Flow and heat transport modelling in the hyporheic zone based on high resolution temperature and geophysics datasets

Jaime Gaona[1,2,3] (gaona@igb-berlin.de), Alberto Bellin[3], Liwen Wu[1,4], Jörg Lewandowski[1,4]

[1]Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Germany [2] Free University, Berlin, Germany

[3] University of Trento, Italy [4] Humboldt University, Berlin, Germany

Freie Universität Berlin · University of Trento - Italy · IGB Leibniz-Institute of Freshwater Ecology and Inland Fisheries · SMART Science for MAnagement of Rivers and their Tidal systems · Erasmus Mundus Joint Doctorate Programme · European Commission ERASMUS MUNDUS

Introduction

The study of hyporheic processes using point measurements can overlook the important spatial variability of hyporheic exchanges. Quantifying the spatial patterns of flow within the hyporheic zone remains particularly challenging. Modelling can help to evaluate the spatial distribution of exchanges. An integration of distributed and point data is required to achieve the multi-scale approach of modelling. We aim:

(1) To evaluate the usefulness of high resolution distributed data to improve the accuracy of hyporheic models to reproduce the spatial variability of exchanges.

(2) To model flow and heat transport to upscale point estimates of hyporheic flow.

Modelling process

1. **Flow Transport models definition:** (FREEWAT$_1$ (Open source MODFLOW$_2$ GUI) with FloPy$_3$)
2. 2a. **Multi-layered hyporheic model (steady state)** (12 layers in the first meter depth, K$_s$ from sediment cores) | 2b. **Distributed model (steady state)** (K$_s$ 3D fields from EC- K$_s$ petrophysical relation)
3. **Vertical hydraulic gradients (VHG) from multi-level piezometers as observations data**
4. **Flow calibration** (FREEWAT$_1$ with UCODE$_2$) with multipiezometers' VHG as HOB data
5. **Validation:** evaluation of heads and vertical flow estimates with data of other time periods (No / Yes)
6. **Heat transport model definition** (FREEWAT$_1$ with MT3DS$_4$ through FloPy$_3$))
7. 7a. **Multi-layered hyporheic model (steady state)** (Same conceptual model as in flow model 2a.) | 7b. **Distributed model (steady state)** (same conceptual model as in flow model 2b.)
8. **Distributed temperature maps from FO-DTS and temperature profiles as observations**
9. **Heat transport calibration** (PEST$_5$) …pending
10. **Validation:** (same as flow transport) …pending (No / Yes)

Study site & field data

Study site at River Schlaube:

90 km E of Berlin, Germany (Fig. 1). Small stream with constant flow due to intense GW discharge and natural regulation by upstream located lakes. The funnel-type valley is excavated in permeable sediments. The heterogeneity of thermal and hydraulic properties allows studying drivers and controls in a 45 m long study section.

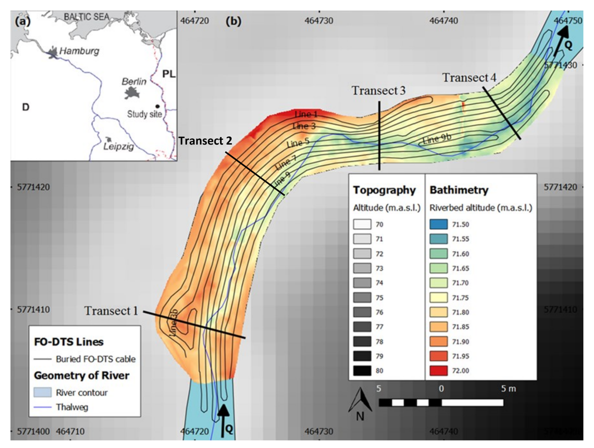


Fig. 1 : (a) Study site location in Germany. **(b)** Topography and bathymetry of the study site identifying transects and the FO-DTS layout.

Point data

- Sediment properties from the SWI and cores.
- Vertical hydraulic gradients (VHG) with multi-piezometers in 8 depths.
- Temperature profiles series at same depths.

Distributed data

FO-DTS

Based on the temperature-dependent back-scattering of a laser pulse in a fiber optic cable.

- Measures temperatures at the sediment-water interface (SWI) at mutiple scales.
- Allows analysis of temperature anomalies for the identification of GW discharge (Fig.2)
- Enables temporal analysis of temperature anomalies at the SWI to recognize interflow discharge / local downwelling.

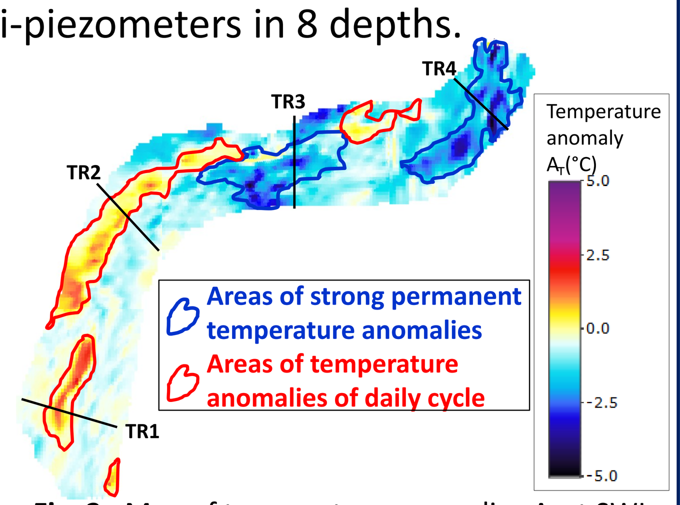


Fig. 2 : Map of temperature anomalies A_f at SWI. Cold contours identify areas of GW discharge

Electromagnetic induction (EMI)

EMI enables a non-invasive exploration of the sediment texture based on the different response of sediment to the primary and secondary magnetic fields (Fig. 3).

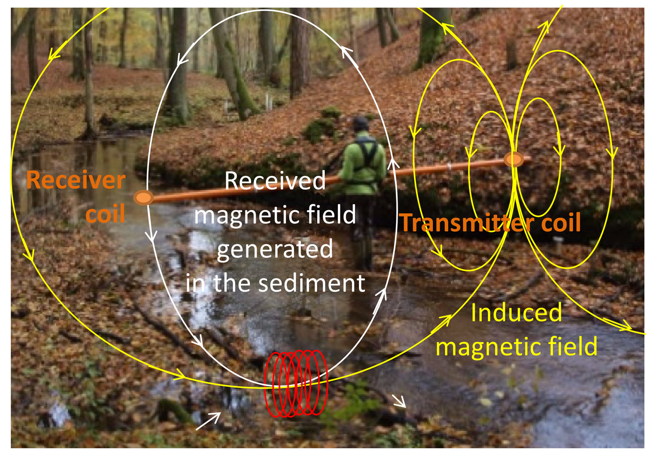
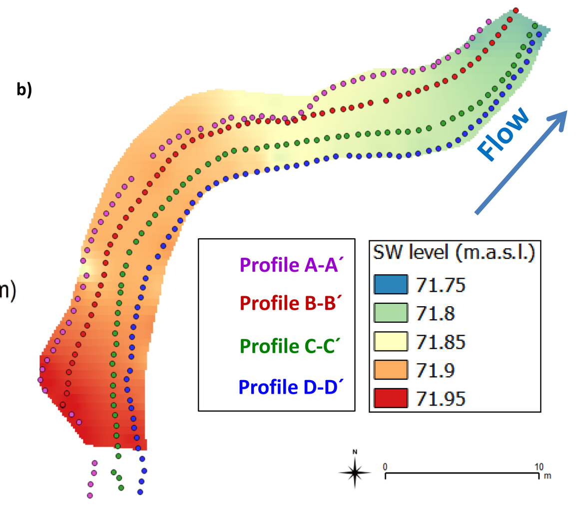


Fig. 3: EMI survey with the induced magnetic field

Electrical conductivity (EC) fields depending on sediment texture (checked no influential pore water EC variability) can give preliminary estimations of hydraulic conductivity (K$_s$) fields.



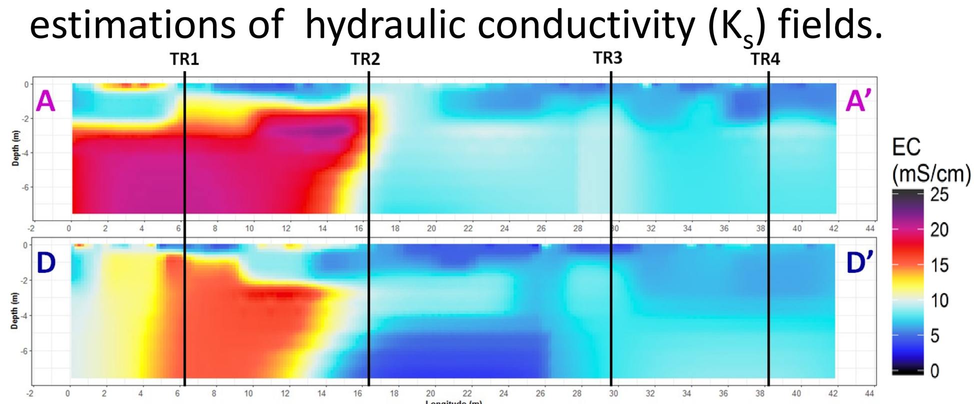
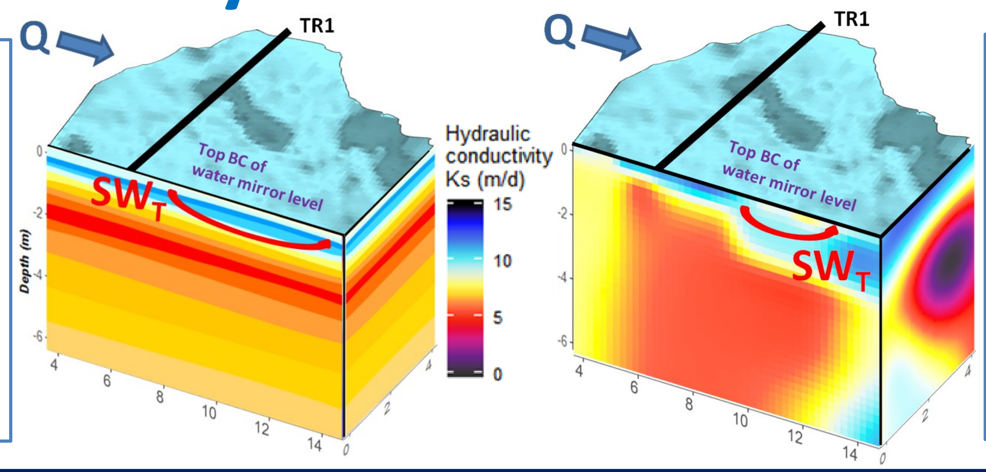


Fig. 4 : (a) Profiles of EMI EC data downstream the study site. **(b)** Profiles location over the site's bathymetry map. The EC values from EMI display the meter scale variability, but not the small scale heterogeneities of the subsurface.

Conceptual layered vs. distributed models

Multi-layer model

Cells 0.2 x 0.2 m
Layer no. 1,
Layers no. 2 to 12 (Thickness according depth of sediment cores of similar properties: K$_s$)
Layers no. 13 to 20 1m thick in z=-1.5-8.5m

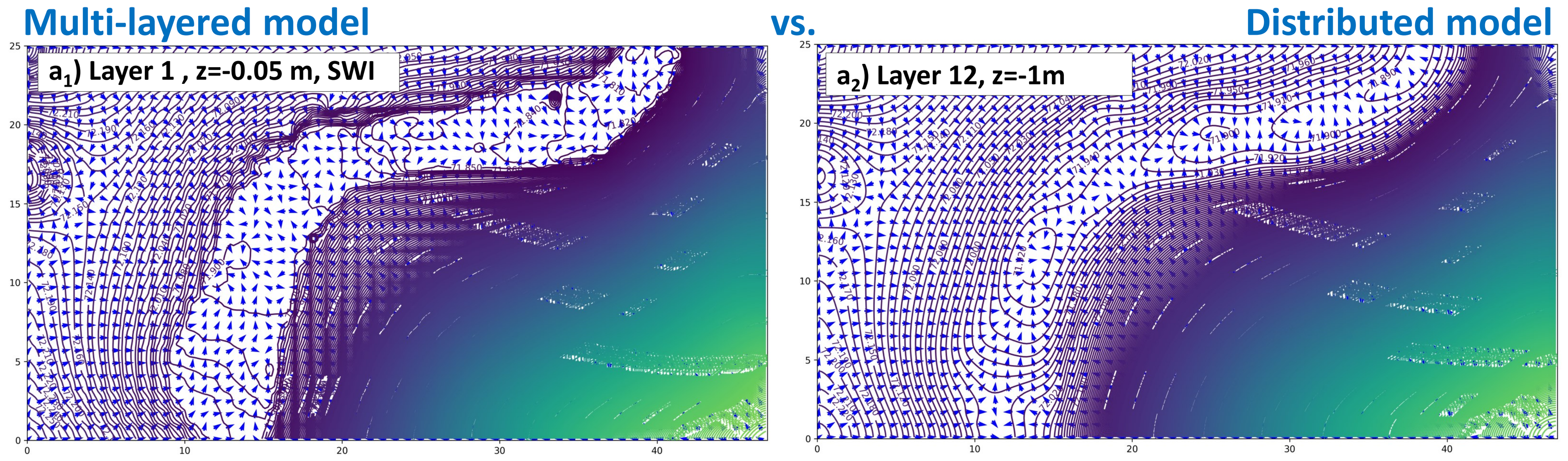


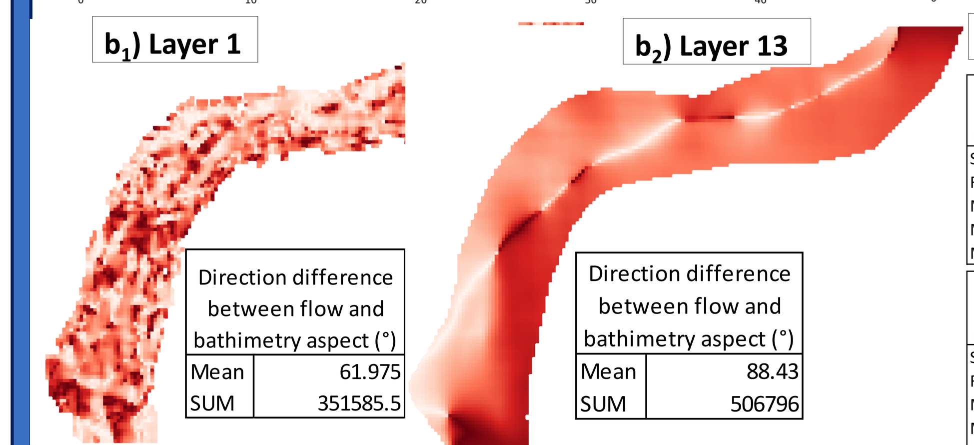
Distributed model

Same cell size 0.2 x 0.2 m
Layers no. 1 to 20 (Same thickness of layers of layered model to be able to compare models, with distributed values of the EC- K$_s$ (R^2=0.4) EMI petro-physical relation.
Same top water mirror BC

Results: Flow transport

Multi-layered model vs. Distributed model





c) Calibration and validation statistics of both models

DISTRIBUTED MODEL UCODE calibration residuals of the 99 observed heads (m) 2017/07/01		DISTRIBUTED MODEL Residuals of observed heads (m) at the validation date 2017/01/18		DISTRIBUTED MODEL Residuals of observed heads (m) at the validation date 2017/03/02	
SD	0.022	SD	0.041	SD	0.036
RMS	0.006	RMS	0.006	RMS	0.001
Mean	0.006	Mean	-0.006	Mean	-0.002
Max	0.072	Max	0.084	Max	0.085
Min	-0.057	Min	-0.131	Min	-0.131

MULTI-LAYERED MODEL UCODE calibration residuals of the 99 observed heads (m) 2017/07/01		MULTI-LAYERED MODEL Residuals of observed heads (m) at the validation date 2017/01/18		MULTI-LAYERED MODEL Residuals of observed heads (m) at the validation date 2017/03/02	
SD	0.031	SD	0.046	SD	0.044
RMS	0.007	RMS	0.009	RMS	0.006
Mean	0.007	Mean	-0.009	Mean	-0.006
Max	0.079	Max	0.090	Max	0.090
Min	-0.111	Min	-0.130	Min	-0.159

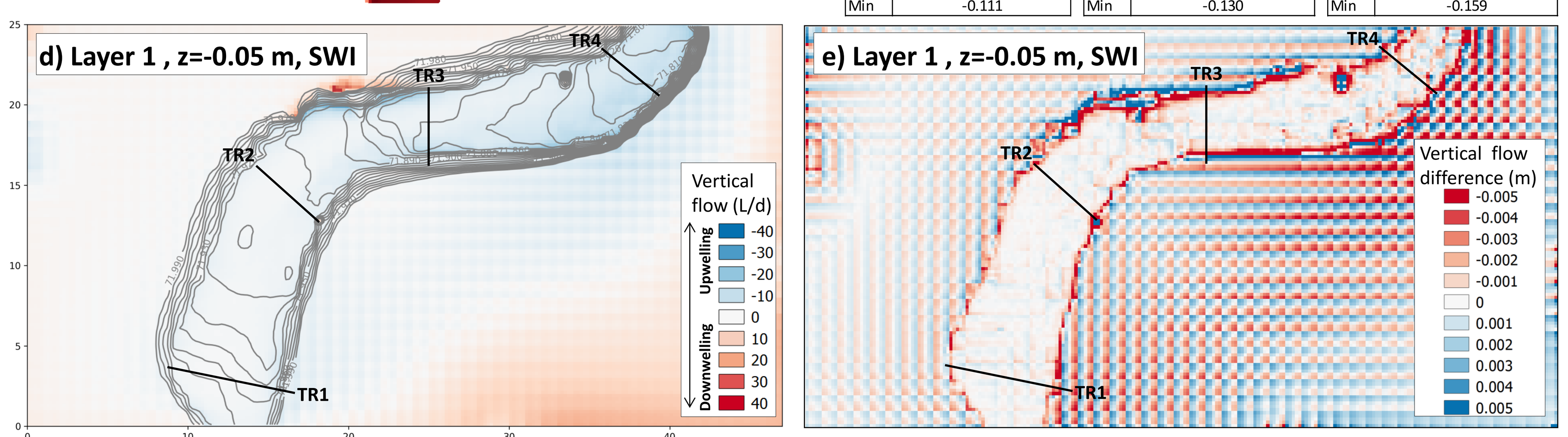
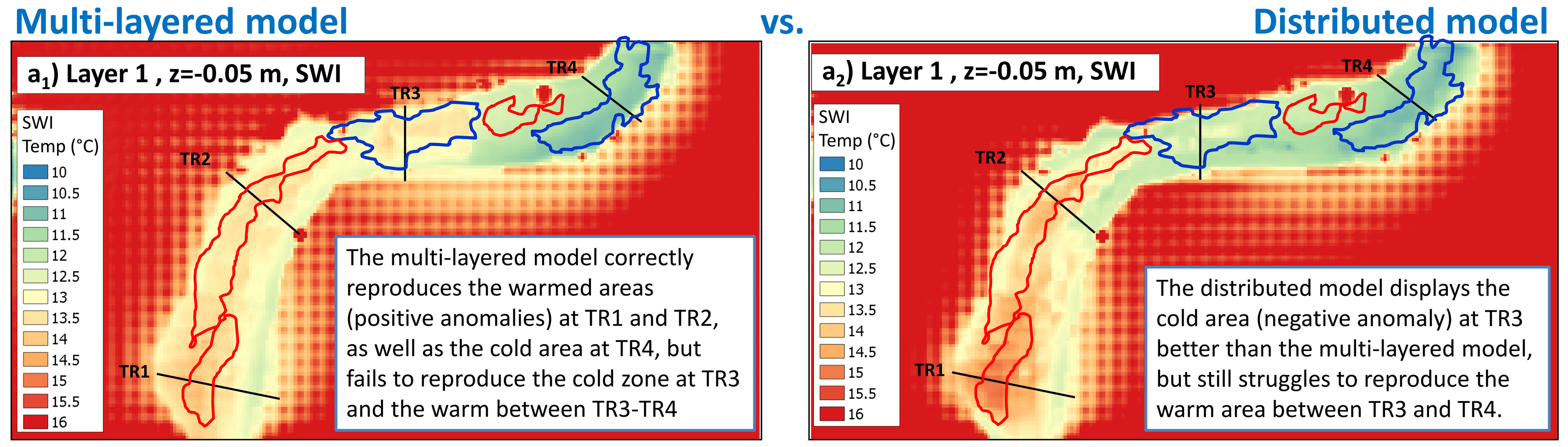
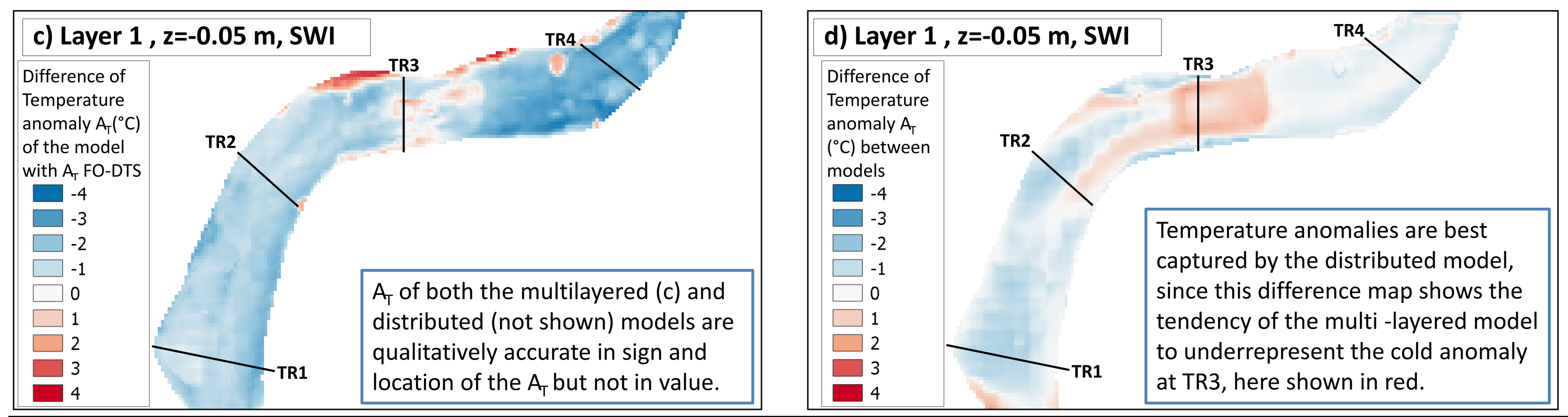


Fig. 5: (a$_1$) Potentiometric surface & flow direction of the multilayered model at Layer L1 (z=-0.05m) and **(a$_1$)** at L12 (z=-1m) of the distributed model. Due to the influence of bedforms, the flow direction variability observed in L1 decreases with depth **(a$_1$ vs. a$_2$)**. **(b)** Correlation map between the face direction of the bathymetric surface and flow direction of the distributed model (Layer L1). **(c)** Calibration and validation statistics of the observed head values at multiple depths (8 depths) of the multi-piezometers located in transects TR1 to TR4 (99 point head observations) at the calibration date of July 2 of 2017, with January 18 and March 2 of 2017 as validation dates. **(d)** Vertical flow of the multilayered model, indicating areas of upwelling prevailing in transects TR3 and TR4, as observed with DTS. **(e)** Difference on the flows of the multilayered and distributed models at Layer L1. The multilayered model tends to underestimate upwelling, a difference that increases with depth.

Preliminary (uncalibrated) results Heat transport

Multi-layered model vs. Distributed model





Pending steps: (1) calibrating heat model dispersion and diffusion based on the point values of thermal properties obtained from sediment cores at multiple depths (2) calibrating and validating Ks against the temperature profiles and FO-DTS distributed observations.

Fig. 6: (a$_1$-a$_2$) Temperature maps at the SWI from uncalibrated multi-layered and distributed models. The anomaly areas identified in Fig. 2 from FO-DTS are displayed overlaying for comparison, also in **Fig. 6(c)** of difference in temperature anomaly A_f of the multi-layered model with the observations derived from FO-DTS. **(d)** Difference in estimates of A_f between the multi-layered and distributed models.

Conclusions

Flow and heat transport modelling is a powerful tool to reproduce the complex hyporheic processes

- Modelling can be used to assess the depth of hyporheic exchange and to estimate head, flows and temperature spatial distributions at areas without observation of these indicators of exchange.

Integrating point and distributed data improves the accuracy of flow and heat transport models

- Distributed definition of the subsurface hydraulic conductivity with EMI geophysics improves the accuracy of flow and heat modelling compared to layered models based on sediment cores.

References

Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Starn, J. J., & Fienen, M. N. (2016). Scripting MODFLOW Model Development Using Python and FloPy. *Groundwater*.
Brookfield, A. E., Sudicky, E. A., Park, Y. J., & Conant Jr, B. (2009). Thermal transport modelling in a fully integrated surface/subsurface framework. *Hydrological Processes*, *23*(15).
Shanafield, M., McCallum, J.L., Cook, P.G., & Noorduijn, S. (2016). Variations on thermal transport modelling of subsurface temperatures using high resolution data. Advances in Water Resources 89, 1-9.
Brosten, T. R., Day-Lewis, F. D., Schultz, G. M., Curtis, G. P., & Lane Jr, J. W. (2011). Inversion of multi-frequency electromagnetic induction data for 3D characterization of hydraulic conductivity. *Journal of Applied Geophysics, 73(4), 323-335.*
Harbaugh, A.W., Langevin, C.D., Hughes, J.D., Niswonger, R.N., and Konikow, L. F., 2017, MODFLOW-2005 version 1.12.00, the U.S. Geological Survey modular groundwater model: U.S. Geological Survey Software Release, 03 February 2017.
McLachlan, P.J. , Chambers , J.E. , Uhlemann, S.S. & Binley, A. (2017). Geophysical characterisation of the groundwater-surface water interface. *Advances in Water Resources*, 109.
Rossetto, R., De Filippis, G., Borsi, I., Foglia, L., Cannata, M., Criollo, R., & Vázquez-Suñé, E. (2018). Integrating free and open source tools and distributed modelling codes in GIS environment for data-based groundwater management. *Environmental Modelling & Software, 107:210-230.*
Wondzell, S. M., LaNier, J., & Haggerty, R. (2009). Evaluation of alternative groundwater flow models for simulating hyporheic exchange in a small mountain stream. Journal of Hydrology, 364(1-2), 142-151.
Zheng, C., & Wang, P. P. (1999). MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide. Alabama Univ University.

Acknowledgments and contact

This research is funded by the SMART Joint Doctoral Programme (Science for MAnagement of Rivers and their Tidal systems), an Erasmus Mundus Programme of the European Union. We thank Christine Sturm, Anne Mehrtens, Wiebke Seher, Jason Galloway, Karin Meinikmann for their help with fieldwork , Amaia Marruedo and Silvia Folegot for their FO-DTS training, as well as the Nature Park Schlaubetal for allowing access to the River Schlaube.