Marie Skłodowska-Curie

Innovative Training Network

“HypoTRAIN”

Hyporheic Zone Processes – A training network for enhancing the understanding of complex physical, chemical and biological process interactions

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Deliverable D4.1

Coupled numerical model for flow, heat and solute transport to identify hyporheic exchange on a small (test-site)-scale

Dissemination Level of Deliverable:

PU	Public	**X**
CO	Confidential, only for the members of the consortium (including the Commission Services)	
Cl	Classified, as referred to in Commission Decision 2001/844/EC	

Contents

Coupled numerical model for flow, heat and solute transport to identify hyporheic exchange on a small (test-site)-scale

1. Aim of the method development/expected results from work package 4 (Integrated Modelling of Hyporheic Processes)

- To develop integrated model concepts for simulating interacting hydrodynamic, chemical and microbiological processes which occur in the temporally and spatially variable pore spaces of the hyporheic zone (HZ).
- To provide an improved understanding of hydrodynamic and biogeochemical processes based on process identification by reactive transport modelling; combination with other ESRs' results allows a hydrodynamic and biogeochemical modelling of the HypoTRAIN field sites.

2. Brief description of what has been done so far:

- Theoretical study of losing and gaining conditions:
  - With the numerical code HYDRUS 2D the effects of surface water levels on hyporheic zone flow was studied;
  - In addition, the role of the unsaturated zone was evaluated (calculating the infiltrating or exfiltrating water volume in dependence of the water level difference.
- Training course (all HypoTRAIN ESRs):
  - Introduction into numerical modelling of saturated/unsaturated flow and transport processes in river bed sediments
  - Training of numerical program HYDRUS 1D and 2D
- Development of a numerical model simulating dynamic gaining and loosing conditions in the HZ
- Joint field experiment in June 2016 (River Erpe), contribution of Mortezza Mojarrad and Anders Wörman (KTH): The use of a natural trace element in combination with temperature measurement for fate and transport modeling of radio nuclide decay chains in groundwater (collaboration with Margaret Shanafield from Flinders University, Adelaide, AUS).

3. Method development (ESRs 5 and 2):

- Step 1:
  - An Advanced Training Course "Modeling of hyporheic processes" was held at KTH in October 2015 (lecturers: A. Wörman, J. Riml, KTH; G. Nützmann, L. Wu, IGB; M. Shanafield, FU). The course aimed at providing the ESRs with knowledge and understanding of the physical and mathematical background of transport of solutes and heat in the hyporheic zone of streams. This included coupling of hydrological transport processes and biogeochemical reactions. The participants particularly developed an understanding of various model approaches to quantify the exchange between the groundwater and surface water. In this context a range of numerical tools as well as exact-solution-methods were introduced.
  - Status:
    - Theoretical part: being finalized

- Practical parts: being finalized

- Step 2:
  - Development of new numerical model based on COMSOL Multiphysics® toolbox. In a first study, the complex interplay among transient driving forces (freshets) and both streambed morphology and groundwater up-welling/down-welling conditions were explored (ESR 6).
  - Status: modeling results showed that HZ emerged, vanished, expanded and contracted during freshet events as a function of freshet duration and symmetry, geomorphology and groundwater up-welling/down-welling conditions. Furthermore, zones of substantially increased residence times or even stagnant water were found to vertically move up and down with the expansions and contractions of the HZ, bearing potential impacts for biogeochemical transformations.
- Step 3:
  - In addition to substantially affecting HZ size, shape and quantity of Hyporheic Exchange Flux (HEF), the investigated transient freshet scenarios proved to cause significant changes in hyporheic residence time distribution (RTD) of relevance for further research into biogeochemical cycling within hyporheic zones and stream-aquifer management at larger scales.
  - Status: open

4. Method development (ESR 6)

Introduction

River hydrology and groundwater flows are of great concern for the safety assessment of geological waste disposals, radon emissions and ecological status of river systems. A river basin is a flow system involving the interaction between surface water and groundwater, which is an interaction processes occurring in the so-called hyporheic zone. This interaction occurs in terrestrial and coastal zones and even in arid and semi-arid areas. The interaction between surface water and groundwater in the hyporheic zone is characterized by stream water that in- and exfiltrate in the permeable sediments surrounding the river corridor. Hence, the presence of the hyporheic zone also affects the flow behavior of deep groundwater that discharge through the zone in a pattern that is partly determined by the local flow behavior. Thus, modeling and understanding of Hyporheic zone processes are the key elements for the whole river management.

Methodology

Choosing a well-monitored catchment which has a good data-base is essential as a basis for the modeling efforts proposed in the project. Krycklan is a well-monitored research catchment in which the data collection for more than 90 years has comprised hydrology, biochemistry, and aquatic ecology (figure 1). The catchment is located in a boreal area of northern Sweden. The head-water stream originates in a mountainous area and discharges into the Baltic Sea near the city of Umea.

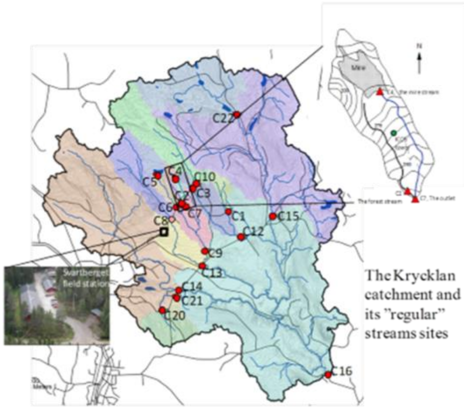

Figure 1: Krycklan catchment area, streams, and infrastructures (Laudon. et al., 2013)

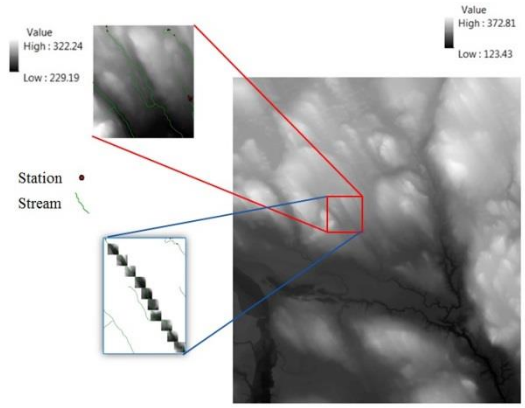

Figure 2: *Krycklan catchment area DEM file, selected region between stations 5 and 6, and 11 small scale regions selected along the stream*

In a first approach one focused on modeling the flow interaction of the large scale groundwater circulation and the hyporheic fluxes with the aims to the effects of the interaction on a) the exchange pattern in the hyporheic zones and b) the discharge patterns in streams for deep groundwater. The two aims are highly related. In other words, we are trying to identify a discharge pattern for hyporheic and large-scale groundwater flows in stream-bottoms (the “Geosphere-Biosphere Interface”, GBI) with respect to their interacting circulation. The general methodology was divided into 3 steps (figure 2): first the whole catchment was modeled in COMSOL Multiphysics simulation software in order to get large-scale groundwater circulation results (figure 3). Then, we focused on a specific part of Krycklan catchment (between stations 5 and 6). The model statement is based on the 3D Laplace equation, which has been applied independently on two ranges of topographical scales to obtain a superimposed solution (figure 4). Steady state simulation has been done based on the simplified assumption of constant boundary conditions of the groundwater surface and otherwise non-flow boundaries. The groundwater surface is assumed to follow the topography, which in general applies to wet climates with shallow soil layers. For small scale, eleven 100 X 100 (m^2) regions were considered along the stream line between the selected stations (figure 5). A Matlab function for numerical spectral analysis of landscape and stream-bed topography (Wörman, 2006) has been used. The main reason for applying a spectral approach is that the topography of stream-beds are difficult to measure in detail and the spectral approach relates known distributions of topography to the small-scale flow pattern. The code uses Fourier series which satisfy Laplace equation based on the discussed assumptions. Finally, the superposition method will be used to include the effects of large and small scale velocity distributions. The pattern for discharge groundwater could be determined by considering the results for 11 small scale regions.

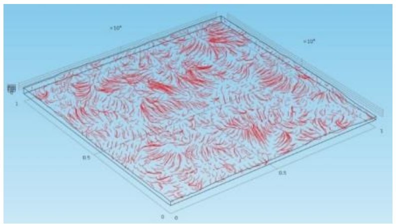

Figure 3: Large scale groundwater circulation result

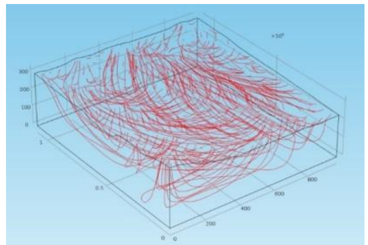

Figure 4: Moderate scale groundwater circulation result

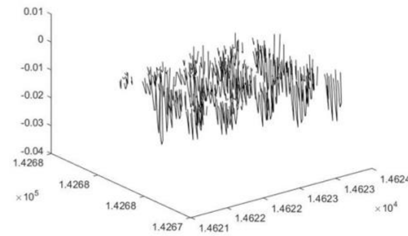

Figure 5: Small scale hyporheic fluxes result

Heidemühle catchment studies

In a second part of the project; as a part of the joint field experiment (JFE) during summer 2016 (6-26 June) temperature measurements and radon concentration sampling in Berlin were used to use a combined approach for detection of down- and up-welling zones in stream-beds. The investigations were part of the JFE and done in collaboration with Margaret Shanafield from Flinders University, Adelaide (Australia). For the experiment, temperature lances were installed in streambed to measure the temperature vertically along the lances in the hyporheic zone. Temperature measurement results would be used in combination with Radon concentration sampling in order to determine large scale up-welling groundwater regions. The experiment was conducted at “Heidemühle”-site, Berlin, 700 m downstream of a wastewater treatment effluent into River Erpe (figure 6). 18 temperature lances were installed in the sediment along the stream in 400 meter scale (figure 7). Finally, the data was analyzed by applying several analytical approaches to calculate the fluxes. ESR 6 is trying to model the river Erpe and couple the modeling results with his experiments results to get the down- and up-welling zones.

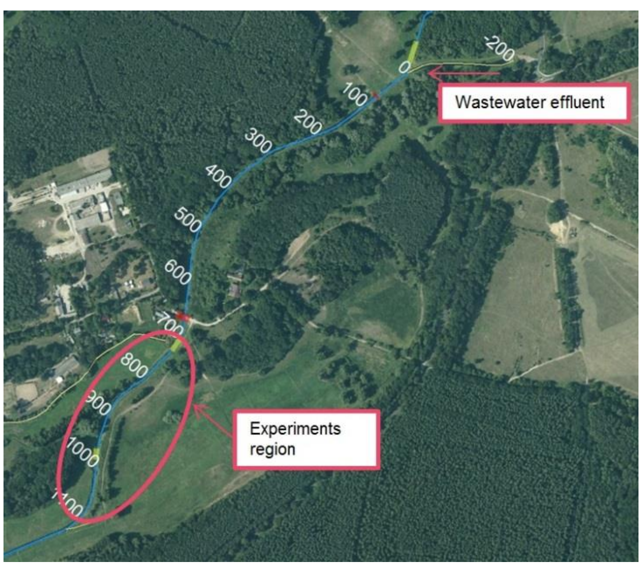

Figure 6: experiment site location

***Figure 7:** Temperature lances location*

Analyzing temperature lance-data resulted in 24 hour-time series of temperature variation along the depth for each location. The high and less temperature variation in deeper depths show that down-welling and upwelling condition dominated, respectively. As an example, in locations where temperature lances IGB-154 and IGB-152 had been installed, up-welling condition dominated (figure 8). In contrast, down-welling condition dominated where temperature lances IGB-147 and IGB 150 had been installed (figure 9).

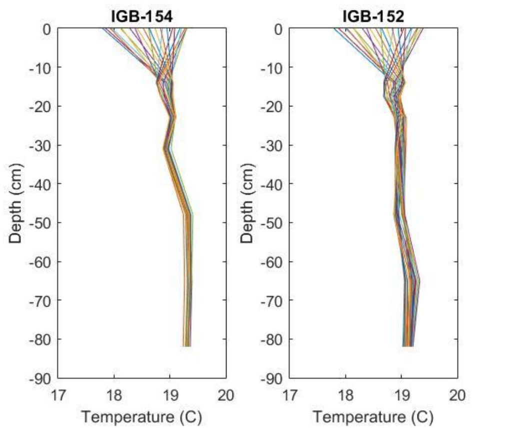

Figure 8: *Hourly temperature variation along depth for up-welling area using mobile long temperature lances*

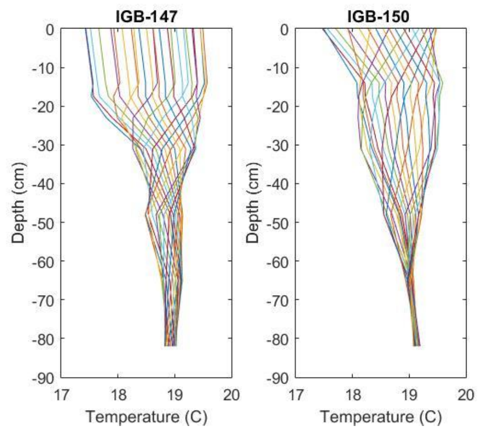

Figure 9: *Hourly temperature variation along depth for down-welling area using mobile long temperature lances*

The VFLUX 2.0 MATLAB code was used to calculate one-dimensional vertical fluxes through saturated porous media under the river bed, based on the heat transport equations. VFLUX uses temperature time series data to calculate flux at specific times and depths (Gordon et al., 2012; Irvine et al., 2015). It calculates the fluxes based on downward amplitude attenuation and phase lag of the surface diurnal temperature signal by 6 analytical solutions for both down-welling and up-welling conditions (figure 10).

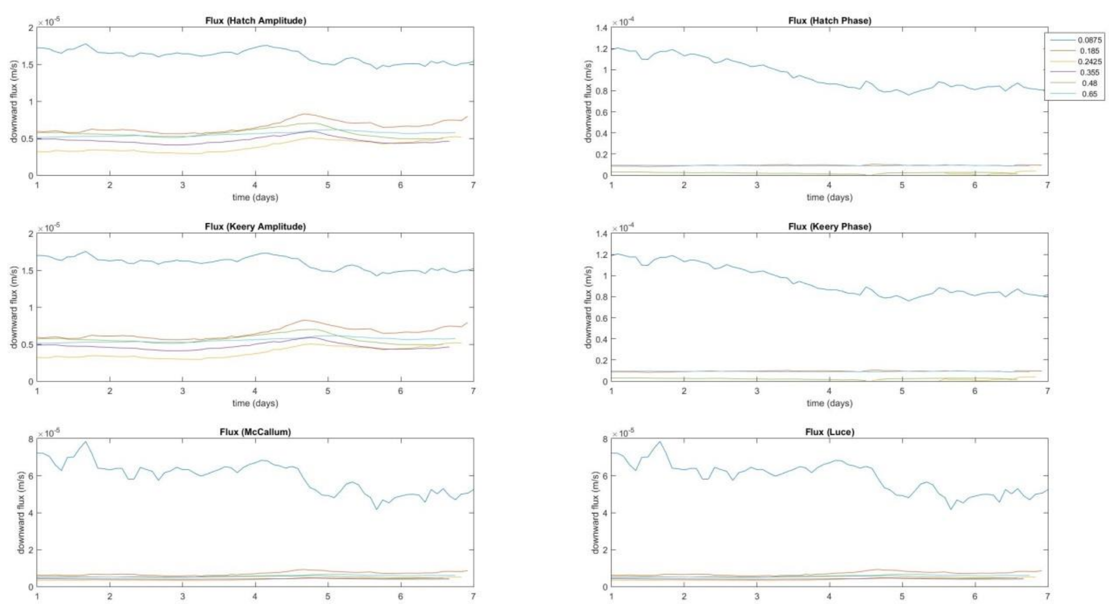

Figure 10: *Calculated fluxes through different depths based on different analytical approach using amplitude attenuation and phase lag*

Based on the preliminary temperature measurement results, more temperature measurements were done at locations where seemed to be dominated by up-welling conditions. Since He wants to do his modeling approach in 3D, the temperature lances were installed on 14 locations in 4 lines to get transects fluxes (figure 11). Temperature variations along the depth for two temperature probes are shown in figure 12.

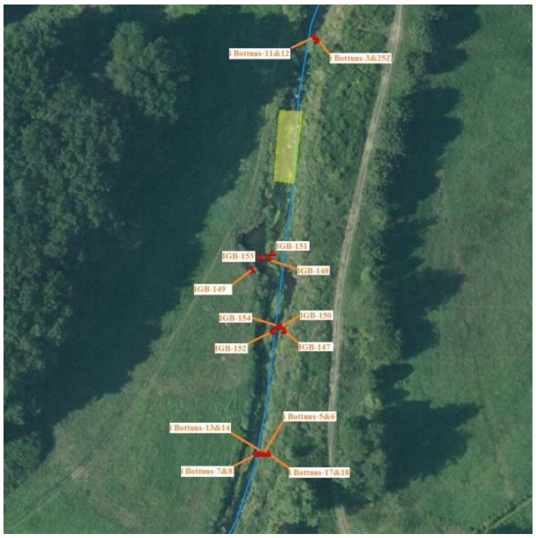

Figure 11: *Temperature lances location for the second experiment*

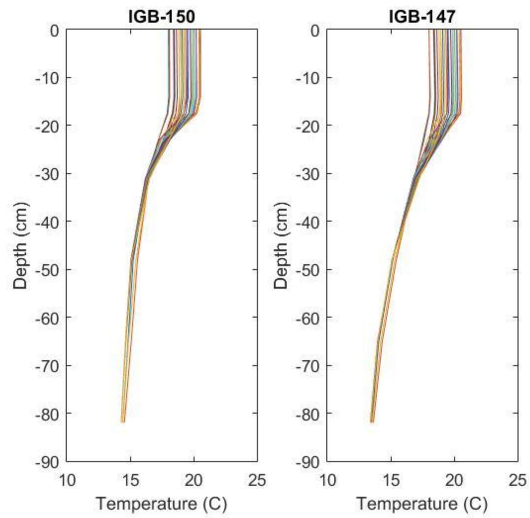

Figure 12: *Hourly temperature variation along depth using mobile long temperature lances*

For the last experiment, radon measurements by RAD7 device for stream water were done (figure 13). Radon (^{222}Rn) is a noble gas with the half-life of 3.82 days. Decay of radium (^{226}Ra) (as an element in uranium (^{238}U) series chain) generates Radon (figure 14).

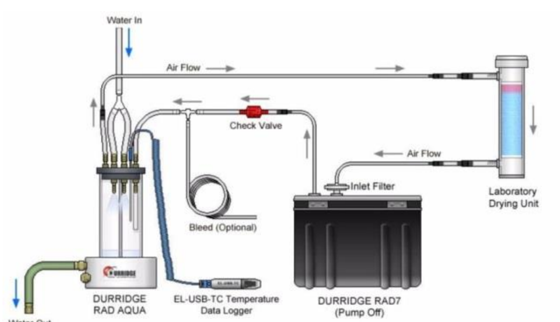

Figure 13: *RAD7 device*

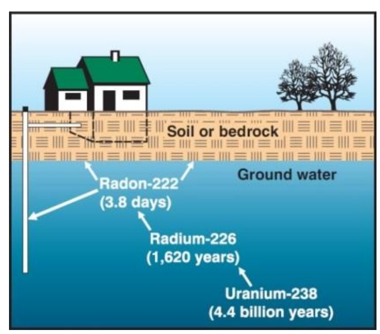

Figure 14: *Uranium decay chain (Clark and Briar, 1993)*

As a general idea, if the radon concentration significantly changes along the stream, it can be concluded that there is a hot spot for deep groundwater discharge on that location. Radon concentrations in the water were measured along the river at 17 locations (figure 15). Stations “J” and “K” have higher concentrations compared to the other sites indicating the presence of a hot spot of deep groundwater discharge in that area.

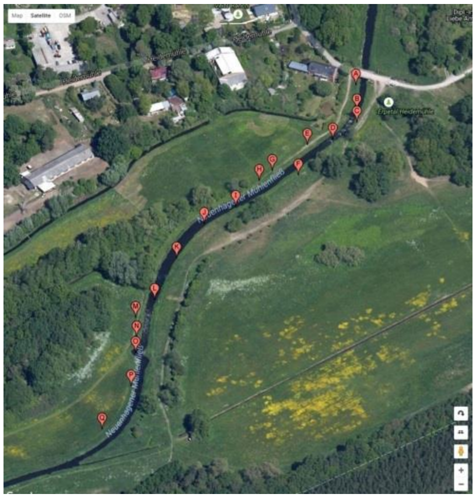

Figure 15: *Radon concentration measurement stations (http://www.geoplaner.com/)*

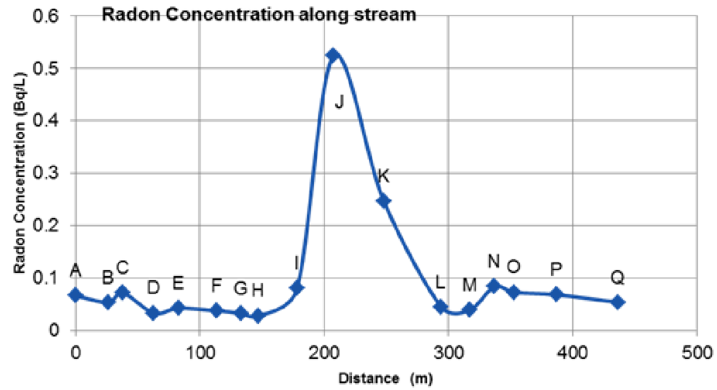

Figure 16: *Radon concentration for different locations*

Moreover, the radon concentrations for each station measured during the time are shown in figures 17 and 18.)

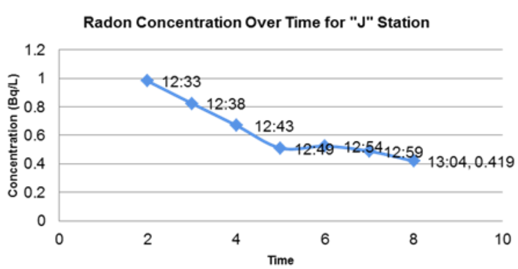

Figure 17: *Radon concentration for location "J" over the time*

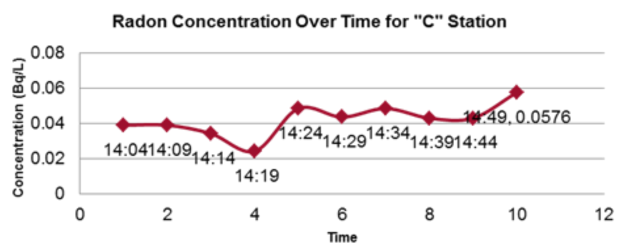

Figure 18: *Radon concentration for location "C" over the time*