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MODELLING OF TRANSIENT RIVER – AQUIFER EXCHANGE USING PRESSURE HEAD AND HEAT MEASUREMENTS: THE HYPORHEIC ZONE'S DIMENSION

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Summary. Water exchange processes in the floodplain of a lowland groundwater-surface water system are studied on the basis of a study site near Freienbrink, NE Germany. The surface water boundaries of this site are formed by an oxbow and the current bed of the river Spree, section Müggelspree. Surface and ground water pressure heads and water temperatures were collected in 12 piezometers and 2 recording stage gauges of a 300 m long transect throughout a one-year-period. Because of water level fluctuations alteration of infiltration and exfiltration occurred. Due to clogging of the oxbow bed with an organic silt layer of different thickness the hydraulic contact between the oxbow and the adjacent aquifer is partially marginal. These features are described quantitatively using SUTRA in order to simulate coupled ground water flow and heat transport. As the main result, the mass transfer between the aquifer and both river sections can be quantified; mostly, groundwater is infiltrating into the surface waters with flow rates between 0.002 and 0.004 l $s^{-1}m^2$ (150 to 350 l m^2 per day). Short periods of surface water exfiltration into the aquifer do not exceed 10 days and the flow rates are in the same range. Results of heat transport simulations generally confirm the transient subsurface flows and allow estimating influence of surface water infiltration into the riparian zone.

1 INTRODUCTION

Exchange of surface water and groundwater water with the riparian zone is closely linked to flow velocity, discharge, and water level in the river as well as to local and regional groundwater levels. The fluctuation of groundwater levels in the vicinity of streams and rivers is strongly coupled to hydrologic events (floods, droughts) and has an influence on the residence times of water and solutes in this zone [9]. At low flow, streams are primarily influenced by aquifer discharge, and surface water penetration into the floodplain is negligible [4]. During high flow, river water penetrates into the floodplain, the aquifer table rises and areas hydrological connected to the river channel may extend laterally [12].

To investigate the mixing zone of groundwater and surface water below the streambed profile in a scale of centimeters to meters, it can be assumed that hydraulic gradients are the main driving forces, and hydrodynamics in the stream channel are negligible [5]. The use of heat as a natural tracer has proven to be an effective method for identifying stream-aquifer exchange [1, 2]. Temperature data are easy to collect and useful to quantify infiltration rates of stream water into the aquifer or groundwater discharge into the stream. In addition, numerical models, such as VS2DH [6] or SUTRA [13] allow to simulate coupled variable saturated flow and heat transport providing insight into near-stream processes.

The objectives of the present study are (1) to investigate numerically flow and heat transport in the floodplains aquifer with special emphasize to the exchange with two hydraulically different river reaches, (2) to estimate directions and rates of surface water-groundwater exchange depending on local and regional hydrological conditions.

2 NUMERICAL MODELLING

Model Setup

In the conceptual model the aquifer was assumed to be unconfined and saturated. In a previous work Nützmann and Lewandowski [11] concluded that analysis of groundwater – surface water exchange of this study site can be conceptualized by a 2D vertical-plane analysis along the piezometers transect, where the flow direction remains the same and is principally parallel to transect oriented from the plateau to the river Spree (Fig. 1+2).

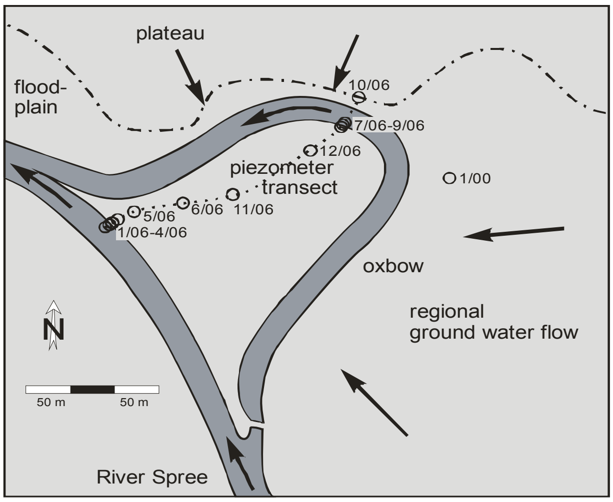

Fig. 1: Scheme of study site with transect of piezometers.

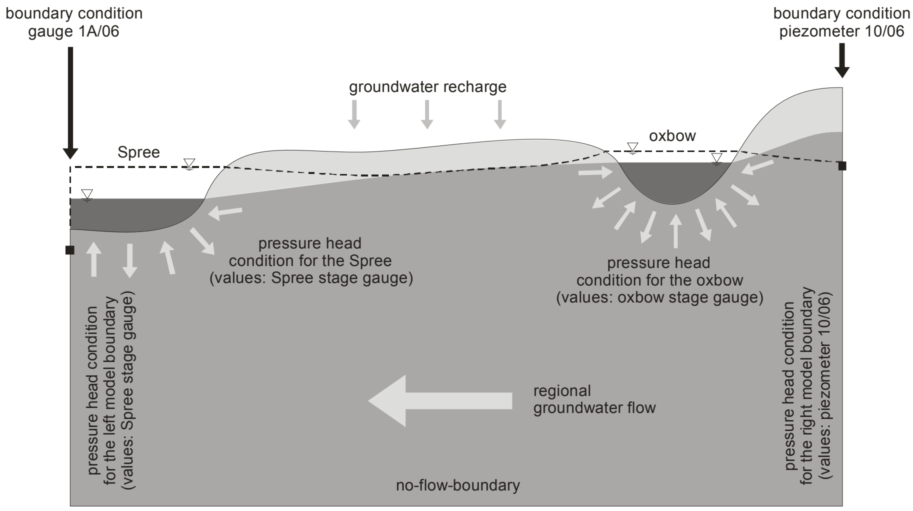

Fig. 2: Scheme of water flow boundary conditions used in the 2D model representing system characteristics of the study site.

The modelled region was vertically divided into three subsections (with a width of 1 m, 1 m, and 18 m) to provide more detailed information in regions near to the surface. Vertical cell sizes of 10 cm, 20 cm and 50 cm (related to the mentioned subsections) were used resulting in a total of 51 layers, 31722 elements and 32396 nodes for the whole model. Horizontal cell sizes were set to 50 cm. The aquifer type was assumed to be unconfined and saturated. The top of the model was set to 32.90 m amsl, the bottom to 12.90 m amsl. For Spree and oxbow river bed morphologies could be implemented into the model. The bed morphologies define the top of the model for these areas. The hydraulic conductivities and porosities of the aquifer and the organic silt layer of the oxbow are selected based on laboratory analyses. The aquifer material consists of medium to coarse sands with $1\times10^{-5} \leq k_f \leq 5\times10^{-3}$ [m s^{-1}], the effective porosity n_e is between 0.15 and 0.20 [m^3 m^{-3}]. For the organic silt layer a hydraulic conductivity in the range of 1×10^{-6} to 5×10^{-4} [m s^{-1}] and a porosity of 0.50 [m^3 m^{-3}] was found. Because of the aquifer's sediment genesis interpreted from borehole profile data an anisotropy ratio of 8:1 between horizontal and vertical hydraulic conductivity was assumed [10]. Organic silt k_f-values were assumed to be isotropic. The longitudinal dispersivity was set to α_L = 30 m following Käss [8], who suggests α_L to be one tenth of the total flow distance (here 311 m). Thus, transversal dispersivity was set to α_T = 3 m representing a ratio of 10:1 between longitudinal and transversal dispersivity.

The heat transport model was set up with the following parameters: aquifer bulk density of 2050 [kg m^{-3}], aquifer heat capacity of c_s = 1396 [J kg^{-1} K^{-1}], water heat capacity of c_w = 4187 [J k g^{-1} K^{-1}], thermal conductivity of λ = 2.91 [W K^{-1} m^{-1}].

To simulate vertical-plane groundwater flow and heat transport, a two-dimensional numerical model was developed with SUTRA, version 2.1, GUI [15] embedded in the ArgusONE modelling environment, version 4.2.0w [3], and the results were mainly evaluated with the post processing tool of SUTRA, GW_Chart 1.22.0.0 [14] and ModelViewer 1.3 [7].

Calibration and Validation

Calibration and validation were carried out only for the flow model with the hydraulic conductivity k_f and the effective porosity n_e as the most sensitive parameters, both for the aquifer's sandy sediment and the organic silt layer. First, in steady-state simulations at different times the initial values of the hydraulic parameters were estimated by an incremental change of these quantities. To check the steady state model performances the root mean square error (RMSE) method was used as the criterion of agreement between measured and simulated hydraulic heads. For flow simulation, an acceptable modelling accuracy was defined with RMSE $\leq$ 0.1 m, a reasonable good accuracy for RMSE $\leq$ 0.05 m and a good accuracy for RMSE $\leq$ 0.025 m. After these steady-state approaches, the hydraulic model was calibrated and validated in two transient simulations (the second halve of February 2008 for calibration, and the second halve June 2008 for validation) with regional groundwater flow parallel to the orientation of transect to legitimate the utilization of a two-dimensional modelling approach (Fig. 2). A step-by-step variation of the parameter values lead to excellent model accuracy with an adjusted R^2 of 0.9651 and a RMSE of 0.017 m on 404 degrees of freedom and a maximum deviation 6.52 cm between measured and simulated values at piezometer 6/06. As results of these calibration runs the following parameter values are found: $k_f = 5\times10^{-4}$ m s^{-1} (aquifer) and $k_f = 2.5\times10^{-5}$ m s^{-1} (organic silt layer) as well as effective porosities of $n_e = 0.15$ (aquifer) and $n_e = 0.50$ (organic layer). Model performance for the validation period in June 2008 with the same parameters was slightly worse but still sufficiently accurate with an adjusted R^2 of 0.9222 and a RMSE of 0.020 m on 376 degrees of freedom. The maximum deviation between measured and modelled hydraulic heads was 5.7 cm at piezometer 12/06. The calibrated as well as the validated models are significant on the 0.001 level with p-values of less than 2.20×10^{-16}. Heat transport was then simulated straightforward based on the flow modelling results using the parameters described in the section above.

Long-term Flow and Heat transport Modelling

A long-term flow and heat transport model was set up based on the validated short-term flow model. The time period for the long-term model ranges approximately nine and a half months from 11/27/2007 to 09/09/2008. The initial distribution of hydraulic or pressure heads were generated for the starting date (11/27/2008, 6 p.m.) with the help of a steady state simulation as described above. The results of the water level and water temperature simulation for the whole study period are shown in Figures 3 and 4 each containing three comparisons between measured and simulated hydro- and thermographs and a scatter plot demonstrating the overall model performance for the particular parameter set.

Hydro- and thermographs are shown for an observation point at a boundary condition (gauge 1A/06, water stage River Spree), close to that boundary (3/06, approximately 2 m apart of the River Spree), and in the middle of the study site (12/06). Again model performances were estimated with the RMSE and the adjusted R^2 with same value classes. The results of the long-term water level simulation show a very precise adjustment to the measured values with an overall accuracy of adjusted $R^2 = 0.9946$ and a RMSE of 0.018 m on 390 degrees of freedom. Furthermore, the adjusted R^2 of each of the twelve observation points was above 0.99 so that the numerical model fits the measured data very well. Despite that, slightly stronger deviations can be observed at piezometers located more in the middle of the study site than close to or at the model boundaries. The model result is significant on the 0.001 level with a p-value of less than 2.20×10^{-16}. The maximal observable deviation between measured and modelled hydraulic heads is approximately 6 cm at piezometer 12/06. The results of the long-term water temperature simulation show an adjustment to the measured values with an overall accuracy of adjusted $R^2 = 0.70$ and a RMSE of 1.58 °C on 390 degrees of freedom. It has to be stated that for the results of the temperature simulation a significant spatial differentiation is observed. Close to the surface water (gauges and piezometers 1A/06, 1/06, 2/06, 3/06, 4/06, 8/06, 9/06, 9A/06 and 10/06) simulated water temperature values represent the measured ones in a good to very good way. The farer an observation point is located from a model boundary the worse its discrepancy between measured and modelled values. This can be seen at piezometers in the centre of the study site (5/06, 6/06, 7/06, 11/06 and 12/06) where thermographs hardly show any fluctuations during the modelled period.

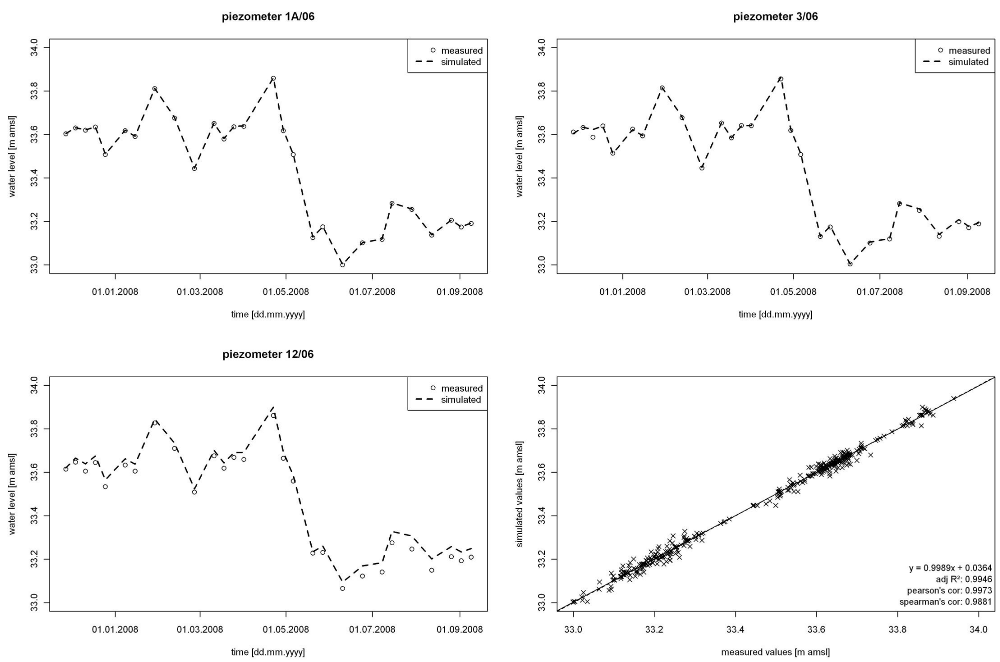

Fig. 3: Long-term simulation results: modeled hydrographs of the piezometers 1A/06, 3/06 and 12/06 compared with measurements, and scatter plot demonstrating the overall groundwater flow model performance.

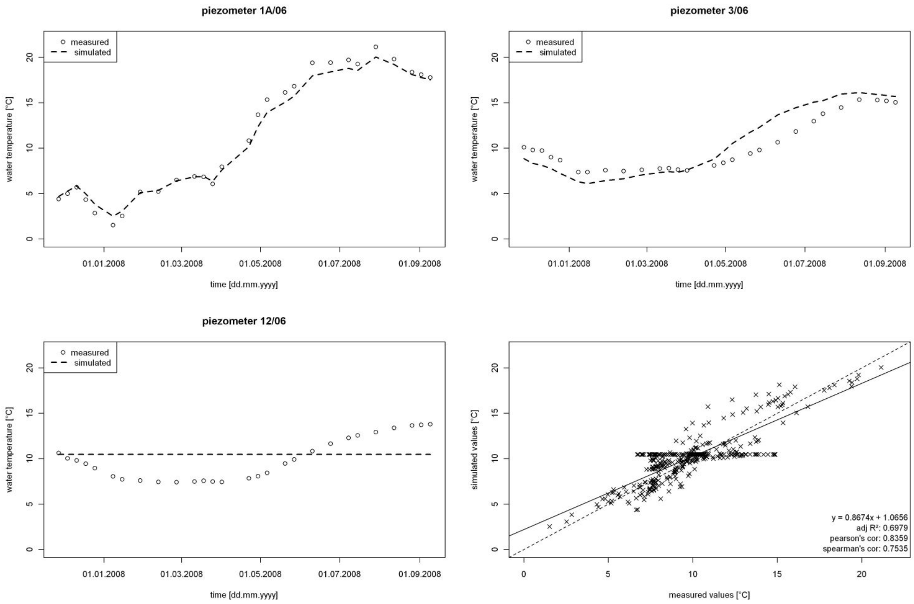

Fig. 4: Long-term simulation results: modeled thermographs of the piezometers 1A/06, 3/06 and 12/06 compared with measurements, and scatter plot demonstrating the overall heat transport model performance.

There are some plausible reasons for that behaviour. One has to consider that the groundwater surface temperature in the model was adopted from air temperature time series, which are available only on a weekly basis. Thus, the heat flux from soil to aquifer was calculated in the model based on this roughly estimated temperatures and the mean groundwater recharge, which is quite different i.e. to the daily rates of groundwater recharge. Because of this so approximated boundary conditions temperature propagation was especially modelled correctly in the vicinity of the surface water. The maximum of the vertical temperature propagation adjacent to Spree and oxbow is approximately 10 m below each riverbed. Horizontal temperature propagation reaches up to 20 m from each bank. Based on that result the extent of the riparian zone can be roughly estimated by defining this zone as the groundwater body which is considerably influenced by the surface water. Divergent heat propagation processes between Spree and oxbow are observable. The temperatures of the surface water infiltrating into the aquifer are less at the oxbow than at the Spree. This is caused by low flow velocities and low water exchange rates of the oxbow due to its disconnection from the natural discharge situation of the Spree. This prevents an interference of warm surface water so the aquifer section below the oxbow remains cool in contrast to the Spree area. Together with the closed leaf canopy along the river banks this causes a lesser warming of the oxbow surface water in contrast to the Spree. The dissolution and the extrusion of cold water zones through a propagating warm zone are well observable (Fig. 5).

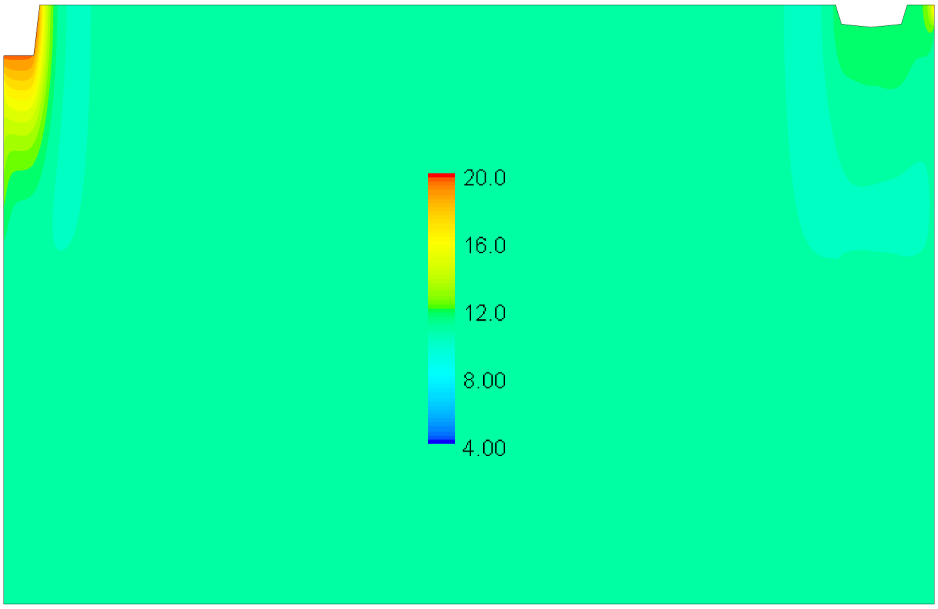

Fig. 5: Simulated heat propagation for maximum warm water intrusion (08/12/2008)

3 SUMMARY AND CONCLUSIONS

Variability of groundwater discharge to the river reach and the oxbow as well as of the groundwater flow directions in the vicinity of both surface waters was determined from a long-term simulation using calibrated and validated flow models. Sensitivity analysis of the coupled groundwater flow and heat transport model shows that only two parameters (temperature boundary-condition factor and the fluid coefficient of density change with temperature) show a noticeable effect on the modelling results, and both quantities were adjusted in a plausible range to improve the overall models performance [13]. With the present study we could show that it is possible to model flow and heat transport in the floodplains aquifer numerically. Regional flow is directed from the plateau to the floodplain followed by a partial exfiltration of groundwater into the surface waters, especially the River Spree. In the vicinity of the surface water bodies locally different flow directions and flow velocities occur.

Due to the low hydraulic conductivity of the oxbow bed flow lines are compressed below the oxbow resulting in increased flow velocities in that zone. Groundwater flow directly below the oxbow is directed upwards towards the surface water body, while groundwater in deeper layers underflows the oxbow and exfiltrates into the River Spree. Due to the large hydraulic gradient between aquifer and oxbow, there is also some backflow of groundwater at the oxbow inner bank in the uppermost layer of the aquifer up to 40 m distance from the oxbow. Nevertheless, near surface groundwater underflows the oxbow and exfiltrates into the River Spree.

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