A comparison study of two different control criteria for the real-time management of urban groundwater works

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ABSTRACT

We present the comparison of two control criteria for the real-time management of a water well field. The criteria were used to simulate the operation of the Hardhof well field in the city of Zurich, Switzerland. This well field is threatened by diffuse pollution in the subsurface of the surrounding city area. The risk of attracting pollutants is higher if the pumping rates in four horizontal wells are increased, and can be reduced by increasing artificial recharge in several recharge basins and infiltration wells or by modifying the artificial recharge distribution. A three-dimensional finite elements flow model was built for the Hardhof site. The first control criterion used hydraulic head differences (Δh-criterion) to control the management of the well field and the second criterion used a path line method (%s-criterion) to control the percentage of inflowing water from the city area. Both control methods adapt the allocation of artificial recharge (AR) for given pumping rates in time. The simulation results show that (1) historical management decisions were less effective compared to the optimal control according to the two different criteria and (2) the distribution of artificial recharge calculated with the two control criteria also differ from each other with the %s-criterion giving better results compared to the Δh-criterion. The recharge management with the %s-criterion requires a smaller amount of water to be recharged. The ratio between average artificial recharge and average abstraction is 1.7 for the Δh-criterion and 1.5 for the %s-criterion. Both criteria were tested online. The methodologies were extended to a real-time control method using the Ensemble Kalman Filter method for assimilating 87 online available groundwater head measurements to update the model in real-time. The results of the operational implementation are also satisfying in regard of a reduced risk of well contamination.

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1. Introduction

This paper presents a real-time control methodology using two different control criteria which has been put into practice for the safe abstraction of drinking water in the city of Zurich, Switzerland. The Hardhof well field delivers 15% of the drinking water demand of the city and serves as one of the main waterworks of the urban water supply net. The growth of residential and industrial areas close to the Hardhof well field over recent decades has led to much higher potential contamination risks in the ground and at the surface. The historic basis for well field management relied on defined well head protection zones to avoid contaminating

activities close to the wells and the additional monitoring of the pumped water quality. Sporadic tracer studies and collections of water samples were used to locate and delineate contamination sources. Meanwhile the HACCP concept (Hazard Analysis and Critical Control Points) (WHO, 2010) was incorporated as a legal obligation in Switzerland (EDI, 2010). It requires all producers of drinking water to guarantee the quality standard of the supplied water at any time. Therefore, the possible inflow of water from parts of the aquifer which may contain sources of contamination must be monitored or controlled in real-time. Online-sensors can be used for the monitoring of aquifers and the operation of wells. These sensors transfer head data, temperature or chemical data, e.g. electrical conductivity in the groundwater and have potential value for the real-time management of well fields. We consider a real-time well field management system as a combination of three technical parts: 1) real-time transferred data, 2) a model that is updated with this

data, and 3) a control algorithm calculating the necessary pumping rates at current time or as a predictive signal for future management decisions. Our current study introduces a control approach which uses path line analysis of particles as control criterion for the real-time management of the Hardhof well field under conditions of temporally variable forcings (natural recharge rates, river stages, boundary conditions and groundwater management).

In a previous study (Bauser et al., 2010) the real-time control of the Hardhof well field aimed at reducing the inflow of potentially contaminated water from the city centre to the well field by using hydraulic head differences (between the area of the well field and an area closer to the contamination sources) as control criterion (Δh-criterion). Although the results of offline-simulations and online-application in the field were satisfactory, the focus on particle paths directly addresses the problem of contaminated water that could reach the drinking water wells. The criterion on the basis of particle paths, hereinafter referred to as %s-criterion, can also address 3D particle paths, whereas the Δh-criterion is in essence a two dimensional measure. Water from polluted areas could still be attracted from deeper layers in the aquifer. This was the main motivation to proceed with control simulations on the basis of the %s-criterion in this study. The method of path lines is used in many instances for groundwater resources management, for example for the estimation of capture zones of operating and planned wells (e.g. Barlow, 1994; Bayer et al., 2004; Mulligan and Ahlfeld, 2007), and for the estimation of contaminant travel times (e.g. Shafer, 1987; Zheng et al., 1988). The EU-funded W-SAHaRA-Project (Stochastic Analysis of Well Head Protection and Risk Assessment) analyzed delineation methods for capture zones (e.g. Stauffer et al., 2005; van Leeuwen et al., 2000). If it is assumed that contaminants do not undergo chemical reactions or decay and do not disperse or diffuse, the contaminant transport problem is reduced to one of delineating the flow pattern (O'Neill, 1990). Contaminant spreading by dispersion and diffusion could be accounted for by randomly dispersing the contaminant "particles" as they move through the aquifer (e.g. Phillips and Gelhar, 1978; Prickett et al., 1981), which is not considered in our study. Several publications (e.g. Katsafirakis et al., 2009; Varljen and Shafer, 1993)

show the coupling of particle path line models with optimization methodologies to comply with management tasks, such as optimisation of pumping schedules for well fields threatened by contaminated aquifer parts, or optimization of remediation processes (Bayer et al., 2004). Path line analysis has also been used for the management of artificial recharge for better protection of groundwater resources from salt water intrusion in coastal aquifers (Shammas, 2008). Another recent study (Tiwary et al., 2005) deals with path line modelling for the assessment of ion migration from a mine into the groundwater in order to judge the degradation of groundwater quality. The effect of sewage water or other contaminants on groundwater resources in urban areas has also been analyzed with the use of path lines (e.g. Pokrajac, 1999; Subba Rao and Gurunadha Rao, 1999).

None of the cited studies used the path line method for an optimal real-time management or real-time control of a well field. Our control method can be of interest for cases involving well fields that are close to non-remediated, potential contamination sources in the subsurface or well fields that are threatened by sewage water from leaking pipes. An important difference with the mentioned studies is that the management in this study is optimized again for each time step. The path line analysis is used in our approach to calculate percentages of path lines which originate from the potentially contaminated part of the aquifer. The percentages are then used as control input for the optimal control of the well field (%s-criterion). The results of the optimal control using the percentage criterion are compared to results of control with the Δh-criterion. The following sections present the well field case study, the methodology, the obtained results, and finally the discussion and conclusion.

2. Study area

The Hardhof well field is situated in the Limmat valley in Zurich, Switzerland and is close to an old industrial zone with waste disposal sites containing inorganic and organic material, which could contaminate the abstraction wells. Fig. 1 shows a map of the well field. The site comprises four horizontal wells (HW A, B, C, and D), 19
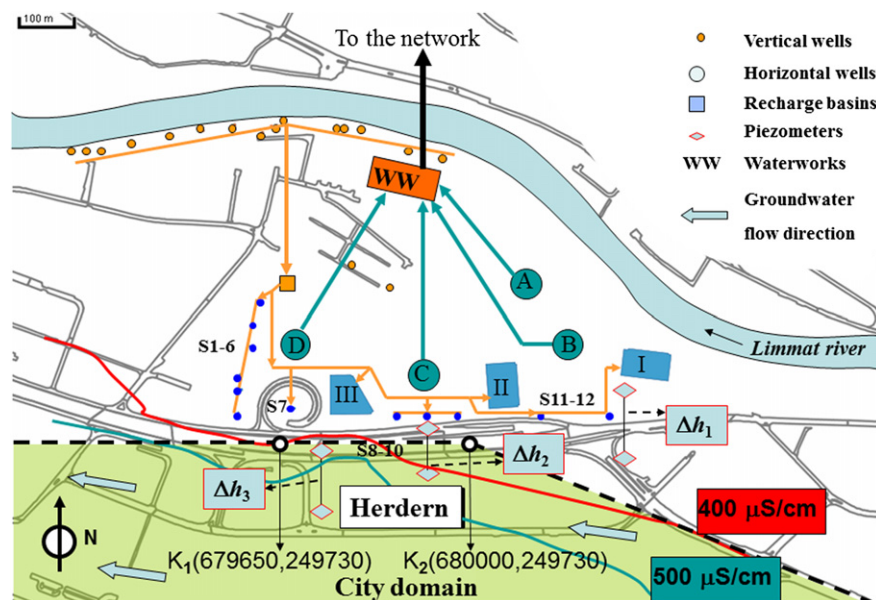

Fig. 1. Scheme of Hardhof well field in Zurich (Switzerland). Four horizontal wells A, B, C and D abstract the daily amounts of drinking water. River bank filtration water is pumped in vertical wells diverted to four groups of infiltration wells S1-6, S7, S8-10, and S11-12 and the recharge basins I–III. The artificial recharge creates a hydraulic barrier protecting the well field. Map of isolines of mean values of electrical conductivity (EC) in the Hardhof area. The EC isoline of 400 µS/cm South of basin II and III is chosen to define the boundary between city water (CW) and non-city water. After Bauser et al. (2010).