International Conference on Hydroinformatics

2014

Application Of Numerical Modelling For Conceptualizing Abstraction Rate Control In A Well Field Under Complex Boundary Conditions

Sebastian Handl

Ernest Mayr

Tobias Gauster

Reinhard Perfler

11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

APPLICATION OF NUMERICAL MODELLING FOR CONCEPTUALIZING ABSTRACTION RATE CONTROL IN A WELL FIELD UNDER COMPLEX BOUNDARY CONDITIONS

SEBASTIAN HANDL (1), ERNEST MAYR (1),TOBIAS GAUSTER (1), REINHARD PERFLER (1)
(1): University of Natural Resources and Life Sciences, Muthgasse 18, 1190 Vienna, Austria

The objective of this paper is a concept for regulating water abstraction from a well field which ensures an efficient exploration of river filtrate while complying with defined minimum residence time of inflowing water. Being located on an island between a river and a corresponding channel, the general conditions of the investigated well field are subject to strong seasonal fluctuations. In order to analyse on-site flow conditions, a three dimensional finite difference model was developed, calibrated and validated. The water balances of 23 observed steady state conditions with different abstraction quantities and varying boundary conditions were computed. The calculated inflow rates from the channel were analysed by comparing them with observed hydraulic heads. It was possible to show a high correlation with the ratio of certain hydraulic head gradients. Also a strong interrelation between the quantity of inflowing water and the residence time could be shown by regression analyses. By combining these findings, it was possible to develop a criterion for restricting abstraction quantity from each well according to a minimum water-flow time without the requirement of a cost and time consuming, parallel operated numerical model. The underlying parameters are computed from hydraulic head values enabling automatic real time control of a non-measurable value through measurable parameters.

INTRODUCTION

The investigated well field is located on a 200m wide artificial island between a river and the corresponding channel and is equipped with over one hundred gauges to observe hydraulic heads. Eight radial collector wells are aligned parallel to the river flow direction and are capable to abstract up to 500m³/s of riverbank filtrate in total. Under normal circumstances (no flood) the water level of the channel lies about 4m below the rivers water level. The infiltrating water from the river follows this gradient naturally. Due to regulation by law a hydraulic residence time of 60 days must be abided for water originating from the channel.
Riverbank filtration (RBF) describes the infiltration of surface water into the groundwater by means of a hydraulic head gradient. It occurs naturally but also can be enhanced by abstraction of groundwater near a surface water. Hiscock and Grischek [1] identify riverbank filtration (RBF) as one of the major resources for drinking water in Europe and point out, that in Slovakia 50%, in Hungary 45% and in Germany 16% of the total water supply are provided using RBF-sites. Caldwell [2] presented data form eleven RBF-sites in Europe and the USA and identified

the three key parameters influencing the yield of a site as (a) water temperature in the river and the aquifer, (b) transmissivity and (c) length of riverbank impacted. Hiscock and Grischek [1] mention the clogging effect on the riverbed, which lowers the hydraulic conductivity in certain layers as another key aspect. Schubert [2] and Blaschke et al. [4] investigated this colmation process and report that it can´t be considered as a constant factor as it is strongly depending on dynamic variables especially due to flood events.

The interaction between the aquifer and the river is very sensible to parameters that are not only difficult to determine but also vary with time. The goal of developing an abstraction rate control for the well field could be met by designing and continuously operating a numerical model that covers the whole aquifer and its interaction with the surface water. Such a strategy might lead to very accurate results but seems both time and cost consuming, while the results of this paper present another approach. A 3D finite difference model of the well field was designed, calibrated, validated and used to analyse the flow conditions (waterbudgets and residence times) during 23 closely observed steady state conditions that represent the natural range of the basic conditions. The comparisons of hydraulic head gradients in the transects through each well with the computed inflow rates and residence times show strong correlations. With these findings it was possible to develop a concept for the abstraction rate control depending only on hydraulic head gradients that can be easily computed from automatically measured hydraulic heads along each transect.

3D Finite Difference Model

Due to the high density of gauges on site that also provided measurements of hydraulic heads in the groundwater in direct proximity to the river as well as the channel and the before mentioned complex process of RBF an exclusive groundwater 3d finite difference model was built using the simulation software PMwin (Processing Modflow). The groundwater gauges closest to the surface waters state the boundary conditions of the model.

A major challenge was modelling the radial collector wells (RCW). The RCW consist of a vertical cylindrical caisson connected to the aquifer only by horizontal lateral arms. The groundwater enters the well in the seepage section of the laterals and flows into the abstraction caisson. Nemeček [5] identifies the radial collector well built by Ranney around 1930 in London as the first application of this system. The benefits of this system are smaller drawdowns and higher capacities. The hydraulic flow conditions in RCW are complex and difficult to simulate. Numerous articles such as in Bakker[6], Kelson [7] or Chen [8] present different approaches to simulate RCW or similar systems. Wang and Zhang [9] as well as Lee et al. [10] apply a concept of simulating the lateral arms as regions with very high hydraulic conductivities and estimate its value from formulations known from pipe-hydraulics and update this value for every timestep. In this study a similar but slightly simplified approach was taken by keeping the before estimated conductivities constant for all simulations.

Unsteady state data from three different pumping tests were used to calibrate and validate the model. The simulated hydraulic heads correlated very well with measured ones (Handl [11]).

Application of the Numerical Model

The main parameters influencing the hydraulic conditions in the well field are: a) colmation of the riverbed, b) groundwater temperature, c) hydraulic gradient between the river and the corresponding channel and d) the abstraction quantity. From a comprehensive database 23 steady state conditions (observed between 2009 and 2013) were selected which cover the scope of the four before mentioned influencing parameters. The selected conditions underwent simulation. Simulation yielded water balances and quantified inflow rates from both sources as well as residence times.

Development of a water abstraction restriction criterion

In order to exclude infiltration from the channel into the well field, the water permit suggests introduction of a so called “hydraulic head criterion”. It states that the hydraulic head in direct proximity to the channel must be at least 0.05m above the waterlevel of the channel.
The objective of developing a new criterion was the assessment of infiltration from the channel. Additionally to find a parameter capable of quantifing the amount and residence time of inflowing water and to define limits for this parameter.
Figure 1 shows a generalized cross-section through the island parallel to the natural groundwater flow direction. The dashed line shows the groundwater table under non pumping conditions. Abstraction lowers the hydraulic head in the well and when abstraction quantity surpasses the inflow capacity of bank filtration water from the channel flows towards the well (groundwater table shown by continuous line). The hydraulic heads in the gauges (GC and GR) near the two surface waters are influenced by all four before mentioned main parameters of the boundary condition. Following a 2-dimensional approach, the hydraulic head gradient between the well and these measuring points indicates the quantity of inflowing water from the two directions. The flow conditions in this system are 3-dimensional. Water originating from the river can bypass the well and flow back to the well before it reaches the channel. Taking this into account the ratio between the two gradients (up- and downstream in the groundwater flow direction from the well) is much more suitable to estimate the inflowing quantities of water from the two sources. The differences in aquifer parameters and geometry make each section of the well field unique as is the correlation between the ratio of the hydraulic head gradients and the quantity of inflowing water.

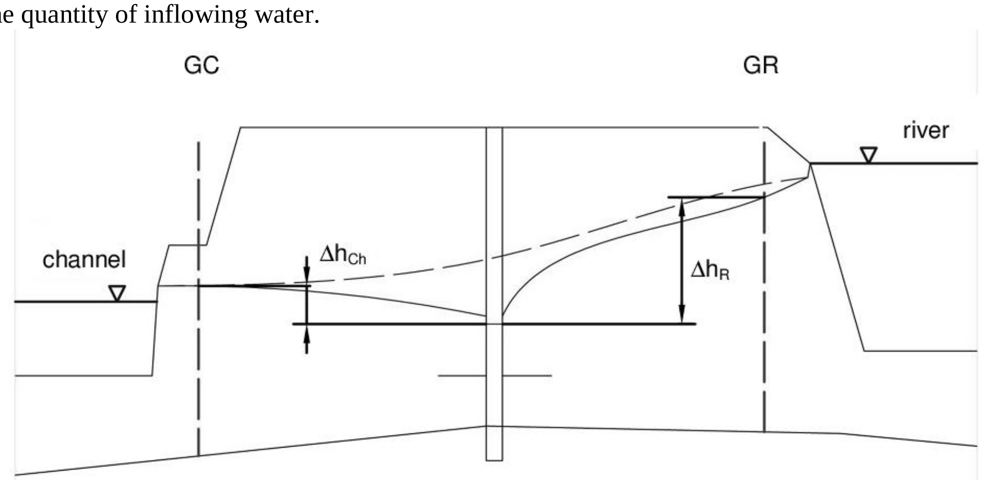

Figure 1 generalized cross-section through the island

For each of the 23 steady state conditions the ratios of the hydraulic head gradients ($R_{\Delta h}$) in all eight transects were calculated and the quantities of inflowing water originating in the channel (Q_{Ch}) to each well were computed. For each transect a linear regression model was fitted to the data and is presented in Figure 2 with observations marked as crosses and models shown in lines. Table 1 shows the coefficients of determination as well as the number of underlying observations for each transect respective model.

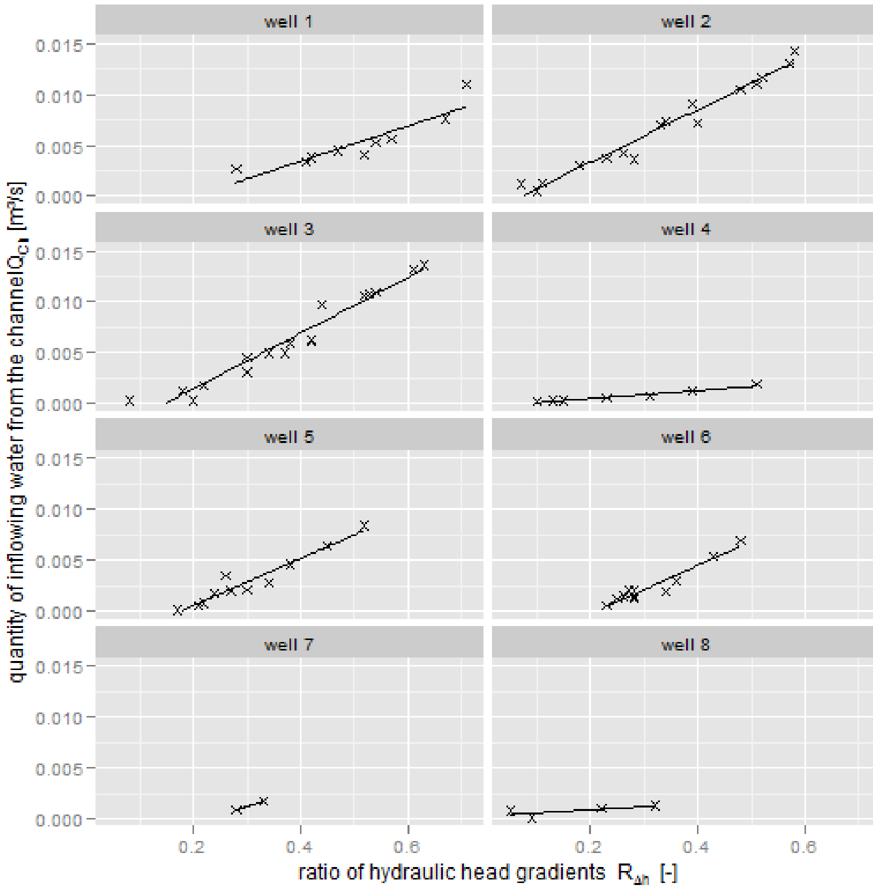

Figure 2 Inflow from the channel as a function of the ratio of the hydraulic head gradients

Table 1 Coefficients of determination and number of observations of the regression models

model	R^2	number of observations
well 1	0,791	9
well 2	0,971	17
well 3	0,957	19
well 4	0,945	7
well 5	0,924	11
well 6	0,915	11
well 7	-	2
well 8	0,655	4

In a further step the sum of inflowing water originating in the channel (ΣQ_{Ch}) over the whole well field was compared with the minimum of the residence time (t_{res}) of these waterpackages.

Figure 3 shows the observations (dots) as well as the adjusted logarithmic function (line).

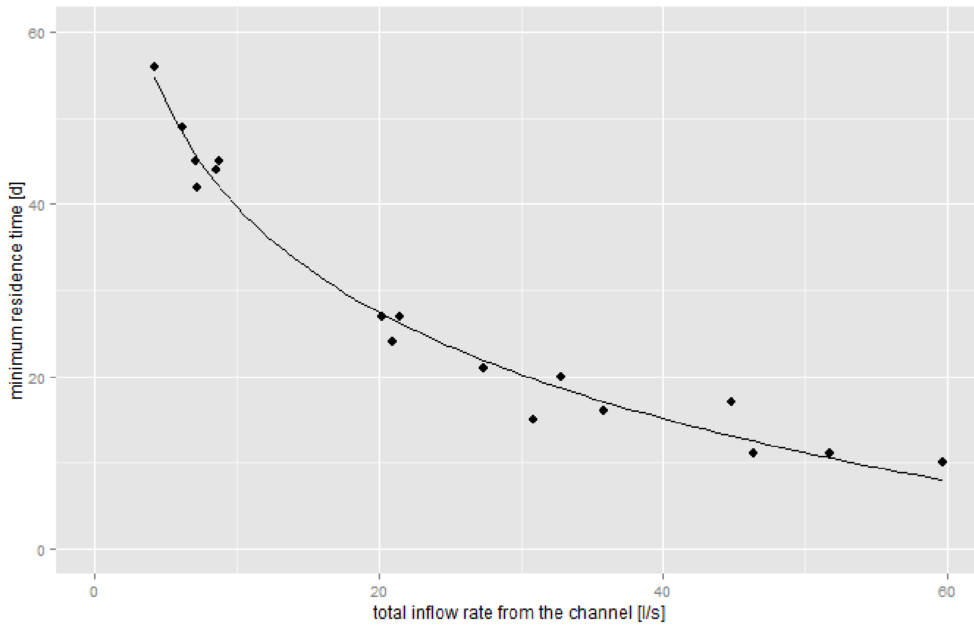

Figure 3 residence time (t_{res}) as a function of total inflow rate (ΣQ_{Ch})from the channel

Discussion and outlook

The coefficients of determination (Table 1) show that the suggested parameter ($R_{\Delta h}$) is adequate for assessment of the quantity of water originating from the channel and reaching the well in the transects of the wells 2 to 6 which represent the main part of the well field. To enhance the fitting of the models for well 1, 7 and 8 more data is necessary.. The coefficient of determination for the regression model linking the total quantity of inflowing water (originating from the channel) (ΣQ_{Ch}) with the minimum residence time (t_{res}) is above 0.9. The equation of this model allows calculation of the maximum allowed quantity of inflowing water ($\max\Sigma Q_{Ch}$) for any minimum residence time (t_{res}). The currently occurring inflow of water from the channel to each well can be estimated properly by measuring the hydraulic heads in the well and in the gauges near the surface waters. This process can easily be automated for operation of the well field. Even a fully automated abstraction rate control system is conceivable and could be integrated into an operational control system.
Besides a closer analysis of the situation in the transects of the wells 1, 7 and 8 validation and testing of the concept in field application would be necessary prior to introduction of the system to regular operation.

REFERENCES

[1] Hiscock K. M.and Grischek T., “Attenuation of groundwater pollution by bank filtration”, *Journal of Hydrology*, Vol. 266 (2002), pp 139-144.

[2] Caldwell T. G., “Presentation of Data for Factors significant to yield from several riverbank filtration systems in the U.S. and Europe”, *Proc. NATO Advanced Research*

Workshop on Riverbank Filtration Hydrology, Bratislava, Slovakia, Vol. 1, (2004), pp 299-344.

[3] Schubert J., "Hydraulic aspects of riverbank filtration—field studies", *Journal of Hydrology*, Vol.266 (2002), pp 145–161.

[4] Blaschke A. P., Steiner K.-H., Schalfuss R., Gutknecht D. and Sengschmitt D., „Clogging Processes in Hyporheic Interstices of an Impounded River, the Danube at Vienna, Austria", *International Review of Hydrobiology*, Vol. 88 (2003), No. 3-4, pp 397-413

[5] Nemeček E. P., „Horizontalfilterbrunnen", *Schriftenreihe zur Wasserwirtschaft TU Graz*, Band 45, Eigenverlag des Instituts für Siedlungswasserwirtschaft und Landschaftswasserbau – TU Graz, (2006).

[6] Bakker M., Kelson V. A. and Luther K. H., "Multilayer Analytic Element Modeling of Radial collector Wells", *Groundwater*, Vol 43 (2005), No. 6, pp 926-934.

[7] Kelson V., "Predicting Collector Well Yields with MODFLOW", *Groundwater*, Vol 50 (2012), No. 6, pp 918-926.

[8] Chen C., Wan J. and Zhan H., "Theoretical and experimental studies of coupled seepage-pipe flow to a horizontal well", Journal of Hydrology, Vol. 281 (2003), pp 159-171.

[9] Lee E., Hyun Y. and Lee K.-K., "Numerical modelling of groundwater flow into a radial collector well with horizontal arms", Geosciences Journal, Vol. 14 (2010), No. 4. pp 403-414.

[10] Wang W. and Zhang G., Numerical simulation of groundwater flow to horizontal seepage wells under a river", *Hydrogeology Journal*, Vol 15 (2007), No. 6, pp 1211-1220.

[11] Handl S., "*Hydraulische Optimierung und Simulation von Qualitätsfragestellungen im Einzugsbereich von Horizontalfilterbrunnen*", Masterthesis, University of Natural Resources and Life Sciences - Vienna (2013)