XXXVIII IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University of Silesia Press 2010

IAH 2010
Krakow

abstract id: **459**

topic: **2**
Groundwater and dependent ecosystems

2.6
Groundwater in eco-hydrology

title: **Proposed classification scheme for groundwater-dependent ecosystems in mountainous regions**

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keywords: groundwater-dependent ecosystems, mountains, hydroecology, stable isotopes, Switzerland

INTRODUCTION

It is increasingly recognized that groundwater-dependent ecosystems (GDEs) are of special interest from an ecological (high natural value) and socio-economical (many supplies of services and functions) perspective (e.g. Groundwater Directive of the European Parliament, 2000/60/EC). Groundwater connects the biocenosis in the aquifer itself and supplies water, nutrients and energy to surface waters and terrestrial ecosystems (Eamus and Froend, 2006). New strategies for the ecological characterization of groundwater bodies and the protection of its biodiversity are currently developed (Hahn, 2009). In particular, specific ecologic (e.g. endemism) and climatic features of mountainous areas (*e.g.* glaciers, snow) have to be taken into account (Viviroli, Weingartner, 2004; Cantonati et al., 2006). In order to evaluate the ecological role of groundwater resource in alpine areas, we are developing two axes of research:

1) Establishment of a typology for GDEs summarizing the different types of interactions between groundwater and vegetation;
2) Eco-hydro-geological field studies in Switzerland, focusing on the groundwater-plants relationships, with a particular interest on the degree of dependency of different species on the groundwater resource.

GDE'S TYPOLOGY IN MOUNTAINOUS AREAS

The GDEs typology takes into account the spatio-temporal variability of flow (hydroperiod, source and movement, quality of the groundwater) and expressions (in caves, in rivers through hyporheic zones, in marshes, etc…). Additionally, the species and communities that depend on groundwater have to be known.

Some drivers, i.e. the factors which influence nutritive and physical role of groundwater need to be characterized at the appropriate scale: roles of groundwater are dependent on (Figure 1):

- Regional scale characteristics, mainly type of climate,
- Aquifer scale characteristics from geometrical ones (Geographical and geological settings) to hydrological ones,
- Emergence scale characteristics (types and geometry of outlets, microclimate, relationship with surface and meteoric waters, type of biocoenosis and its metabolism and strategies of development).

The groundwater occurrence constrains numerous factors that control existence and biodiversity of GDEs. Several ecological attributes related to hydrogeological system functioning that can be important for GDEs:

- Hydrologic regimes: quantity, timing, location and duration of water delivery,
- Water chemistry: groundwater integrates initial chemical conditions of the recharge water and then the geologic materials composition through which the water circulates. Groundwater can also be punctually or continuously influenced by dissolved species in relation with the land occupation and management,
- Specific temperature conditions: One of the specificity of groundwater is that temperature is maintained stable along the year. Temperature exerts a direct control of all metabolic processes,

- Biocoenosis feedbacks on its biotope, including the hydrogeological processes, such as infiltration, evapotranspiration, and chemical feature of discharging water.

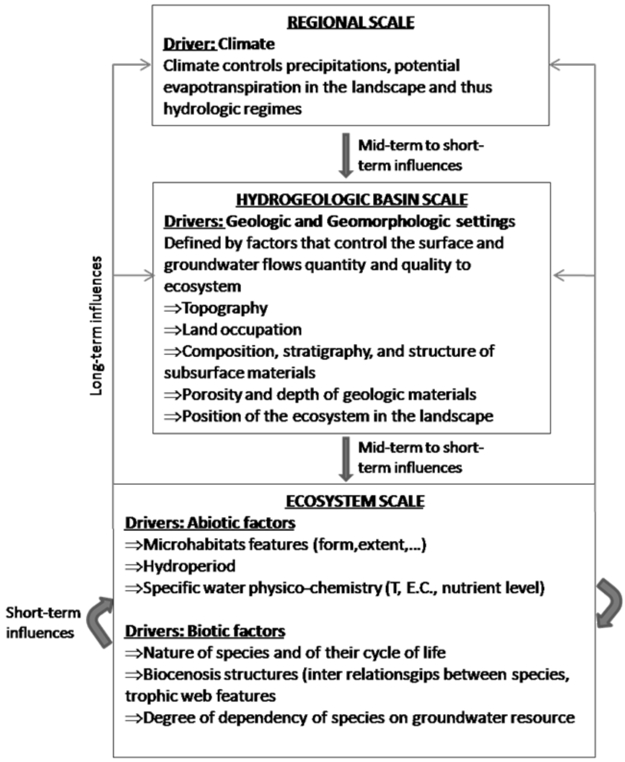

Figure 1. Conceptual scheme of drivers and variability relevant with aquifers functioning and ecological consequences on the GDEs.

By following the water cycle from recharge to surface waters depending on groundwater discharge, the main GDEs identified in mountainous areas are: ecosystems linked with springs, lentic ecosystems (lakes, wetlands), lotic ecosystems (streams fed by springs, rivers) and associated phreatophytic or terrestrial ecosystems (riparian zones, alluvial plains). In order to propose a complete scheme of eco-hydrogeological functioning at the ecosystem scale, a case study site representative of specific conditions in mountainous areas has been selected.

ECO-HYDRO-GEOLOGICAL FIELD STUDY

The second axis of the study consists of an eco-hydrogeological study of the Bois de Finges site (Figure 2) which is a 6 km long alluvial zone in the upper Rhone valley, near Sierre (Wallis, Switzerland). From a hydrological point of view, the Rhone has a glacio-nival regime type in this area. Between low-flow and high flow periods, groundwater levels strongly vary (about 8 m) near the main river-aquifer interaction zone in the most upgradient part of the site. In contrast, the downstream part of Pfyn is characterized by a low groundwater level fluctuation of about 1 or 2 m.

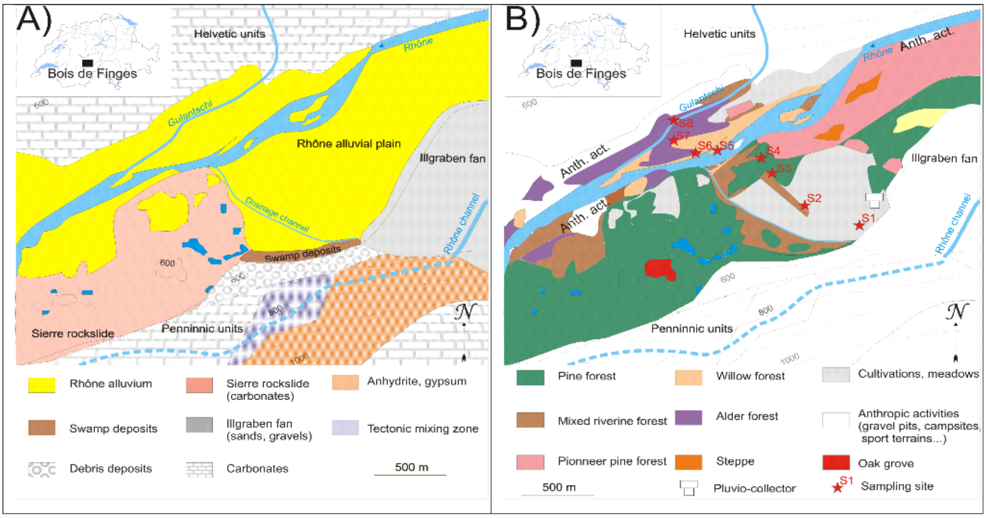

Figure 2. Hydrogeological (A) and ecological (B) settings of the Bois de Finges site. Sampling sites used for this studyare also located on (B).

From an ecological point of view, the riverine fringe at Pfyn presents a broadly recognized natural value but faces many threats due to human activities (derivation channel located upstream, gravel pits). Phytocoenosis vary from dry environments associations (*Pinus sylvestris, Stipa sp.*) upstream to active floodplain associations (*Alnus incana, Salix sp.*) downstream. Between these two end-members, a transition mixed forest occurs. The hydrological continuum described above could, at least partially, explain the ecological continuum between dry ecosystems resulting from the strongly variable water availability and more typical groundwater-dependent ecosystems.

To evaluate the groundwater-phytocoenosis relationships, isotopic characterizations ($\delta^{18}O$, $\delta^{2}H$) of each water compartment (precipitations, groundwater, river, soil, plants) along a transect through the alluvial valley (Figure 2B), coupled with the evaluation of the water balance is planned. This approach makes it possible to characterize pathways of water supplying plants and to assess ecological use of groundwater under diverse hydrological conditions.

Preliminary results shown on Figure 3 indicate a moderate variability of groundwater signatures_(-14.0 ‰ < $\delta^{18}O$ <-12.4 ‰; -108 ‰ <$\delta^{2}H$<-101 ‰) In contrast, soil and plant water signatures vary on both temporal and space scales.

Concerning the atmospheric compartment, rainfall events occurred between 16 and 22 April 2010 (H= 1.5 mm; $\delta^{18}O$=-6.1 ‰; $\delta^{2}H$=- 52 ‰) provided enriched water in the first centimeters of the soils. Mean soil compartment $\delta^{18}O$ signatures (obtained from 10, 30, 50 cm depths signatures weighted by their water volume content) is quite homogenous on the 22 April 2010 for the sampled sites (S2, S4, S6) and $\delta^{18}O$ ranges from -14.2 to -15.4 ‰. One week later (28 April 2010), the $\delta^{18}O$ signatures in the same soils range from -12.2 to -16.7 ‰. Except for one individual ($\delta^{18}O$ = -9.4 on S7), *Salix* (-11.9 ‰ < $\delta^{18}O$ <-14.0 ‰); seems to uptake water mainly from the groundwater source, whereas others (*Alnus, Populus*) show different patterns. Water used by these plants is enriched on 22/04/2010 (-7.9 ‰ < $\delta^{18}O$ <-12.9 ‰), what could be related with the rainfall events during the past week, and less enriched (-11.8 ‰ < δ18O <-13.1 ‰) on 28/04/2010. This would be consistent with the fact that *Alnus* and *Populus* are facultative wetlands plants (Reed, 1988); therefore, a strategy of adaptation as a function of water availability would be possible.

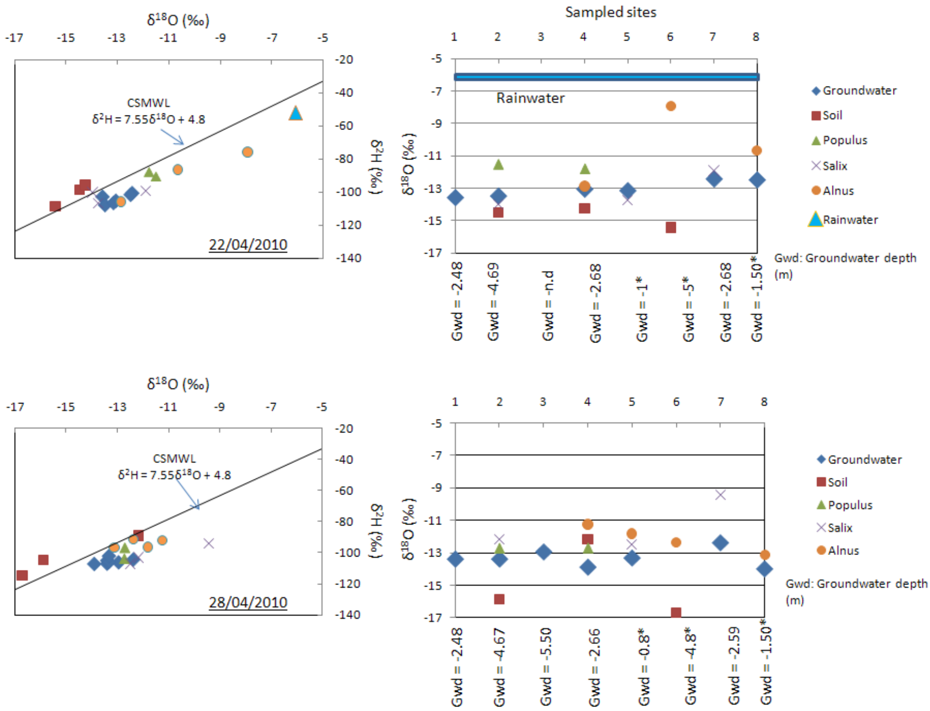

Figure 3. $\delta^{18}O$ and $\delta^{2}H$ signatures of the different compartments of the water cycle at Bois de Finges (22 and 28 /04/2010). CSMWL is Central Switzerland Meteoric Water Line (Kullin, Schmassmann, 1991). Groundwater depth values are the distance between ground and water table. Values with asterisk are estimations.

These first observations must be considered with care: groundwater and soil water values were similar in some place. In this case the interpretation of water uptake by plants is not evident. Furthermore, mixing between 2 different sources of water is possible (e.g. rainwater and deep soil water). In this case, some plant water isotopic signatures need to be evaluated on longer period. Therefore, a number of environmental factors not yet characterized in this study could be necessary to explain the water use patterns for the site. Soil hydrodynamic properties (e.g. water percolation rates) in alluvial settings (Li et al., 2007) need to be taken into account. Moreover, the influence of groundwater depth needs to be investigated. The observed differences between individuals must be clarified in order to understand if individual ecology or adaptations to phytocoenosis structure, e.g. competition in water uses (Snyder and Williams, 2000), could explain the isotopic signatures variability.

CONCLUSION

This work will help to improve the understanding of GDEs functioning in mountainous areas. It will also provide the basis to evaluate how GDEs might be affected by anthropogenic pressures (water abstraction, land use changes) and climate change at the hydrogeologic basin scale. In order to clarify these points at the ecosystem scale, intensive field campaign, analyses of soils structure and monitoring of hydrological variations of the Pfyn alluvial aquifer are currently done.

AKNOWLEDGEMENTS

This study is supported by the GENESIS project (7th Framework Project of the European Union) that aims to understand how changes in land-use and climate affect Groundwater Dependent Ecosystems (GDEs).

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International Association of Hydrogeologists

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