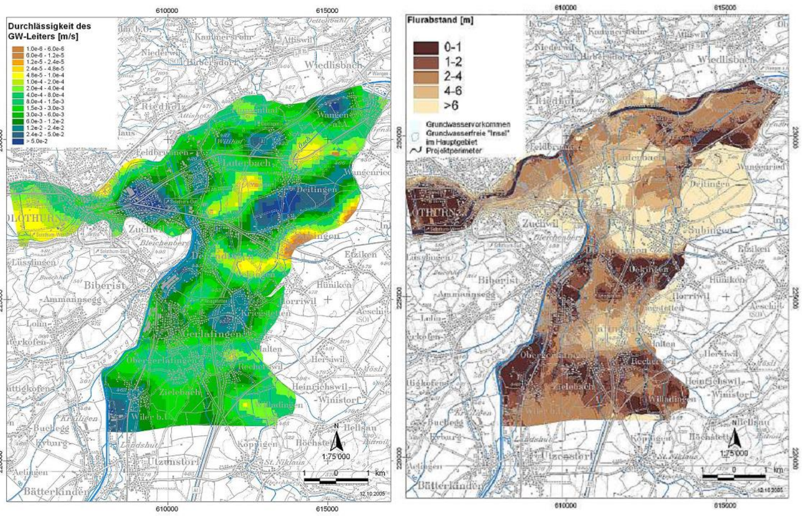
Project: Groundwater model „Wasseramt“



Left: calibrated hydraulic conductivity; Right: minimum groundwater depth in the period 2002-2005.

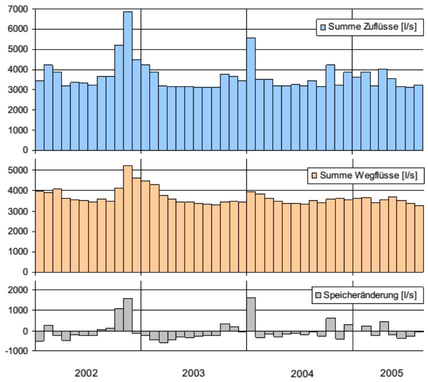
Employer: Amt für Umwelt, Canton Solothurn

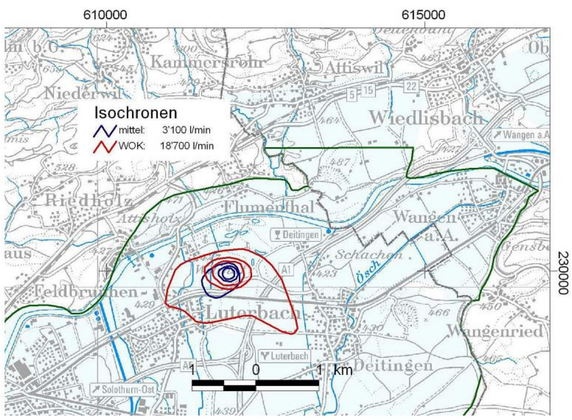
Task: Construction of a groundwater model for the region Wasseramt. Calculation of recharge according to Thornwaite, Calculation of low-, middle- and high-water conditions in the period 2002-2005, Maps of groundwater depth, mass balance and inflows

Model: 2D finite element model, dimensions ~ 10x10km, 13'000 nodes, 15'000 elements. A salient feature is that the many streams in the area are included as leakage boundary conditions.

Software: Spring 4.0

Calibration Transient calibration of hydraulic conductivity and leakage coefficients using data from 2002. Model validation in the period 2003-2005. .





Left: Mass balance in the whole model area; Right: Isochrones of a pumping test (10 / 20 / 100 days using 2 different flow rates).

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Summary

In 2006, a 2D groundwater flow model was built and calibrated using hydraulic data in the period 2002-2005. Since 2006 many things have changed in the area. For instance, new pumping wells have been drilled, or the pumping rates at existing wells have been modified. This projects updates the existing model with the new topology and includes new data, e.g., heads at new wells or extension of the existing records, new hydraulic tests, etc.

A major modification to the existing model is the transient modelling of the two main rivers in the area, i.e., Emme and Aare. The water table there is included in the model as prescribed (transient) head boundary conditions. One of the main novelties in this work is the use of an enhanced version of the software Spring. The previous model was calibrated using version 3.4, whereas the new model is calibrated using version 4.1, which amongst other enhancements, greatly improves the treatment of boundary conditions like leakage at water courses. Spring 4.1 is coupled with PEST (Parameter ESTimation software; Watermark Numerical Computing, 2010). PEST undertakes the automatic calibration of model parameters (hydraulic conductivity and leakage coefficient at water courses in this work) via the pilot points method incorporating prior information of model parameters.

Data

Overall, there are 95 wells with measurements, out of them 29 with a long measurement record (Figure 1). The model calibration is based mainly on these long monitoring records and a total of 30504 groundwater levels are used to calibrate model parameters. This vast amount of data is handled by (1) a QGis database that summarizes the spatial location, description, etc., of the different boreholes, wells, groundwater heat pumps, etc. and (2) by a single Excel file containing all measurement records. This methodology allows an easy updating of the model at any time, simply complementing the 2 data bases to add, e.g., new boreholes or new measurements at an existing borehole.

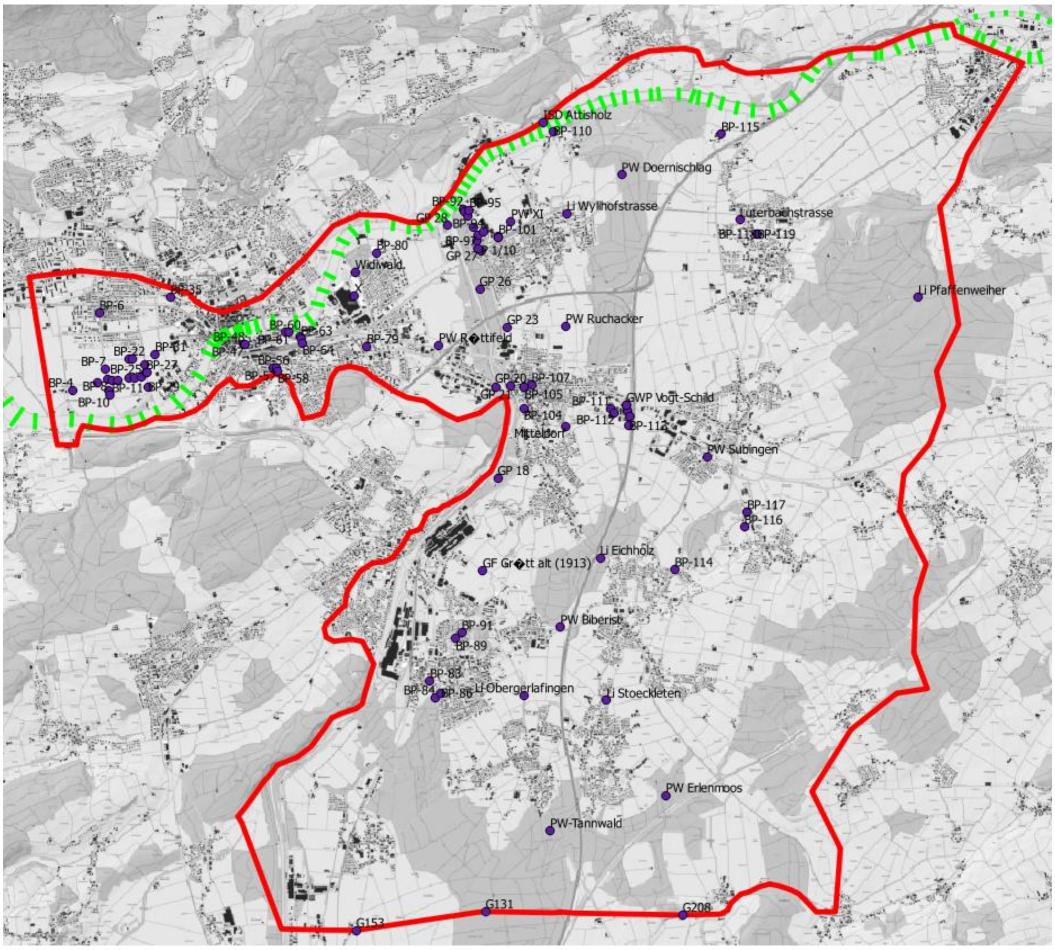

Figure 1.Available observation boreholes/wells. The red line depicts the model perimeter. Green lines depict measured cross sections at the Aare river.

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The quality of the long monitoring records is outstanding, what favours the goodness of the calibration of the model. An example of such monitoring records at two selected wells is presented in Figure 2. Of particular interest are the piezometers G208, G131 and G153 at the southern boundary of the model, which allow us to estimate a transient prescribed head boundary condition (Figure 3). Prior information of model parameters like hydraulic conductivity K is also accounted for in the calibration of the model. Overall, 75 points with available K estimates are available. The location of those points and the histogram of available K values is presented in Figure 4. In the average, hydraulic conductivities are rather high.

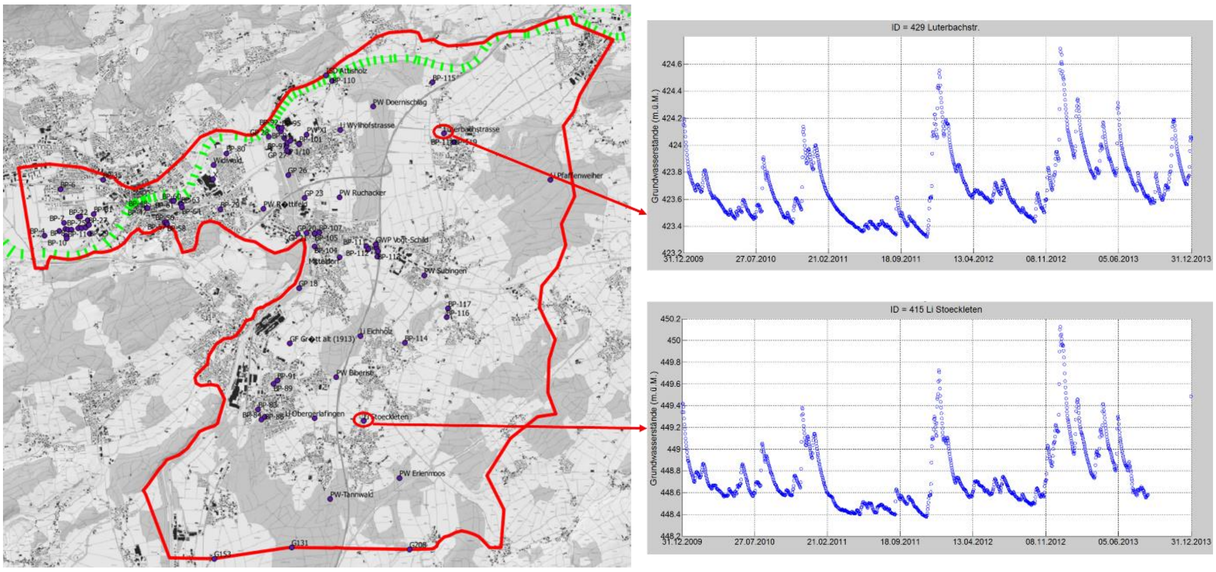

Figure 2.Monitored groundwater levels boreholes in Luterbachstrasse (above) and Stoeckleten (below).

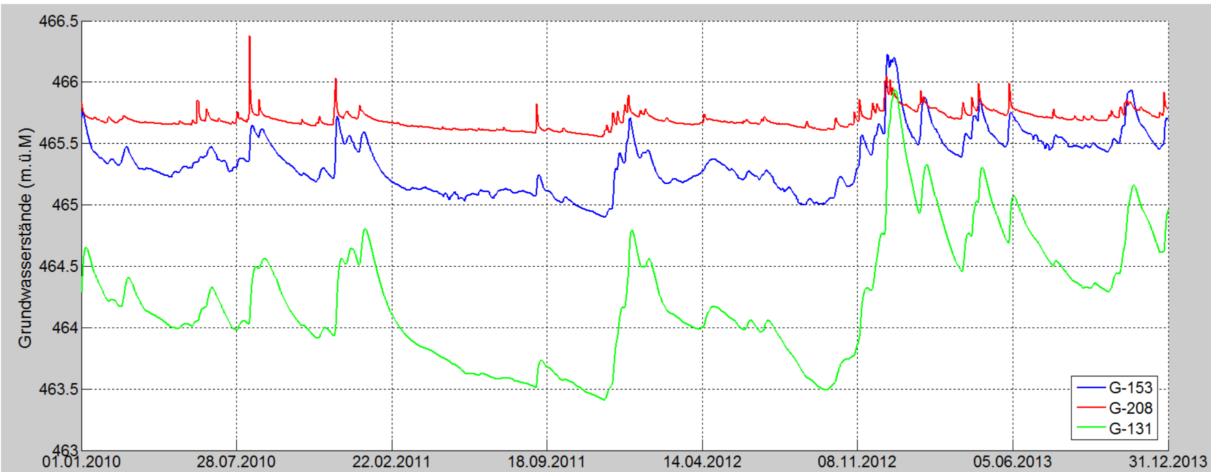

Figure 3. Monitored groundwater levels at piezometers at the southern boundary of the model. A transient prescribed head boundary condition is interpolated at the nodes in between.

The location of the 34 pumping wells in the area is displayed in Fig 5. 9 wells are monitored daily. The quality of the monitored records is high. Available measurements are also handled by QGis and Excel databases.

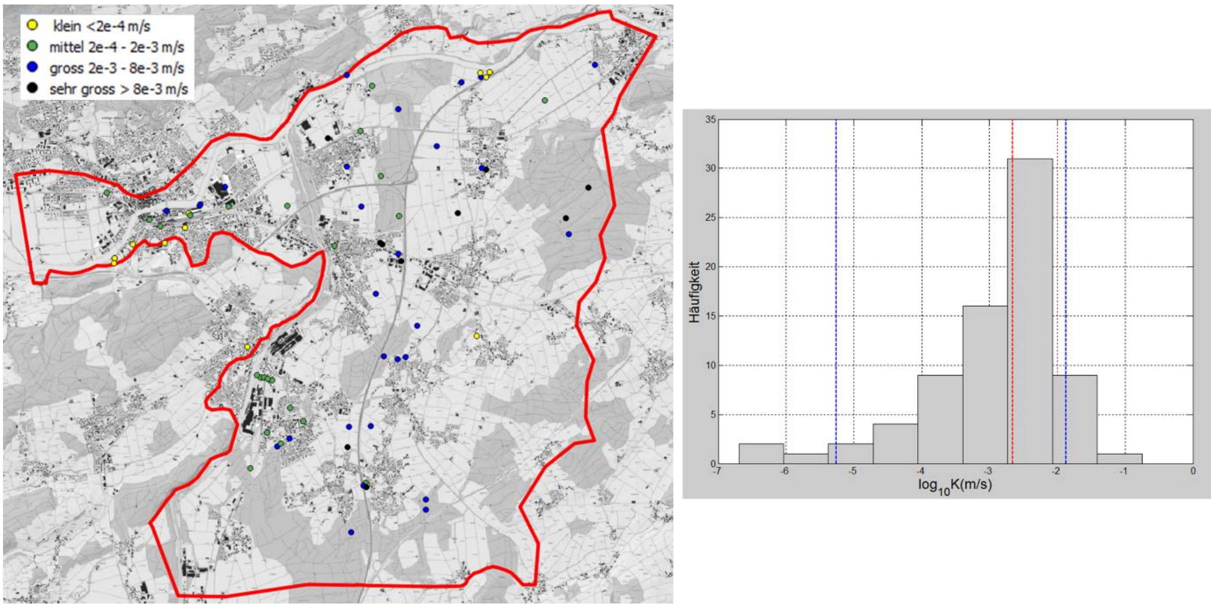

Figure 4. Location of available K estimates (left) and histogram of log10K values. Blue lines represent the 5 and 95% quantiles ($10^{-5.3}$ and $10^{-1.9}$ m/s respectively), whereas the red line depicts the mean value ($10^{-2.6}$ m/s).

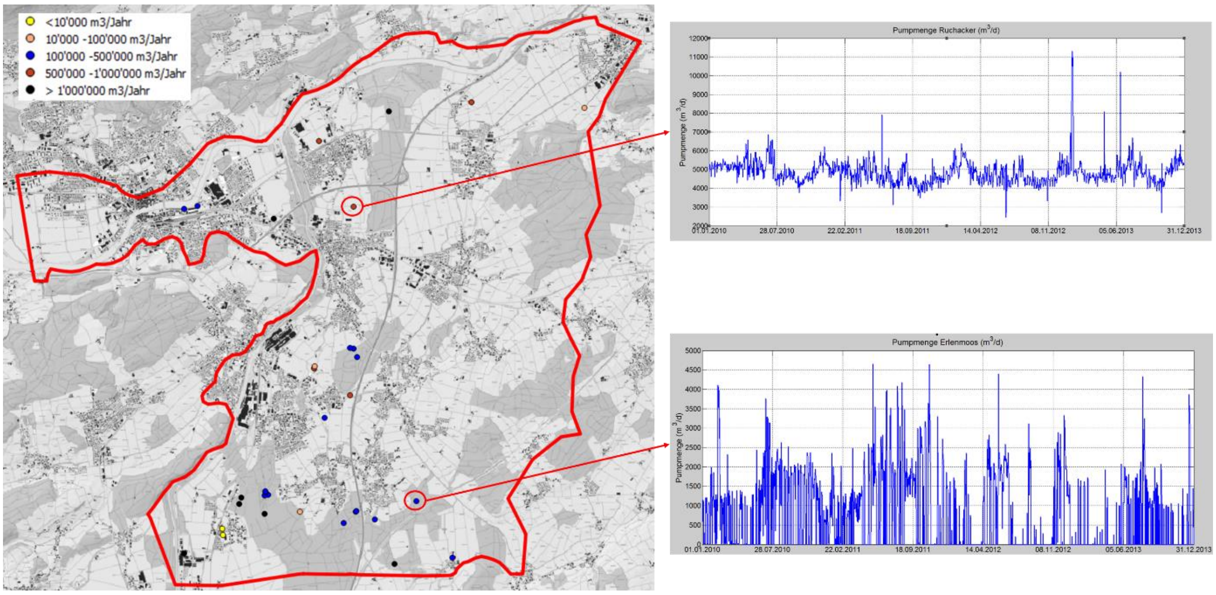

Figure 5. Location of pumping wells (left) and monitored pumping rates at PW Ruchacker (upper right panel) and PW Erlenmoos (lower right panel).

Groundwater recharge

Groundwater recharge is calculated from potential evapotranspiration by water mass balance. Evapotranspiration is calculated by Thornwaite method using rainfall and temperature data from the meteorological station in Koppigen. The model domain is discretized by 6 zones delineated according to soil uses, etc. Groundwater recharge in the period 2010-2013 is depicted in Figure 6.

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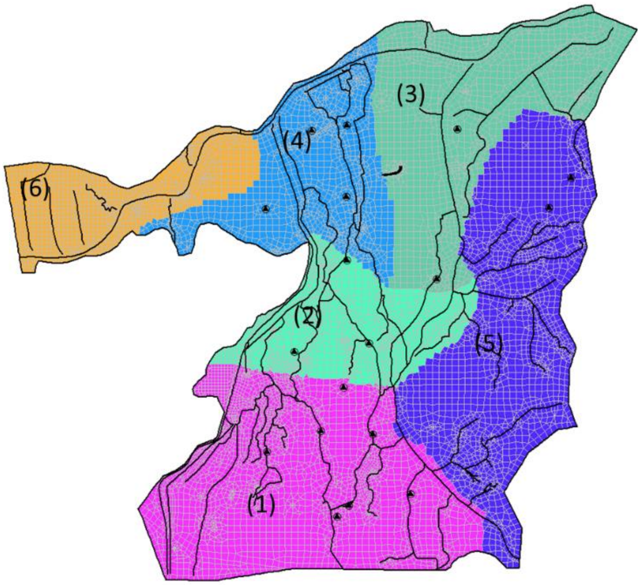

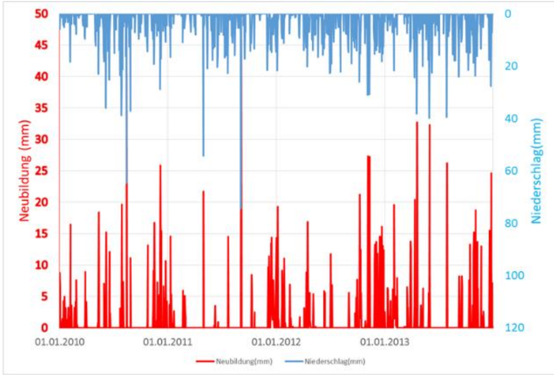

Zone	Mittel (Tage)	Verzögerung (Tage)
Süden (1)	3	0
Mitte (2)	5	5
Nordosten (3)	3	3
Nordwesten (4)	9	5
Ost (5)	30	20
West (6)	8	4

Figure 6. Left panel: zones of groundwater recharge. Upper right panel: Temporal evolution of recharge (red curve, left vertical axis) and rainfall (blue curve, right vertical axis). Lower right panel: smoothing parameters used in the evaluation of temporally distributed recharge (Mittel means the number of days over which a rainfall episode is distributed, whereas Verzögerung means the time shit, the travel time of water from the surface to the water table).

Transient water elevation at Aare and Emme Rivers

Rivers exchange water with aquifers. Depending on local conditions, e.g., topography, they can infiltrate or exfiltrate water, thus becoming a source or a sink of groundwater respectively. These inflows/outflows are not steady because they depend, amongst others, on weather seasonal conditions. Thus, transient models of the water elevation at rivers are a necessary input to groundwater flow models. In this work, the availability of geometrical data defining the river courses allowed us to calculate transient water elevations at Aare and Emme rivers. The software to that end is Basement, developed by the Laboratory for hydraulic engineering, hydrology and Glaciology of the ETH in Zürich. BASEMENT resolves the 1D / 2D surface water equations using the finite volumes method.

The morphology of the Aare in the study area is well defined by 271 cross-sections (**Error! Reference source not found.**). An important feature in this model is the presence of the regulated conditions, e.g., a weir or a gate has a certain height depending on the water level or the flow rate elsewhere. In this case, the height of the weirs in Flumenthal and Bannwil are regulated according to the water flux downstream and upstream respectively.

Boundary condition upstream is the flux measured in Wehrport (Figure 7). Boundary condition downstream is the controlled weir in Bannwil. A source term at the junction with the Emme River is inserted into the model. This corresponds to the flux coming from the Emme, as measured in Wiler (Limpachmündung). Main outputs are the transient water elevations along the river course. Screenshots at selected times are presented in Figure 8. As observed, water levels at the Aare River do not depend much on the weather season or on the peaks of high flow rate (only at its upstream part and right after the Flumenthal weir).

The morphology of the Emme River in the study area is well defined by 60 cross-sections (Figure 9). No regulated conditions are present in this model. Upstream boundary condition is the measured flow rate in Wiler (Limpachmündung), whereas the downstream boundary condition is the water table at the Aare River. Figure 10 displays screenshots at selected times. As occurred with the Aare River, water levels at the Emme are not too sensitive to weather season or to the peaks of high flow rate. Animations of the water levels at both the Emme and Aare rivers are presented separately.

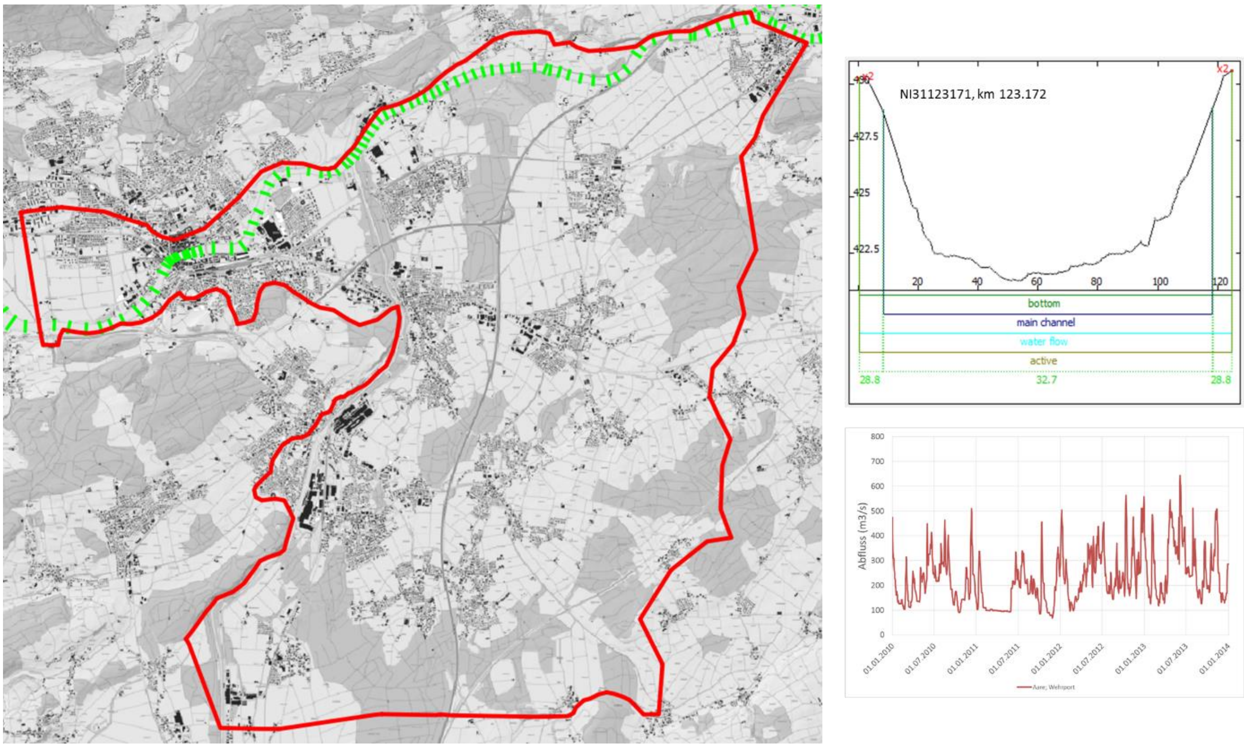

Figure 7. Left panel: Cross sections at Aare River (green lines). Upper right panel: example of a cross section. Lower right panel: inflow measured in Wehrport, used as upstream boundary condition.

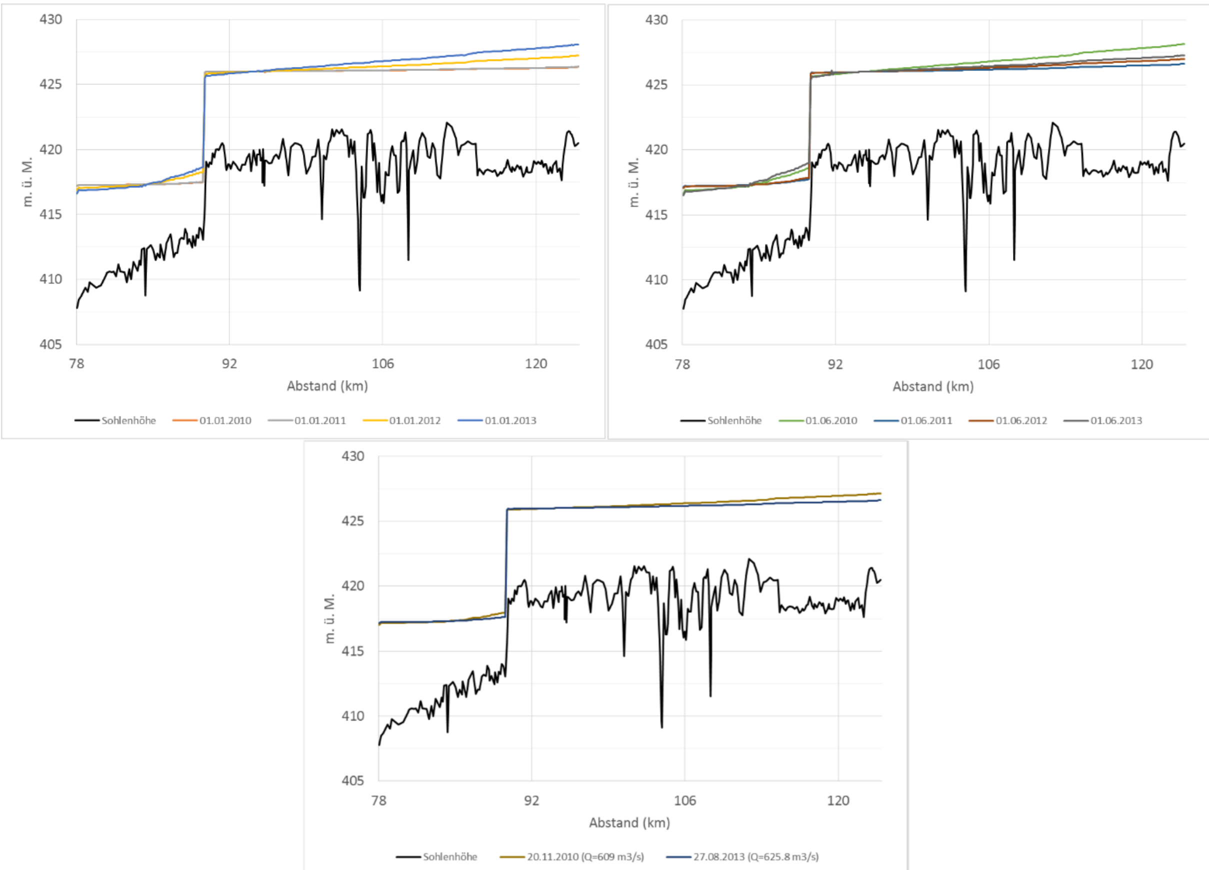

Figure 8. Water levels at Aare River at selected dates. Upper left: 1st of January. Upper right: 1st of June. Lower panel: water table at high water episodes in 2010 and 2013.

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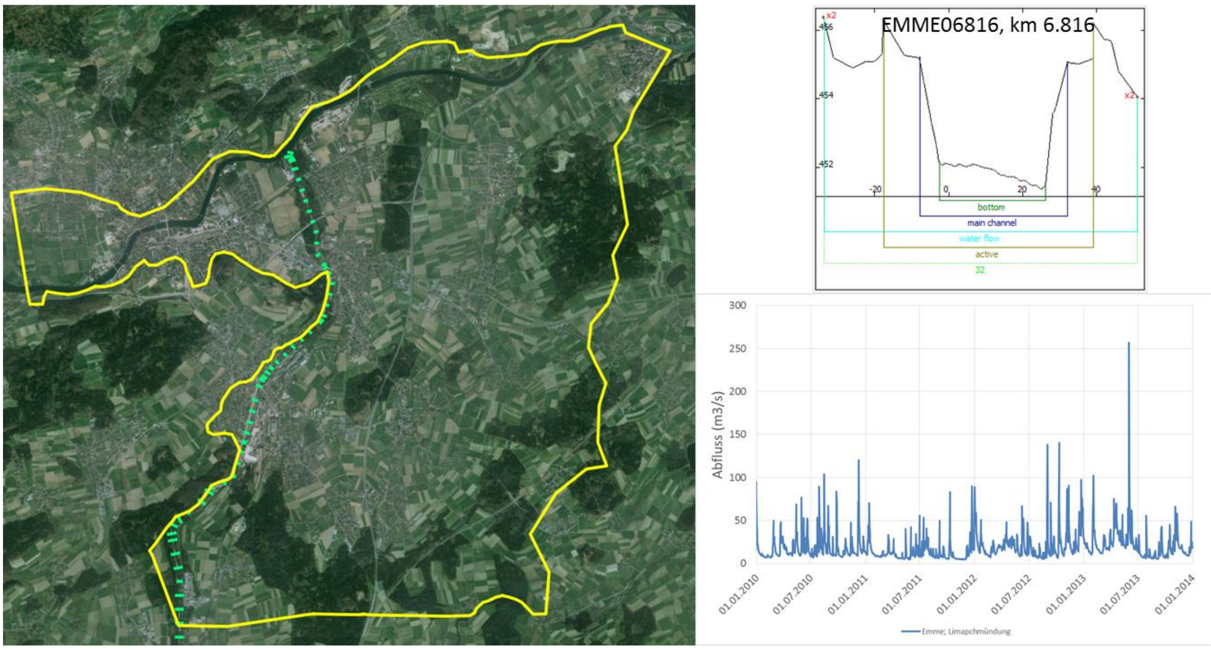

Figure 9. Left panel: Cross sections at Emme River (green lines). Upper right panel: example of a cross section. Lower right panel: inflow measured in Wiler (Limpachmündung), used as upstream boundary condition.

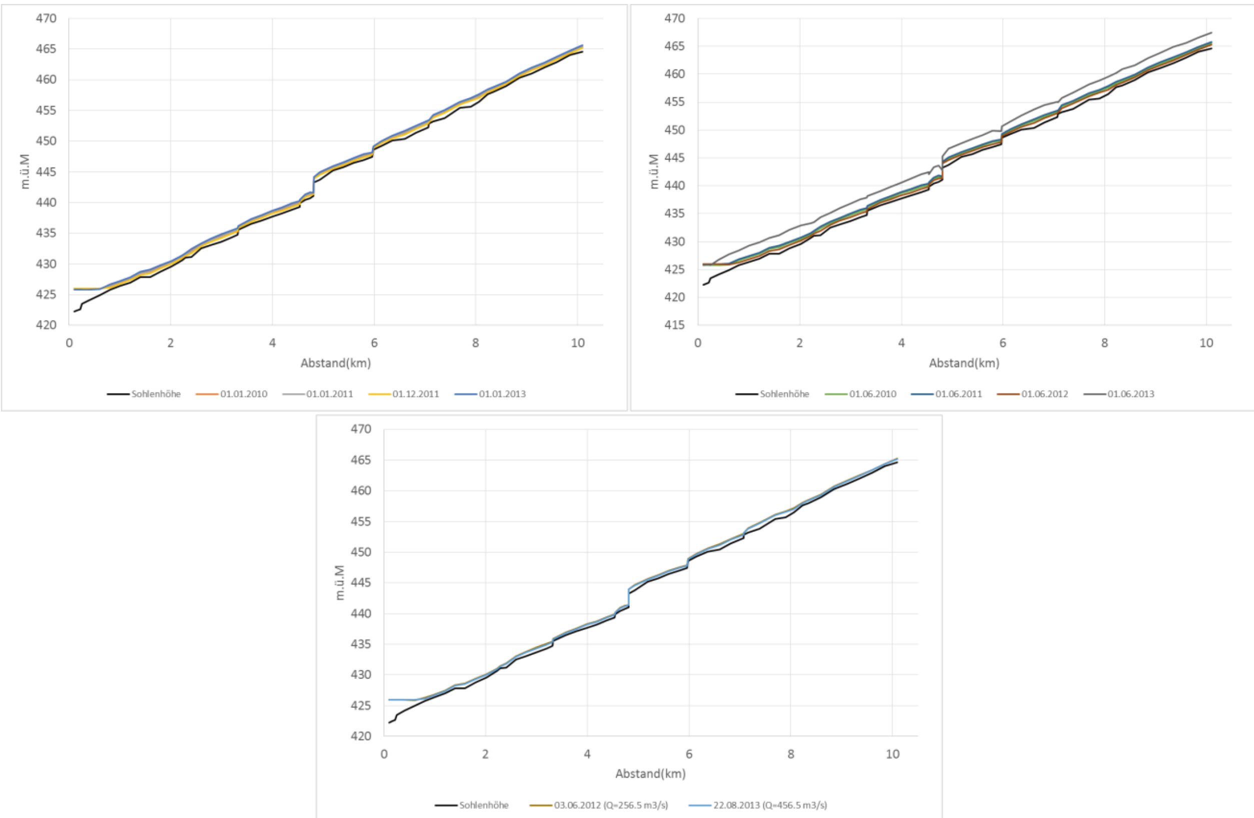

Figure 10. Water levels at Emme River at selected dates. Upper left: 1st of January. Upper right: 1st of June. Lower panel: water table at high water episodes in 2012 and 2013.

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The finite element mesh

The mesh of the previous model has been enhanced to accommodate new wells, observation boreholes, a new water channel and to extend the model slightly to the west. The new mesh is displayed in Figure 11.

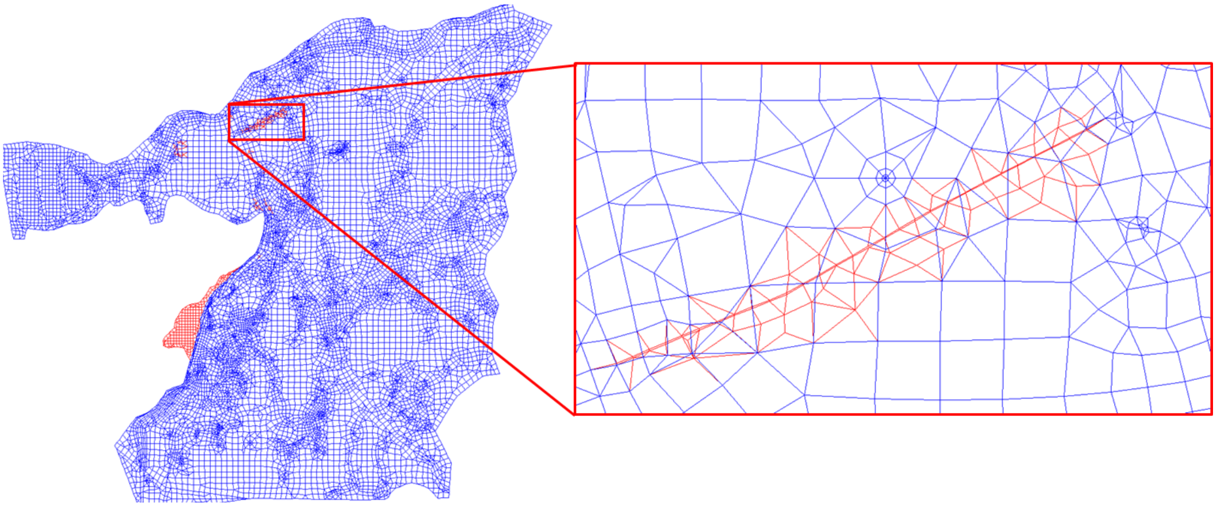

Figure 11. Enhancements on the mesh (in light red).On the inset, mesh refinement including the channel at the vicinity of PW XI.

Model calibration and validation

This section presents the results of model calibration and validation. Hydraulic parameters are calibrated to best fit the available measurements described above. Hydraulic parameters do not vary much with time. Therefore, a subset of available data corresponding to 2012 is used only for the calibration. Remaining data (periods 2010-2011 and 2013) are used for the validation of the model. That is, these periods are simulated using the calibrated parameters (that theoretically fit well only the data of 2012). If the calculated heads at the validation periods 2010-2011 and 2013 is good enough, is a good sign of the goodness of the model.

The mean residual of misfits of head measurements is displayed in Figure 12. The model is properly calibrated, since the mean residual is 0 and the lower and upper quartiles (5% and 95%) are smaller than ±50cm. Actually, the only points outside the inter-quartile range are those with one single measurement (termed 'BP' before), taken right after the drilling operations and possibly disturbed by the presence of drilling fluids in the borehole. Head fits at selected boreholes is displayed in Figure 13. As observed, the fit during the calibration period (greyed vertical strip) is almost perfect in most cases and, as expected, slightly degrades at the validation periods of 2010-2011 and 2013 because those measurements were not taken into account for the calibration of model parameters. At some points, there is a large misfit at early times caused by the uncertainties in the initial condition applied to the model. The fact that the fit during validation periods is good confirms the goodness of the model.

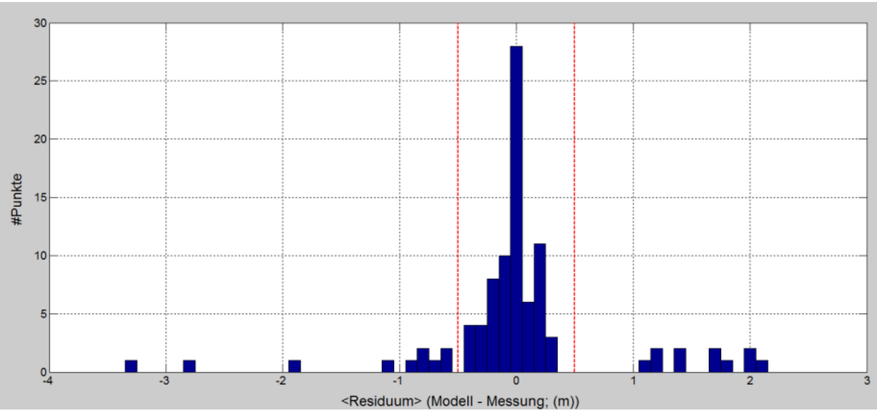

Figure 12. Histogram of model residuals, i.e., calculated minus measured values. The vertical axis depicts the number of monitored boreholes/wells with a given residual. The vertical blue line depicts the mean residual, whereas vertical red lines depict the 5 and 95% quartiles.

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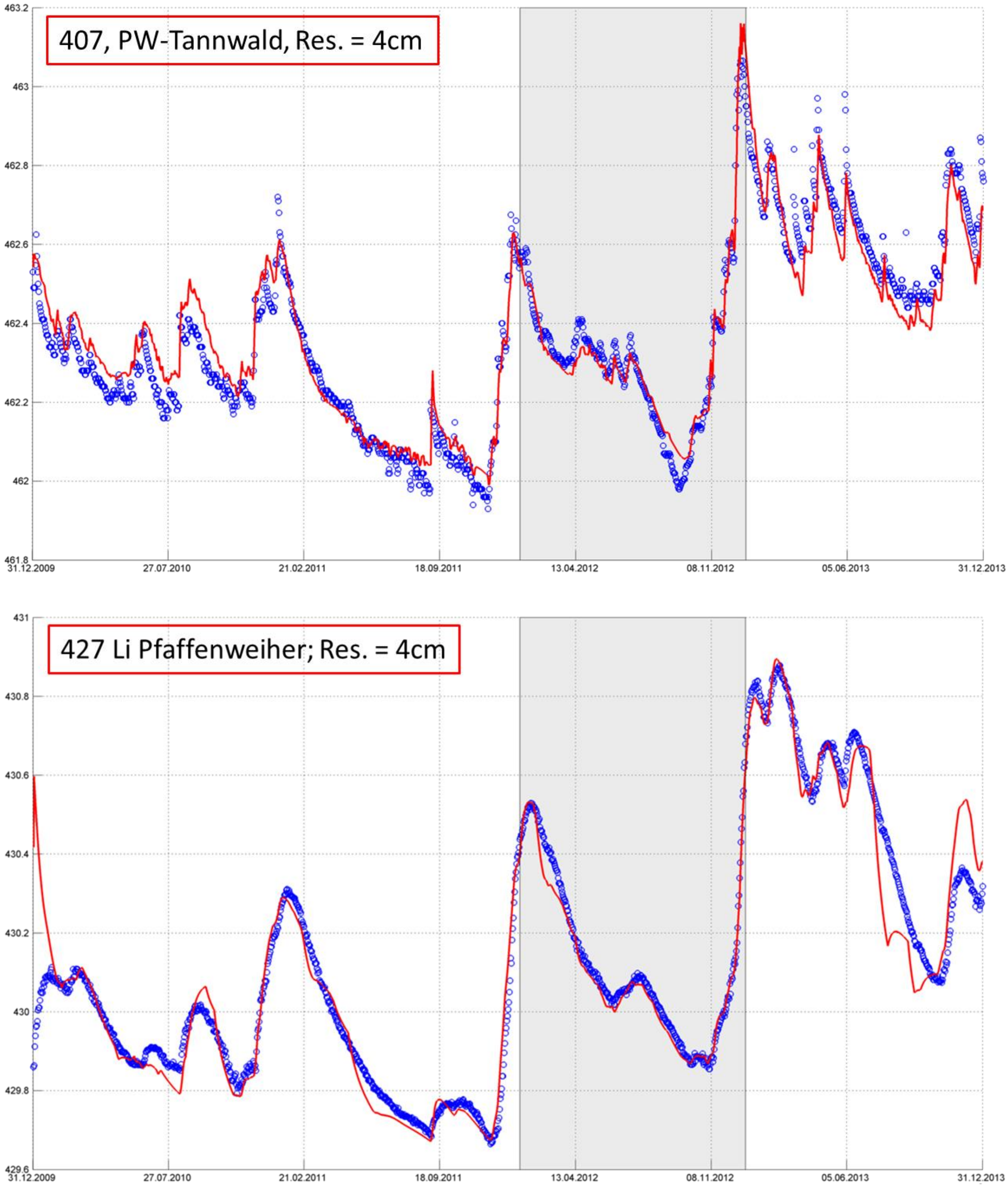

Figure 13.Head fits at PW-Tannwald and Li-Pfaffenweiher. The vertical grayed strip corresponds to the calibration period (2012). The remaining periods 2010-2011 and 2013 are used for validation purposes. Inset: mean residual in the period 2010-2013.

A model must fit not only measurements of the state variable (heads in this case), but also the parameters leading to the best fit of those measurements must be plausible (in the sense of reasonable). That is, if the aquifer is made of sand or of clay, then the estimated hydraulic conductivities must be those of a sand of or a clay. The pilot points method, as implemented in PEST, allows the incorporation of prior information of model parameters. This information usually arises from the prior interpretation of pumping tests. Available estimates of hydraulic conductivity have been described before. These estimates are incorporated into the calibration process. Note that the final calibrated parameters do not need to honour available estimates. Yet, they should not deviate much from them, provided that the quality of the prior information is good enough.

Figure 14 displays the histogram of calculated and a priori estimated hydraulic conductivities, whereas Figure 15 displays the ones of leakage coefficients controlling the amount of in/exfiltration at water courses. As observed in Figure 14, calculated hydraulic conductivities are sometimes larger than the corresponding prior estimates. In fact, the mean of the calculated values is half an order of magnitude higher than the one of the prior estimates. Yet, the calculated values are still reasonable. The upper tail of high conductivity values K>1 m/s (or logK > 0) can be explained by the fact that the pilot points are mostly located at well locations, where hydraulic gradients are high due to the pumping. Another possible explanation is that the pumping tests out of which prior estimates are obtained are of short duration and therefore do capture information of the closest vicinity of the well, typically affected by the mud cake caused by the drilling fluids. On the contrary, calibrated leakage coefficients (Figure 15) are quite similar to the prior information and no outliers leading to very high or low infiltration/exfiltration are observed.

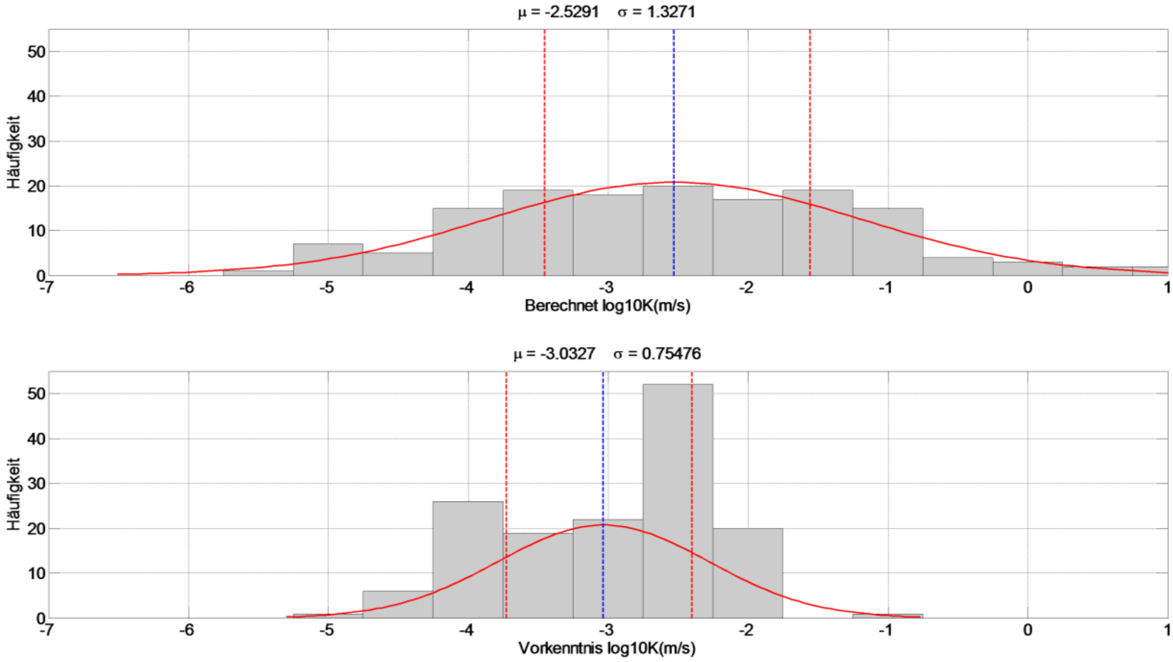

Figure 14. Histogram of the log10 transformation of hydraulic conductivities. Upper panel: calibrated values. Lower panel: prior information.

Future work

Once the model is calibrated and validated, it can be utilized to forecast impacts on the aquifer, e.g., drawdowns caused by new pumping wells. It can also be used to model the catchment areas of drinking-water wells and the corresponding protection perimeters (Figure 16).

The model can also be utilized for the design of an optimum monitoring network based upon geostatistical information. Such network would yield a maximum amount of useful information at a minimum cost. In the same line of arguments, the model can also be used to simulate thermal use of groundwater, contamination episodes, soil remediation systems, etc.

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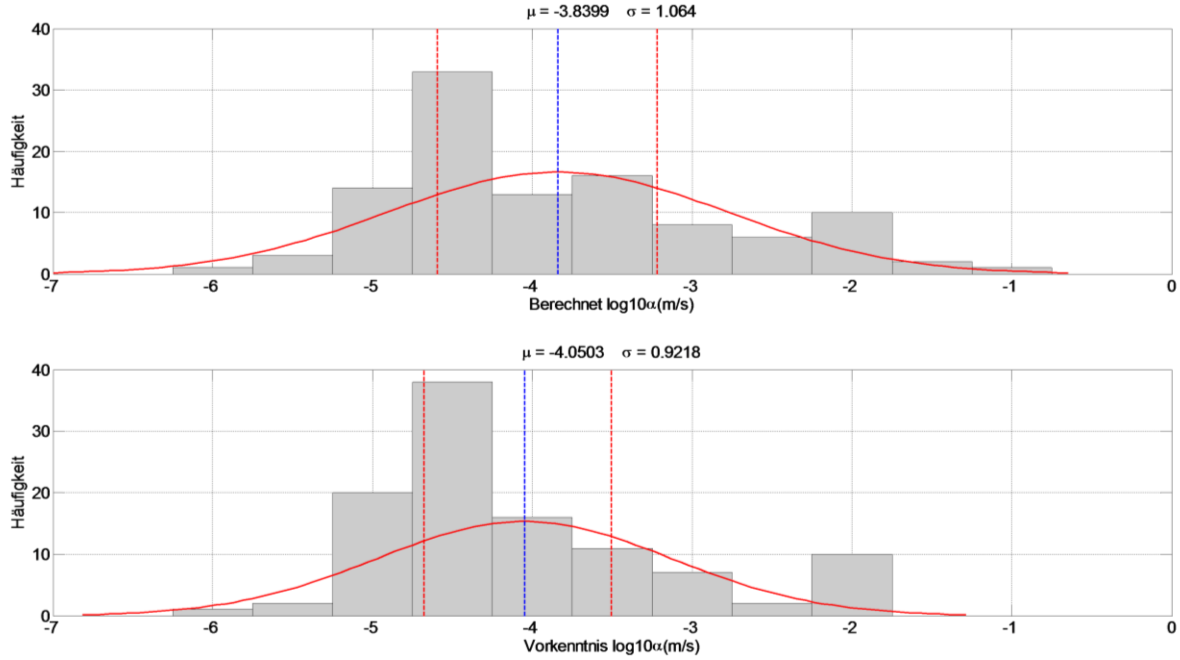

Figure 15. Histogram of the log10 transformation of leakage coefficient. Upper panel: calibrated values. Lower panel: prior information.

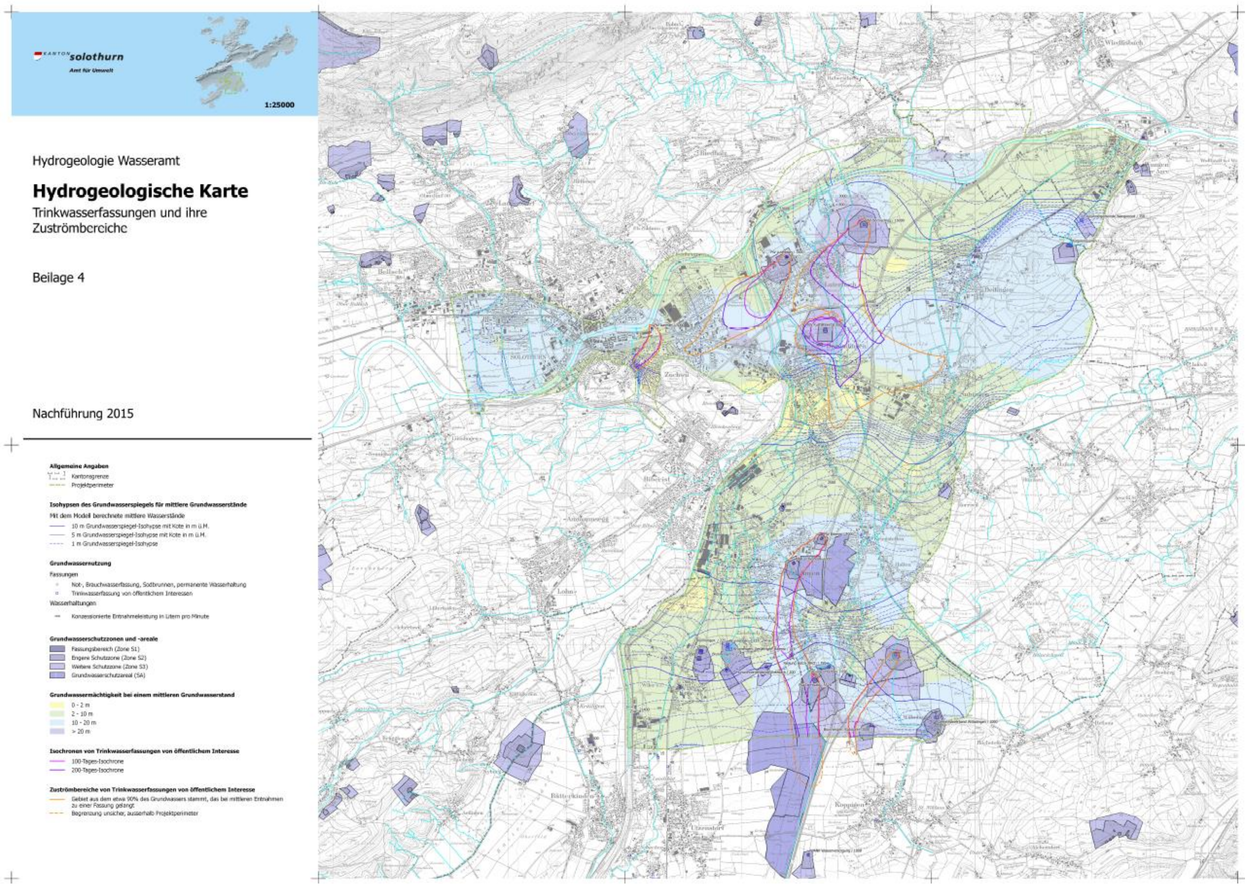

Figure 16. Catchment areas of groundwater wells.