XXXVIII IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
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University
of Silesia
Press 2010

abstract id: **451**

topic: **2**
Groundwater and dependent ecosystems

2.3
Interactions of surface and ground waters

title: **Hydropower regulation impact on river-groundwater interaction and the riparian zone – a geochemical approach**

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keywords: geochemistry, pristine, Northern Sweden, Kalix River, Luleå River

INTRODUCTION

Hydropower regulation of rivers was for a long time considered to be an environmentally friendly source of energy (e.g. Renöfält et al., 2009). However, damming of rivers has later been recognized as one of the most dramatic anthropogenic impacts on the natural environment (Petts, 1984). Today about two-thirds of the fresh water flowing to the oceans is obstructed by about 40,000 large and more than 900,000 smaller dams (Petts, 1984; McCully, 1996). The zone beneath and close to the river, where most of the exchange with the groundwater takes place, is sometimes called the hyporheic zone (Boulton et al. 1998; Hyporheic network, 2009) and sometimes the riparian zone (e.g. Swanson et al. 1982). The two concepts overlap but they have different focuses; the riparian zone focus is on the river and its environment, while the focus for the hyporheic zone is on the interaction between the river water and the groundwater. From here on only the concept riparian zone is used here.

The conditions in the riparian zones differ from the conditions in the river itself and in the adjacent aquifers. Riparian zones in natural rivers are diverse, dynamic, and multi featured ecosystems that participate in the regulation and maintenance of landscape biodiversity (Dynesius, Nilsson, 1994). The extent of these zones varies with stream order, season, morphology and characteristics of the river (e.g. Curie et al., 2009). Water flow into and out of this zone is largely influenced by advective exchange between the river and the groundwater controlled by vertical and lateral channel morphology, the pressure heads of the river water and the groundwater, as well as by the hydraulic conductivity of the river bed sediments and adjacent aquifer (Wörman et al., 2002; Cardenas, Wilson, 2007). These zones provide retention of water and nutrients, physical filtration as well as cycling of nutrients and organic matter with dissolved oxygen and NO_3 reduction (Claret, Boulton, 2008).

For northern pristine rivers the normal situation is that spring snowmelt produces a distinct flow peak and that the rivers normally are gaining water from the groundwater even if shorter stretches of the river might be loosing (e.g. Johansson et al., 2001). However, in regulated rivers, stored water released during summer results in smoothing of the spring peak and a combination of low groundwater levels and high river water stages, and long river reaches will then lose water to surrounding aquifers. If also short time regulation is applied frequent river water level fluctuations cause alternating fluxes in and out of the riparian zone disturbing the natural flow (Silliman, Booth, 1992) and geochemical patterns.

The overall aim of this study is to increase the knowledge regarding effects of river regulation on riparian zone geochemistry by:

a) analysing previous measurements of river water geochemistry with respect to river-groundwater exchange for the regulated Luleå River and the pristine Kalix River,
b) measuring a one-year cycle of riparian groundwater and river water quality for the same rivers.

This paper is focused on aim a) and initial findings from the measurements presented.

MATERIAL AND METHODS

A comparison between the geochemistry of two northern Swedish rivers, the heavily regulated Luleå River (2000–2001) and the pristine Kalix River (1991–1992) with otherwise similar features (geological settings and climatic conditions) has already been conducted, but not fully analysed. The Luleå River comprises 15 reservoirs where 72% of the annual river runoff can be stored (Dynesius, Nilsson, 1994) and has been regulated for almost a century. The Kalix River, the last major unregulated river in Europe, was used as a reference even if the flux in this river is slightly lower. The sampling methodology was similar in the two studies, thus permitting comparison. The only difference was in the filtered phase sampling, with filter pore sizes of 0.22 μm and 0.45 μm for the Luleå River and the Kalix River, respectively.

Monitoring of effects of river water geochemistry on riparian zone processes has started for both rivers in spring 2010. Sampling sites in the rivers were chosen approximately 100 km upstream of the river mouth (Fig. 1).

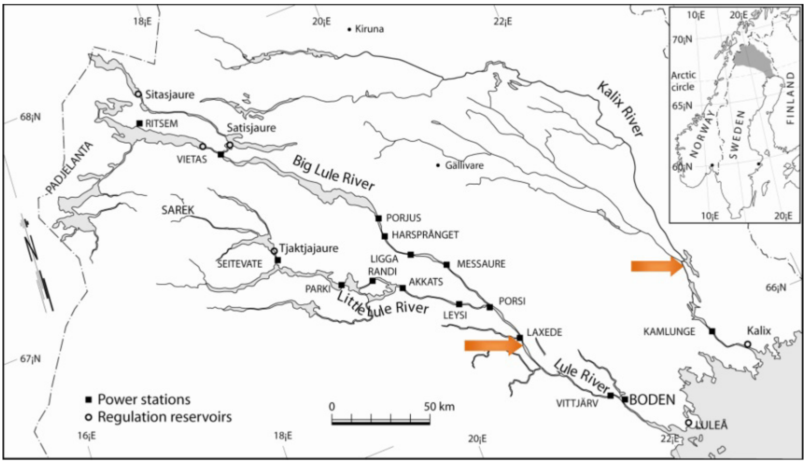

Figure 1. River catchments and location of monitoring stations for previous (Boden and Kamlunge) and present (shown with arrows) studies (modified after Drugge, 2003).

Monitoring at the two sites was made in the river and in two groundwater wells located orthogonal to the rivers, equipped with data loggers recording water levels, temperature, pH, specific conductivity, dissolved oxygen (DO) and oxidation-reduction potential (ORP) (Fig. 2). The well nearby the river is located close to the shore while the other tube is about 20m away. Water quality measurements both in the rivers and in groundwater wells were preformed using the in-situ Hydrolab MS5 Multiprobe. Water samples filtered through 0.45 μm filter were taken weekly or bi-weekly for metal and nutrient analyses. Analyses for Ca, Mg, Na, K and S in the dissolved fraction were determined using inductively coupled plasma atomic emission spectroscopy (ICP-AES), while ICP mass spectrometry (ICP-MS) was used for the other elements. Ion chromatography was utilized to obtain Cl, NO_3, NH_4 and PO_4 anion concentrations. Hydraulic conductivities at the sites will be determined from soil samples.

River groundwater interaction along the reaches in the sampling areas will also be studied using field seepage meters (Rosenberry, 2008).

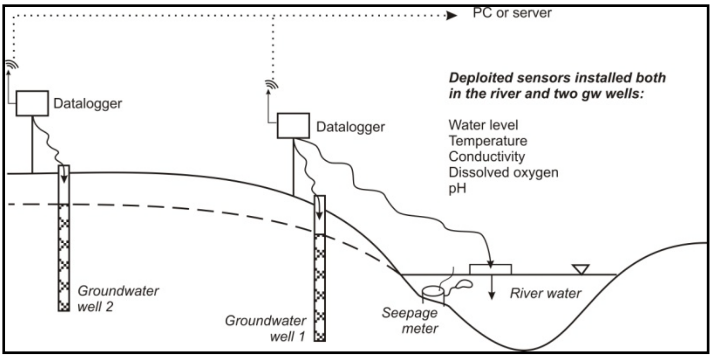

Figure 2. Schematic illustration of groundwater and river water measuring equipment.

RESULTS AND DISCUSSION

The previous study by Drugge (2003) showed, as expected, that water storage in reservoirs influenced the seasonal water discharge (truncated and postponed spring peaks, increased base flow). For the pristine river the highest conductivities were found for the lowest discharges (Fig. 3a) indicating a large content of groundwater in the river water during low flow conditions (base flow) while for the regulated Luleå River it was hard to find any obvious explanation for the conductivity discharge relationship (Fig. 3b). This suggests that the geochemistry of the regulated Luleå River is strongly influenced by the mixing of river water and groundwater in the riparian zone.

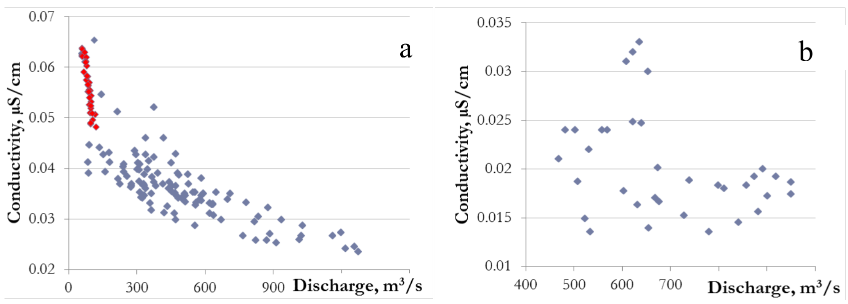

Figure 3. Discharge versus conductivity in the Kalix and Luleå Rivers (Drugge, 2003).

If similar geological and hydrological settings in both rivers can be assumed, the observed reduction in the transport of Ca, Fe, Mn, Na, S, and Si (Fig. 4) can be attributed to sedimentation in the reservoirs, and the smaller variations in element concentrations in the regulated Luleå River, to the reduced seasonal discharge variations in the regulated river (Drugge, 2003).

Judging from the observed differences in river water quality between the regulated and the natural river (Figure 3 and 4) the groundwater quality of the riparian zone in the regulated river has also been affected (Drugge, 2003).

The first results from the 2010 sampling campaign showed increasing specific conductivity with distance from the river for the Kalix River and a slightly reduced riparian zone in comparison with the river water and the reference well 2 (Figure 5).

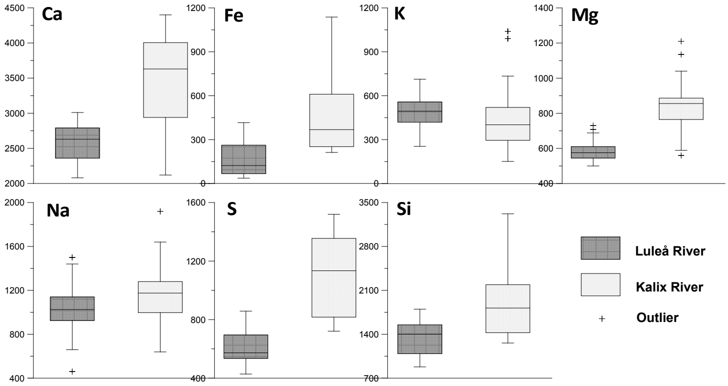

Figure 4. Dissolved element concentrations (μg/l) in river water for Luleå and Kalix Rivers measured in Boden and Kamlunge (modified after Drugge, 2003).

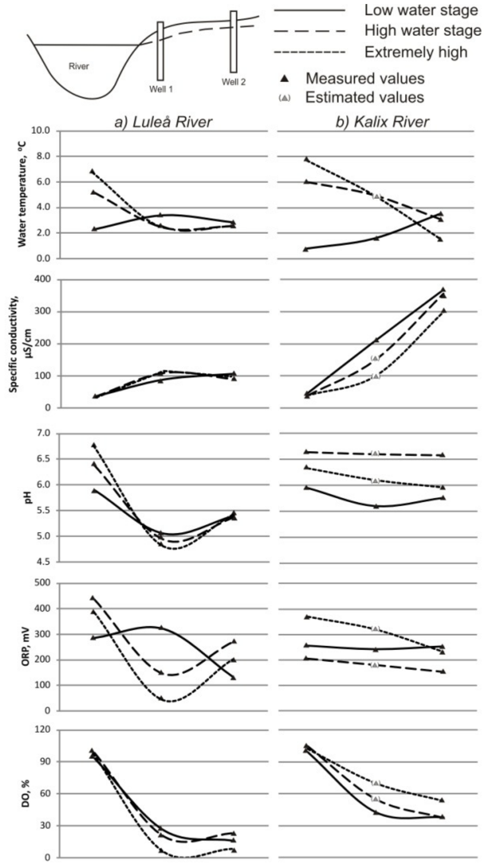

Figure 5. Geochemical profiles (water temperature, specific conductivity, pH, ORP and DO) of the Luleå and Kalix Rivers including their riparian zones, for low, high and very high water stages. Note: For the Kalix River only low water stages were measured in Well 1, so the high and extremely high values in this well were estimated.

This corresponds with the results obtained by Bourg and Bertin (1993). The reduced zone in the Kalix River shows decreased pH values, slightly lower redox potential, as well as dissolved oxygen concentration.

Although the general pattern in the Luleå River was rather similar, some important differences were found. Considerably lower pH (4.8–5.0) and conductivity values were registered in the riparian zone and it showed different pH patterns along the profile as well. In the Luleå River conductivity in Well 2 was three times higher than in the river, while in the Kalix River the groundwater conductivity in Well 2 was 10 times higher. This suggests continuous mixing of the Luleå River water with riparian waters due to river water level fluctuations. In the vicinity of the Kalix River decreased conductivity in both wells during high water stages testifies turning of the reach at spring flood into a loosing one. ORP and temperature patterns in the riparian zone are affected by short term regulation in the Luleå River as well.

The riparian zone plays a key role in river water DOC balance, since it is a major source of DOC in boreal rivers together with water from adjacent mires (Drugge, 2003). In the Kalix River, DOC originates mainly from the riparian zone during winter base flow conditions, and is extensively flushed out during the spring flood. In contrast, the Luleå River doesn't show any pronounced annual variations in DOC concentrations. We assume changes in geochemistry of adjacent areas and alteration of riparian processes under regulated conditions. A new monitoring program in the riparian zone will increase our understanding of these modifications. We expect DOC concentrations to be naturally lowered in the riparian zone due to its bacterial degradation and oxidation by easily available O_2, NO_3 and other electron acceptors.

CONCLUSIONS

Hydropower regulation appears to affect the geochemistry of the riparian environment. A better understanding of processes occurring within the riparian zone will be possible with results from the ongoing sampling campaign and from further research. Major questions to be answered are the geochemical fate of redox elements in riparian zone, their correspondence with fluctuating water stages and major differences with pristine conditions.

ACKNOWLEDGEMENTS

This research is part of the pan-European project GENESIS and the authors of this paper would also like to express their gratitude to The Kempe Foundation, who provided financing for the measuring equipment.

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2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0