in the boreal region (e.g., Ilmonen et al., 2012; Juutinen and Kotiaho, 2009) and the main emphasis in these has been on community ecology patterns. We sought to identify the main drivers of variations in spring water quality and quantity. We assumed that the springs could be classified by the level of anthropogenic influence, groundwater flow routes, bedrock type, and possible surface runoff to the spring pool. We then applied the results to assess the vulnerability of springs in the Oulanka region and to assess the overall potential of our methods for spring management.

2. Materials and methods

2.1. Study area: Oulanka National Park and its surroundings

The springs included in the study are located in Oulanka National Park and its surroundings in north-east Finland (Fig. 1). The Oulankajoki river valley lies to the south of the study area and the springs discharge into tributaries of the Oulankajoki. The landscape in the area consists mainly of protected, and thus near-natural, boreal pine forest with a mosaic of peatland. The variable topography and geology has resulted in high diversity of plants and animals in the area (Malmqvist et al., 2009). Oulanka is the southernmost limit of distribution for many northern and Arctic species, and it also hosts eastern and southern species living at the extreme edge of their range. Thus the area is considered a 'biodiversity hotspot' with high conservation interest (Malmqvist et al., 2009).

The main anthropogenic impacts in the area originate from Liikasenvaara village in the east and from forestry activities beyond the boundaries of the national park (Fig. 1). Liikasenvaara village is a small and declining settlement with 20 current inhabitants. Agriculture was practiced actively in Liikasenvaara until the late 1960s, but the fields are now uncultivated. Commercial forestry is actively practiced in the immediate vicinity of the national park, and clear-cutting and maintenance of forest drainage networks have been conducted recently, especially in the north of the study area.

The geology of the area is dominated by dolostone–limestone bedrock deposits surrounded by greenstone and orthoquartzite bedrock (Pekkala, 1985; Silvennoinen, 1982, 1991) (Fig. 2). Oulanka is one of the few areas in Finland with dolostone–limestone bedrock, which enables rare flora to thrive within the national park (Söyrinki et al., 1977). The bedrock increases the alkalinity of local water, as dolomite ($CaMg(CO_3)_2$) and calcium carbonate ($CaCO_3$) increase the concentration of HCO_3^- when dissolved. The solubility of dolostone and limestone depends on pH and pCO_2 (Evangelou, 1998). Lakes in the boreal zone of Finland are usually dark-colored due to high concentrations of dissolved organic matter (DOC) originating from peatland and other organic matter sources (Kortelainen, 1993). However, most of the lakes in the study area have clear water because of their high alkalinity. Most of the springs studied are within or near dolostone–limestone areas. The soil on top of the bedrock mostly consists of shallow layers of dead-ice ablation till formed during the retreat of the glacier at the end of the last ice age (Koutaniemi, 1979; Räisänen et al., 2012). The soil has similar geochemical characteristics to the local bedrock (Räisänen et al., 2012). The springs discharge either directly from bedrock fractures or partially from the thin soil layer. Peat formations occur locally on top of the bedrock and the till. Groundwater in the study area mainly flows from north to south toward the Oulankajoki river valley and groundwater recharge occurs mainly in spring (ablation) and late fall (rainfall excess).

2.2. Field sampling and data collection

We sampled a total of 41 springs, six streams, and five lakes in early June and August, 2013. Six wells and/or boreholes in the area were sampled in August 2013. Meteorological data were collected by the Finnish Meteorological Institute at Oulanka Research Station (Fig. 1). No major rainfall preceded the sampling sessions (Fig. 3). During the June survey, some local showers were observed, but none occurred during sampling at any of the spring sites. The June samples were assumed to contain a snowmelt signal but, due to unseasonably warm weather in April and May 2013, these samples also partially represented summer base flow conditions.

In the field, we measured (i) spring discharge with a current meter (Mini Air 20, Schiltknecht) and (ii) water pH, oxygen content (O_2), temperature (Temp), and electrical conductivity (EC) with a field meter (WTW Multi 350i meter, accuracy: pH ±0.005, O_2 ±0.5% of the measured value; ±1 mV for EC and ±0.1 °C for temperature). We also determined geomorphology, such as surrounding surface geology, vegetation, slope, and spring dimensions (width, depth of the main pool, width and length of the main outflow), during field work.

We extracted water samples for stable isotope ($\delta^{18}O$, $\delta^{2}H$) analyses in bottles (50 ml high-density polyethene), which were rinsed with the sampled water before filling. We also collected water samples (1 l pre-acid washed bottles) to analyze total phosphorus (P_{tot}), orthophosphate ($P\text{–}PO_4^{3-}$), total nitrogen (N_{tot}), ammonium ($N\text{–}NH_4^+$), nitrate–nitrite ($N\text{–}NO_3^- + NO_2^-$), iron (Fe), dissolved organic carbon (DOC), total inorganic carbon (TIC), water color, alkalinity, potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), chloride (Cl^-), sulfate (SO_4^{2-}), and dissolved silica (SiO_2). We collected all spring water samples from the main spring pool, by a syringe or as a grab sample, as close to the outlet as pos-