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ScienceDirect

Energy Procedia 76 (2015) 371 – 380

Energy Procedia

European Geosciences Union General Assembly 2015, EGU

Division Energy, Resources & Environment, ERE

Numerical evaluation and optimization of depth-oriented temperature measurement for the investigation of thermal influences on groundwater resources

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Abstract

High-resolution depth-oriented temperature measurements have been introduced to investigate a groundwater body in the urban area of Basel. In total, four devices were installed with up to 16 sensors - located in both the saturated and unsaturated zone. Measurements were performed over a period of 4 years and provide sufficient data to set up and calibrate high-resolution numerical local heat-transport models. Calibration was performed for the saturated and unsaturated zone, respectively.
Model results show that although depth-oriented measurements provide valuable insights into local thermal processes, the identification of governing and impacting factors strongly depends on appropriate positioning of the measurement device.

Peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: groundwater temperatures; urban aquifers; heat-transport modeling; depth-oriented temperatur measurements

1. Introduction

Several anthropogenic impacts such as urbanization, geothermal energy use and climate change can alter thermal

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Peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2015.07.844

regimes in the subsurface, especially in shallow groundwater systems which have been increasingly used for geothermal energy production. Increased public interest and the contribution of geothermal energy to regenerative energies are discussed in detail in the following papers, please refer to e.g. [1-4].

Groundwater protection issues related to increased temperatures and the prevention of any usage conflicts mean that carrying out a robust assessment of the various natural and anthropogenic thermal impacts on groundwater is necessary (Fig. 1). Any such assessment should ideally be based on a comparable, precise spatiotemporal acquisition of groundwater temperatures. This is essential for reliable prediction and evaluation of heat-transport processes in the subsurface.

Groundwater temperature can be easily measured and used to evaluate groundwater flow due to its tracer-like behavior [5]. However, heat-transport is also influenced by heat storage processes, which provide different conditions from an “ideal” tracer. Therefore, it is crucial that temperature measurements correctly reproduce the temperature of surrounding soils and groundwater. This can only be achieved by installing measurement devices directly in the aquifer body or by restricting the vertical flow within groundwater observation wells [6]. Commonly, such measurements are often only taken a few times per year alongside groundwater level measurements. For example, in large German cities, comprehensive temperature monitoring is the exception rather than the rule [7]. Often, appropriate monitoring strategies are only considered when significant impacts on native groundwater temperatures have already developed or occurred. However, site-specific adaptive management strategies based on appropriate groundwater temperature measurements can help to mitigate negative effects that may occur in anthropogenically influenced groundwater bodies [8, 9].

Finally, evaluating the effect of geothermal systems and urbanization on subsurface environments requires appropriate monitoring and modeling tools (e.g. [10]). As stated in [9], simple and reliable temperature measurement devices are available recently and can be used together with analytical modeling approaches (e.g. [11]) and 3D numerical heat-transport models [9, 12] to facilitate heat-transport investigation at different scales and also with complex settings in the urban subsurface. However, in order to identify and quantify the previously mentioned thermal impacts and boundary conditions on groundwater resources, these monitoring and modeling tools have to be further developed and potentially combined where possible. Concerning the complex interactions that commonly occur in urban groundwater bodies, more frequently, regional heat-transport models will be required for adequate thermal management of such aquifers.

The setup and monitoring results from state-of-the-art groundwater temperature measurement devices are taken to investigate to what extent depth-oriented temperature measurements are capable to determine selected thermal impacts. Additionally, based on 4 years of temperature measurements, local process models were set up and calibrated. The results illustrate the suitability of the approach used here to gain further understanding of local heat-transport processes and to provide insights which are critically required to be able to adequately implement regional models. In this context, several impacts affecting temporal behavior and extent of temperature changes are examined, with focus on river-groundwater interaction, the effect of heated buildings reaching into the saturated and unsaturated zones of the aquifer, and direct thermal use by an open-loop system.

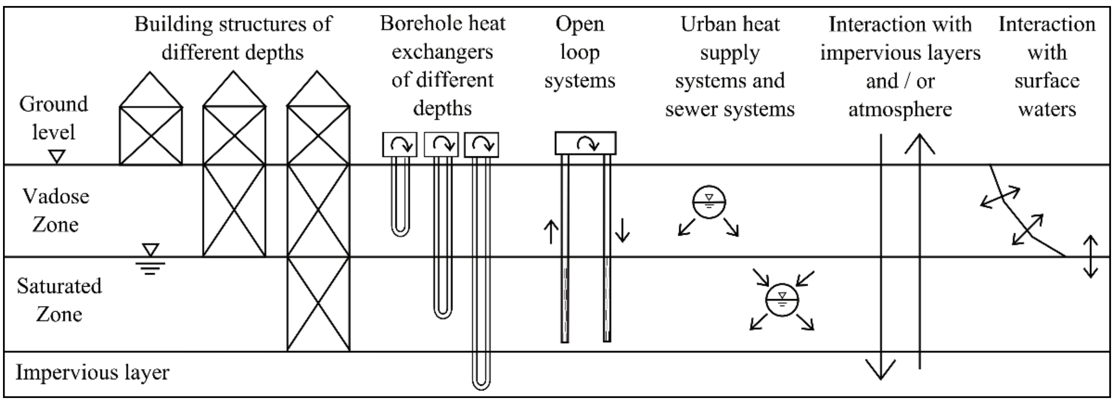

Figure 1: Natural and anthropogenic impacts on urban subsurface resources and thermal groundwater flow regimes.

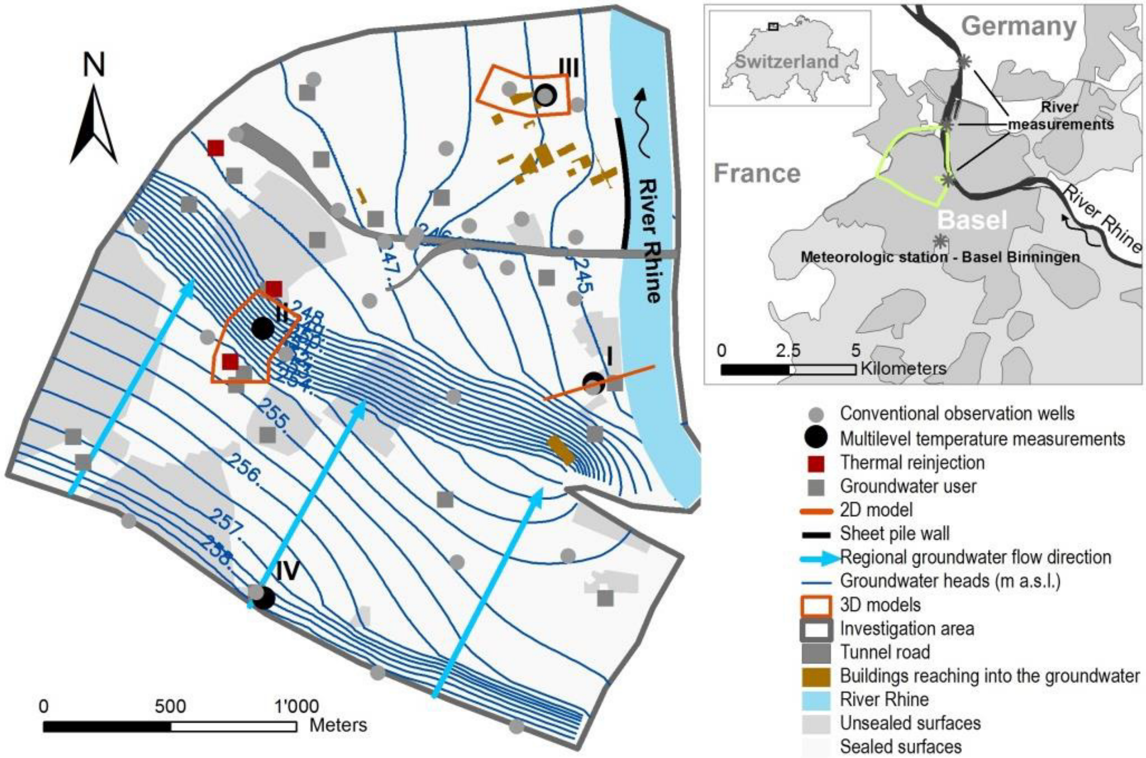

Figure 2: Upper right: Location of the study area in Switzerland and in the agglomeration of Basel. Left: Study area with the locations of groundwater use, as well as conventional observation wells and multilevel temperature measurements I-IV. Also shown is the regional groundwater flow regime with the main flow directions, as well as the selected locations for the setup of 2D and 3D heat-transport models. Note the steep hydraulic gradient in the center of the modeling domain resulting from the progression of the bedrock and the backwater effects along the tunnel road and sheet pile wall (after [9]).

2. Settings

The settings are described in [8] and [9] and can be summarized as follows: Basel City (47°33'N, 7°35'E, approx. 174.000 inhabitants) represents a typical European densely populated region located in a river valley where the aquifer mainly consists of unconsolidated alluvial sediments. Often those aquifers are intensely used for drinking and process water supply and, as they act as a relatively stable geothermal source or sink, can be particularly applied for the geothermal groundwater use.

The shallow unconfined aquifer in the Basel area is comprised of late Pleistocene gravels which are deposited by the river Rhine to thicknesses between 15 and 32 m. The depth to groundwater table ranges from 6 to 30 m with a mean of 19 m. The thickness of the saturated portion extents from 0 (in areas of outcropping bedrock) to 14 m. The aquifer is underlain by an impervious layer consisting of mud to clay-rich sediments (Oligocene). The main direction of the regional groundwater flow in the investigation area is from South to North and from West to East with flow velocities ranging from 0.5 up to 5 m/d (Fig. 2).

The land surface of the investigated area is characterized as follows: 38% sealed, 23% building structures, 6% water and 33% open space (e.g. green area). The southeast and northern parts of the area are densely urbanized.

The temperature of the river Rhine is measured at two locations within the study site (Fig. 2) by either the Federal Office for the Environment, Switzerland (FOEN) or the Agency for Environment and Energy of the city of Basel (AUE BS). Soil temperature data at 5 cm and 20 cm depths are measured at the Basel-Binningen meteorological station (Fig. 1, 47°33'N, 7°34'E, MeteoSwiss 1940).

3. Methods

3.1. Monitoring setup

The setup of four multi-level observation wells (Fig. 2) is described in detail in [8] and [9] as follows: These multi-level observations measure temperatures continuously in time within the saturated and unsaturated zone at discrete points along a vertical line with intervals of 0.5 to 1 m. Thermistor thermometers (PT 100, Ott Logosens data logger) were installed, which have an accuracy of ±0.1 K and a resolution of 0.01 K. Calibration (compensation of offset) was done in a thermally isolated room including four reference measurements. Currently, data is available starting from 2010. As the measurement intervals were separated from each other by using a mixture of Bentonite-Opalite-cement, thermal free convection is not expected here [9]. The multilevel observation wells were installed to investigate distinct thermal processes, such as: [I] river-groundwater interaction affecting the thermal groundwater regime; [II] down-gradient influence of thermal groundwater use; and [III] down-gradient thermal effects of building structures reaching into the groundwater, also considering seasonal heating [9]. Additionally, a fourth [IV] multi-level temperature monitoring well exists which characterizes the diffuse thermal influence of the densely urbanized area in the Southern region of Basel (not discussed in this paper).

3.2. Model setup

High-resolution local 2D and 3D heat-transport models (Fig. 3) were set up using FEFLOW© [13] to study selected thermal impacts on a groundwater body in the urban area of Basel and to investigate the capability of depth-oriented temperature measurements in detecting and determining selected thermal impacts. The software is applicable to model flow and heat-transport processes in fully and partially saturated porous media.

At the location of the multi-level observation well [I], the focus is placed on the investigation of river-groundwater interaction; therefore, a 2D vertical model was set-up. The flow conditions between the aquifer and the river Rhine are predominantly effluent, inverting only during flood events.

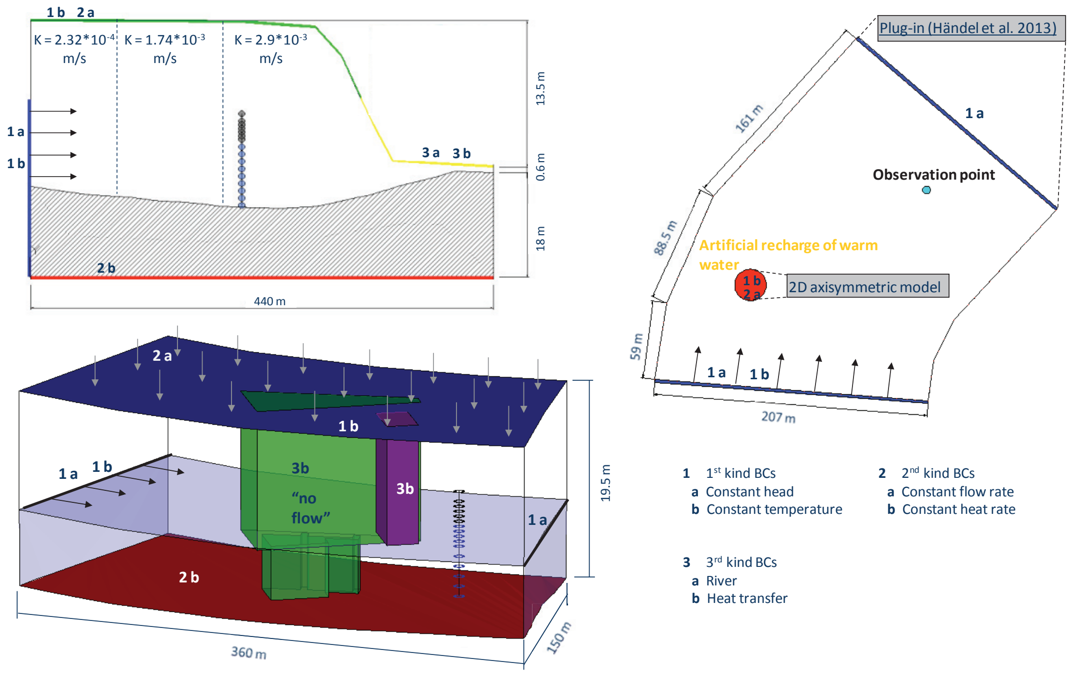

Figure 3: Conceptual model setups and boundary conditions (for locations of local models see Fig. 2), including the plug-in used for local 2D model of multi-level observation well [II], that simulates surface temperature and heat transfer from underlying layers.

At the location of the multi-level observation well [II], the focus is placed on investigation of the impact of up-gradient thermal groundwater use, where water with elevated temperatures is injected through a soakaway into the unsaturated zone. Here, a 3D-setup is technically required to reproduce the flow and thermal processes accurately. However, for practical reasons, a 2D horizontal model has been selected instead in order to compute the flow and heat-transport processes in the saturated zone, complemented by an InterFace Manager (IFM) tool (that is further described in [12]) which considered local heat transfer through the unsaturated zone and interaction with the underlying structures. Furthermore, a 2D vertical axisymmetric heat-transport model was set up to simulate selected heat transfer processes of warm water infiltration through the unsaturated zone. Results of this model provide the boundary conditions for input temperatures and infiltration rates at groundwater level for the 2D horizontal model.

At the location of the multi-level observation well [III], complex flow and transport processes can be observed down-gradient from two nearby buildings, which are situated near to the groundwater table and bedrock respectively and as such required a 3D-setup.

Table 1 and Fig. 3 summarize the geometric setup of the three models, including the definition of boundary conditions. Table 2 summarizes parameterization for flow and heat-transport. For each local heat-transport model, a parameter analysis (influence of e.g. heat transfer coefficient, volumetric heat capacity, soil surface temperature) was performed, followed by a manual calibration of flow and heat-transport for the temperatures in the saturated and unsaturated zone respectively.

A regional 3D heat-transport model of the entire investigation area for the year of 2010 was used to derive adequate initial boundary conditions. Setup, calibration and results of this 3D heat-transport model are covered in sections [8, 9].

Table 1: Setup of the local heat-transport models (for locations see Fig. 2), Roman numerals indicate the model setup for the respective observation point

	Model geometry	Boundary conditions
I	2D vertical cross-section, 440 m length, 20 m average thickness, 20 m thick bedrock layer, 34‘000 elements	River (only I): Transient Cauchy boundary conditions (3rd kind) for flow and transport with daily intervals of head and river water temperature data (Fig. 2).The transfer rate was initially calibrated using the regional 3D heat-transport model. Groundwater use (only IIa): Mean monthly values of warm water recharge rate and daily values of warm water temperature (assumption: groundwater temperatures derived from nearby unaffected observation point data heated by 3 K)
IIa	2D vertical axisymmetric, 20 m radius, 25 m average thickness 10 m thick bedrock layer, 15’783 elements	Groundwater use (only IIb): Warm water recharge rate and temperature simulated by model IIa, areal groundwater recharge implemented by IFM tool Building structure (only III): No flow condition and transient Cauchy boundary conditions for heat-transport with estimated monthly intervals of building structure temperature based on heating cycle
IIb	2D horizontal, 320 m length, 210 m width 3’159 elements	Daily values of regional groundwater flow and thermal regime up-gradient derived from regional 3D heat-transport model and nearby observation points
III	3D, horizontal extensions: 360 m x150 m, 19.5 m average thickness, 20 m thick bedrock layer, 162’370 elements	Areal groundwater recharge by percolating meteoric water (inflow on top): Assumed as sealed (urbanized) surface. Monthly running average of cumulated daily precipitation from Basel-Binningen station (Fig. 1) reduced by a factor of 1/30 (see [14]). Upper thermal boundary: Dirichlet boundary condition (1st kind) as top of the unsaturated zone (Fig. 2). Soil temperature data measured at 5 cm depth (Basel-Binningen station). Lower thermal boundary: Defined by the basal heat flux of approx. 0.07 W/m².

For all models, a fine discretization of the unsaturated (only vertical and three-dimensional models) and saturated zone was used and a bottom layer with a comparably small hydraulic conductivity (less than $1*10^{-8}$ m/s) was considered. This layer is important to reproduce the vertical transport processes dominated by conduction into and out of the underlying bedrock [9]. This acts as a kind of thermal buffer for the propagation of a temperature signal. The location of the aquifer base was derived using information from more than 400 drill-cores. GoCAD©

(Geological Objects Computer Aided Design) was used to model the aquifer base. The topography could be obtained from a digital elevation model with 25 m horizontal resolution and river bed location was estimated by high-precision echo sounding [9]. For the local 2D and 3D heat-transport models, geometries were extracted from the regional interpolations.

Aquifer hydraulic conductivities for the local 2D and 3D heat-transport models were derived from the previously mentioned regional 3D heat-transport model for which conductivity zones were interpolated based on drill cores and pumping tests (available at database of Applied and Environmental Geology of the University of Basel called GeoData) as well as information assessed from depositional processes. Based on these data sets, values for the hydraulic conductivity ranged from $1*10^{-4}$ to $5*10^{-3}$ ms^{-1} [8, 9, 15, 16]. The ratio of horizontal to vertical hydraulic conductivity is assumed to be 10 due to the alluvial character of the aquifer sediments. In the same manner, the flow gradient was extracted from the regional model and further extended beyond the year 2010 by using data from conventional borehole measurements in the vicinity. Parameter analysis of temperature data in the vertical quasi one-dimensional profiles of the multi-level observation wells [III] and [IV] (not depicted) indicated that thermal effects from different sediment structures within the unsaturated zone are insignificant. This supports the approach of using depth-averaged hydraulic conductivity. However, it must be taken into consideration that temperatures within the unsaturated zone may vary significantly when transient infiltration is considered. For the models used here, reduced recharge levels due to sealed surfaces has been considered [8] (Table 1).

Table 2: Material properties selected for the saturated and unsaturated domain of the heat-transport models, Roman numerals indicate the model setup for the respective observation point

Parameter	Porous media	Bedrock
n (-)	0.12	0.4
Hydraulic conductivity K (m/s)	$1.74 \cdot 10^{-3}$ (I + III), $2.50 \cdot 10^{-4}$ (IIa + IIb)	$1.00 \cdot 10^{-9}$ (I + III), $1.16 \cdot 10^{-14}$ (IIa)
Longitudinal dispersivity α_L (m)	20.0 (I + III), 1.0 (IIa), 7.5 (IIb)	20.0 (I + III), 1.0 (IIa), 7.5 (IIb)
Transverse dispersivity α_T (m)	0.20 (I + III), 0.10 (IIa), 0.75 (IIb)	0.20 (I +III), 0.10 (IIa), 0.75 (IIb)
Transfer rate for Cauchy boundaries (In/Out) Φ_T (J/m²/d/K)	$2.00 \cdot 10^{5}$ (I), $4.32 \cdot 10^{6}$ (III)	-
Volumetric heat capacity of matrix $c_S \cdot \rho_S$ (J/m³/K)	$2.87 \cdot 10^{6}$	$2.00 \cdot 10^{6}$
Thermal conductivity of matrix λ_S (J/m/s/K)	2.70	1.75
Volumetric heat capacity of water $c_w \cdot \rho_w$ (J/m³/K)	$4.20 \cdot 10^{6}$	$4.20 \cdot 10^{6}$
Thermal conductivity of water λ_w (J/m/s/K)	$6.00 \cdot 10^{-1}$	$6.00 \cdot 10^{-1}$
Unsaturated flow porosity ε	0.384	-
Residual saturation Θ_r (-)	0.115	-
Maximum saturation Θ_s (-)	1.00	-
Van Genuchten shape parameter α (1/m)	3.984	-
Van Genuchten shape parameter n (-)	3.477	-

Flow in the unsaturated zone for the models from observation wells [I] and [III] is simulated by Richards' equation applying the empirical Mualem van-Genuchten model to describe the retention behavior and the saturation-hydraulic conductivity function. Rosetta Lite network prediction system [17] was used to estimate residual and maximum saturations as well as shape parameters of Mualem van-Genuchten model (Table 2). These parameters were considered to be homogeneously distributed in the models and a thickness-weighted average was calculated using stratigraphic information of the borehole at the multi-level observation well [III] (3D-model observation point) [9].

Dispersivity is assumed to be anisotropic by a factor of 10 in the transverse direction (3D model) and 100 in the transverse vertical direction. Selecting a comparably large porosity value (unsaturated flow porosity, see Table 2) for heat transport allowed considering the strong conductive impact of the atmospheric boundary. Flow-effective porosity would lead to an overestimation of thermal conduction due to the higher thermal conductivity of the solid. Values for thermal conductivity and heat capacity for the porous media and groundwater (Table 2) were derived using relevant literature [18, 19].

4. Results

4.1. Monitoring

A detailed discussion of the temperature time-series of high-resolution multi-level observation wells from 2010 can be found in [8] and [9]. Fig. 4 shows monitoring data from 2010 to 2014 and Table 3 summarizes some of the monitoring results. In all four observation wells comparably high groundwater temperatures were observed, for example, rising up to 17 °C in well [III]. The elevated groundwater temperatures result from the respective anthropogenic thermal impacts at the observation well locations [9]. Seasonally elevated temperatures imply a direct influence of heating periods. Thermal memory effect can be observed from retardation of thermal propagations, i.e. the predominant temporal shift of elevated temperatures resulting from heating periods or for example, from flood events (only well [I]). For all wells, vertical temperature distribution is very complex. Preferential thermal propagation is positively correlated to more conductive coarse fluvial deposits. Beside well [IV], for which interaction between the unsaturated and the saturated zone can be identified, vertical thermal stratification within the saturated zone cannot be detected. We assume that for groundwater bodies within heterogeneous high-conductive aquifers and with high groundwater flow velocities, geogenic seasonal temperature fluctuations (e.g. [20, 21]) resulting from propagation of surface temperatures are superimposed by natural and anthropogenic disturbances dominating thermal groundwater regimes ([8] and [9]).

Table 3: Monitoring results of the multilevel observation wells I to III (for locations see Fig. 2)

	Min T(°C)		Mean T(°C)		Max T(°C)		STD*** T(°C)	
	SZ*	USZ**	SZ*	USZ**	SZ*	USZ**	SZ*	USZ**
I	14.1-14.8	14.0-14.7	14.5-15.1	14.8-15.0	14.8-15.5	15.3-15.7	0.1-0.2	0.1-0.4
II	13.5-13.6	13.4-13.8	13.7-13.9	13.7-14.0	14.0-14.4	14.0-14.4	0.1-0.2	0.1-0.2
III	13.6-14.4	12.7-14.0	14.8-15.7	14.0-14.9	15.7-17.0	15.4-16.2	0.6-0.8	0.8-0.9

*SZ=saturated zone; **USZ=unsaturated zone; ***STD=standard deviation

4.2. Local heat-transport modeling

Local 2D (multilevel observation well [I] and [II]) and 3D (multilevel observation well [III]) heat-transport models generally resulted in a very good conformity of simulated and observed temperatures within both, the saturated and unsaturated zone (Fig. 5). Therefore, it can be assumed that the models can simulate the local heat-transport processes in general. In this context, it is worth mentioning that calibration was performed using the most sensitive model impacts: up-gradient boundary temperatures, volumetric heat capacity, heat transfer coefficient (model setups [I] and [III]), soil surface temperature and, for the model set-up [IIb], the radius of the infiltration area of warm water. Almost all of these parameters revealed an impact on the modeling results, even though differences between the local heat-transport models arose. For instance, the impact of the soil surface temperature depends on the distance between the groundwater table and the soil surface.

Due to mainly effluent flow conditions regarding river-groundwater interaction processes (model setup [I]), variation of the heat transfer coefficient did not result in a change in simulated temperatures. After all, no significant correlation between river and groundwater temperature regimes could be detected. Therefore, river temperatures do not affect groundwater temperatures significantly, except at locations in the direct vicinity of a river.

In contrast, the impact of the heated building on groundwater temperatures is apparent, whereas advective heat-transport within the saturated zone is the dominating process. Furthermore, the heat transfer coefficient considerably affected the simulated temperatures ‘down-gradient’ of the building structures at the locations of multilevel groundwater observation well [III]. A rising trend of measured and simulated groundwater temperatures can be observed at the location of the multi-level observation well [III], which can be attributed to the heating effect of the building being directly situated upstream of the observation well (see Fig. 5). With this model, it could be investigated how nearby building structures affect groundwater temperatures.

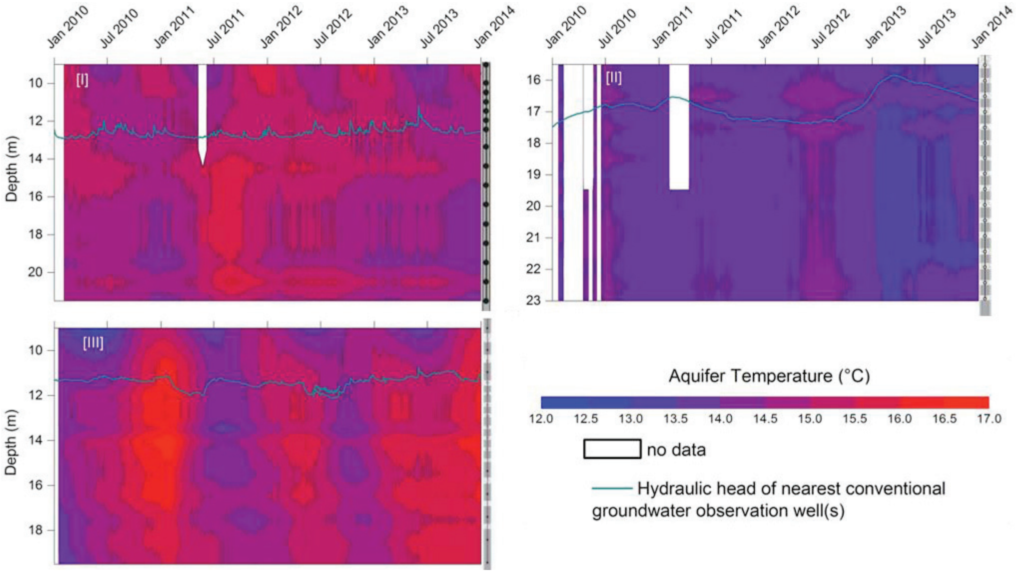

Figure 4: Measured seasonal temperature distributions for multilevel groundwater observation wells I to III for the years 2010 to 2014 (for locations see Fig. 2), including the setup of multilevel observation wells showing the sensor depth and the locations of filter sections.

At the location of multi-level groundwater observation well [II], the variation of infiltration radius regarding the infiltration of warm water into the saturated zone did not result in a change of simulated groundwater temperatures. Moreover, except for a short period, the computed temperature plume did not affect the simulated temperature distribution in the vicinity of the observation point (Fig. 6). This can be explained by the positioning of the soakaway beyond the upstream contribution area of the observation well [II]. The previously-mentioned time period when groundwater temperatures at observation point [II] are indeed affected by infiltration includes very high infiltration rates. Since the simulated rise of temperatures due to infiltration within this period cannot be explained by measured temperatures, this local model revealed data uncertainty which must be clarified before including it in the regional modeling.

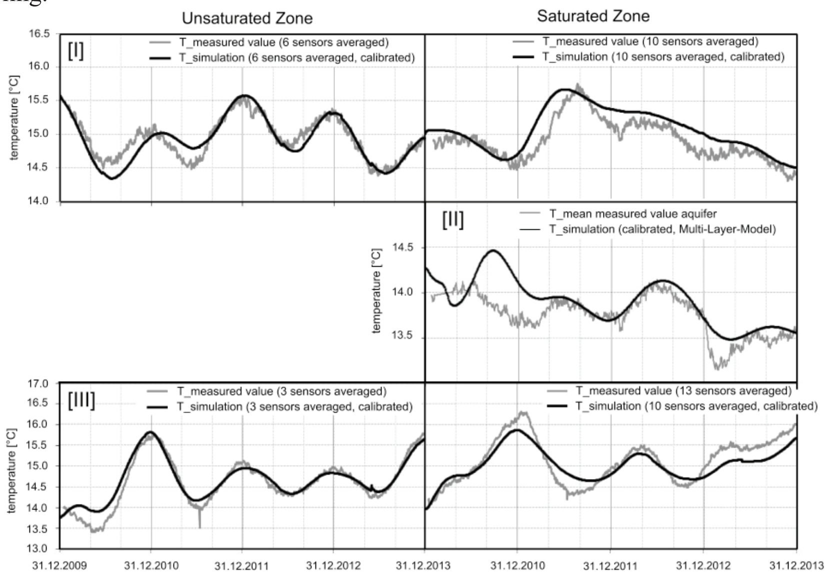

Figure 5: Comparison of measured (grey line) and simulated (black line) temperatures in the saturated and unsaturated zone for the local 2D and 3D heat-transport models at the locations of multilevel groundwater observation wells [I] – [III] (for locations see Fig. 2). Temperatures from the unsaturated and saturated zone were averaged respectively.

5. Conclusion and outlook

For the sustainable management of urban subsurface resources, adequate modeling and measurement tools are required to evaluate the thermal regime in the subsurface. The extensive use of geothermal technologies is still limited, mainly because of concerns about possible long-term environmental effects [9]. Besides this, increased groundwater temperatures have already been observed in many urban areas and have necessitated the provision of tools that allow evaluation of future construction and exploitation scenarios [9, 22, 23].

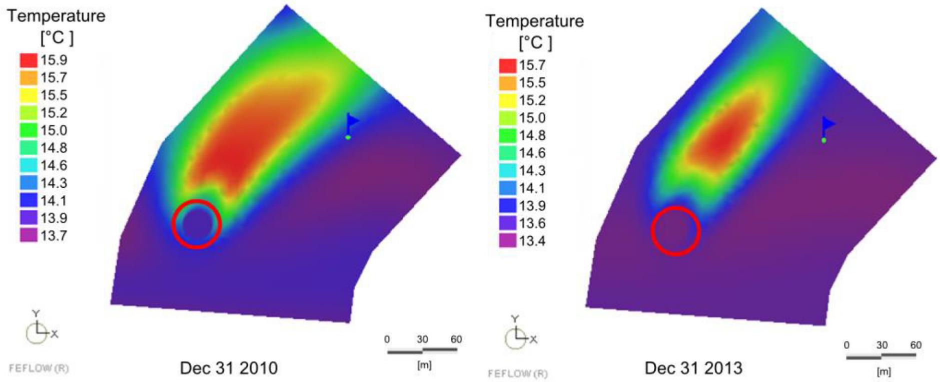

Figure 6: Simulated temperature distributions for the local model [II] (for locations see Fig. 2). Red circle and blue flag indicate the position of warm water recharge and observation point respectively, left figure shows temperature distributions for only time where artificial recharge influenced the area of observation point [II].

A common procedure for the evaluation of thermal regimes of shallow groundwater systems is to calibrate and validate flow and heat-transport models with laboratory and field measurements. However, in terms of heat-transport, processes may be complex and temperature varies temporally and also spatially as a result of various thermal impacts. Adequate boundary conditions have to be introduced to reproduce these variations numerically. Besides thermal processes within the unsaturated zone [12], other boundaries can also be important and need to be studied in detail, including groundwater-surface water interactions and subsurface buildings [9]. Until now, it is not known exactly how to identify, quantify and eventually adequately consider these structures for regional modeling, although the basic processes have been thoroughly investigated [24].

By applying local models based on depth-oriented measurements, this study illustrates (A) how to analyze building structures reaching into the saturated zone and their effect on nearby groundwater temperatures, (B) whether surface water temperatures from rivers significantly propagate inland and (C) that data for thermal applications includes uncertainty which has to be clarified before including the information into regional modeling. Thereby, depth-oriented temperature measurements can be used as a perfect base to set up and calibrate local process models and, therefore, to obtain valuable insights into local processes.

Nevertheless, depth-oriented temperature measurements are relatively expensive compared to conventional temperature measurements. Furthermore, the spatial arrangement of these wells with respect to the thermal impact to be studied is uncertain, as a-priori information is mostly limited. In this context, it must also be mentioned that an attribution of a signal measured to a distinct thermal impact is not possible without related information from, for example, conventional borehole measurements.

The current version of the local models can be seen as a first step towards reproducing and gaining insights into local processes. In this context, further analyses should focus on extended uncertainty and sensitivity studies. However, such studies are site-specific and can only be carried out with improved subsurface characterization and process quantification. This can only be accomplished efficiently using field investigation methods. Good knowledge of a site to be investigated may also lead to a better adaptation of measurements and possibly rethinking model conception. This may also be applied for the models discussed here.

This study illustrates that adequate local temperature measurements can contribute significantly to process-understanding and hence, have the potential to improve our understanding of the concepts underpinning regional heat-transport models.

Acknowledgements

This study is based on the master thesis of Mandy Köhler and was supervised by the Technische Universität Dresden and the Applied and Environmental Geology of the University of Basel. The work was supported by the Swiss national Federal Office for the Environment (FOEN) SI/501044-01 and the local Agency for Environment of the city of Basel (AUE BS). Furthermore, we thank Christopher Higgins of the UFZ Leipzig for language editing the manuscript. We acknowledge also DHI Wasy for the use of FEFLOW software during the thesis.

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