A combined groundwater and pipe network model for well-field management

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ABSTRACT

Numerical modeling of groundwater well-fields can be used to analyze different operation strategies to provide more cost-effective water withdrawal and pump scheduling schemes while at the same time minimizing the adverse impacts. An integrated, dynamically coupled hydrological and hydraulic well-field modeling system is introduced for modeling the flow of water in the aquifer, through the wells and pipe system to the waterworks. The model combines a groundwater model (MIKE SHE), a well model (based on the Multi-node well model in MODFLOW) and a pipe network model (EPANET). Results from a preliminary application of the model to a well-field test site are presented.

INTRODUCTION

Groundwater management involves a number of often conflicting objectives, such as to maximize reliability of water distribution, minimize operation and maintenance costs of water abstraction and distribution, minimize environmental impacts, and minimize the risk of contamination of groundwater aquifers and well-fields. Optimization is widely recognized as a key element in water resources management. In this regard, model-based predictive control and optimization that combines simulation models with numerical optimization procedures has shown to be effective. Recent applications that focus on groundwater well-field design problems and optimization of pump scheduling include Fowler et al. (2004) and Barán et al. (2005).

In an ongoing research project real-time optimization and adaptive control of groundwater management at well-fields is considered (Madsen et al., 2007). This project involves development of a well-field modeling system for simulation of the water flow at the well-field, from the aquifer through the wells and pipe systems to the waterworks. This model forms the core of the optimization and real-time control system for well-field operation. The optimization and control system will be linked to an on-line monitoring system for measuring different state variables at the well-field, which will be used for real-time assimilation and updating of the well-field simulation model to adapt to dynamic changes in the system.

In this paper the developed well-field simulation model is described and preliminary applications of the model are presented.

WELL FIELD MODEL

An integrated, dynamically coupled hydrological and hydraulic well-field modeling system has been developed that combines a groundwater model, a well model and a pipe network model. The model suite allows a detailed simulation of water flow at the well field, which is characterized by the pumping, pump characteristics, flow and pressure in the pipe network and drawdown in the aquifer. The development is based on a generic shell which allows coupling of different numerical engines using the OpenMI standardized modeling interface (Gregersen et al, 2007). In the present version, the shell combines the MIKE SHE hydrological modeling system (Graham and Butts, 2006), a well model based on the Multi-Node-Well (MNW) package for MODFLOW (Halford and Hanson, 2002), and the EPANET pipe network model (Rossman, 2000).

A pumping well acts as a source in the pipe network model, and the pumping rate is determined by the head in the well and the head in the pipe network. In the groundwater model a pumping well acts as a sink, and the groundwater head is determined by the pumping rate. The integrated model is solved dynamically at each modeling time step by iteration between the groundwater model (via the well model) and the pipe network model.

The fundamental difficulty in simulating wells in groundwater models is the difference in scale between the dimensions of the well and the dimensions of the groundwater model. In a groundwater model a well is normally simulated as a sink term in a numerical cell. This ensures that the water balance is correct but it does not give a good representation of the water level in the well. Close to a pumping well there may be a steep gradient in hydraulic head, which would require very small numerical cells for the groundwater model to resolve. Thus, a standard groundwater model without mesh refinement cannot be expected to provide a good representation of the head in a pumping well. Another problem occurs when the screened part of the well penetrates multiple numerical cells. In this case the total pumping rate has to be distributed between the cells according to the heads and conductivities of the cells and the head in the well.

The MNW module for MODFLOW was developed to provide a better simulation of the heads in a well and a more realistic way of distributing the flow rates between cells. A MNW is a well that is screened over multiple numerical cells. The total pumping rate from the well is divided into the individual flow rates between the cells and the well

$$Q = Q_1 + Q_2 + ... + Q_n \qquad (1)$$

where Q is the pumping rate from the well, and Q_i is the flow between the i'th cell and the well.
To relate the flow rates to the head in the well, Jacob's well loss equation as modified by Rorabaugh is used. This equation describes the steady-state drawdown in a well as a function of the flow rate. The drawdown is a linear function of the flow rate where the coefficient describes a head loss in the aquifer and a head loss in the well, typically because of a skin effect. Furthermore, the head loss can be a nonlinear function of the flow rate due to the flow in the well. In the MNW package an equation of this type is set up for all the cells that the well penetrates giving the following system of equations

$$\begin{aligned} h_{well} - h_1 &= A \cdot Q_1 + B \cdot Q_1 + C \cdot Q_1^P \\ h_{well} - h_2 &= A \cdot Q_2 + B \cdot Q_2 + C \cdot Q_2^P \\ &\vdots \\ h_{well} - h_n &= A \cdot Q_n + B \cdot Q_n + C \cdot Q_n^P \end{aligned} \qquad (2)$$

where h_{well} is the head in the well, h_i is the head in the i'th cell, A is the linear aquifer-loss coefficient, B is the linear well-loss coefficient, C is the nonlinear well-loss coefficient, P is the power of the nonlinear discharge component of the well-loss, and n is the number of grid blocks that the well penetrates.

Equations (1)-(2) form a system of n + 1 equations with n + 1 unknowns of flow rates between the cells and the well and the head in the well. Because of the non-linear term these equations has to be solved using iteration. A new iteration scheme based on the Newton-Raphson method has been implemented to solve the system of equations. This method has shown to be faster and more robust than the iteration scheme implemented in the MNW package.

APPLICATION EXAMPLE

Sonderso Waterworks, which is located in the Northern part of Zealand, Denmark, is used as test case. The waterworks includes three well fields connected to a common reservoir and produce about 8 million m^3 per year. A total of 21 abstraction wells are included in the system, of which 11 wells are installed with submersible pumps and 10 wells are siphon wells connected in a series with a single pump. The well field model has been setup that includes a detailed model for the pipe network, wells and pumps. A simplified groundwater model that only covers the area with the wells has been used in this test case (see Figure 1).

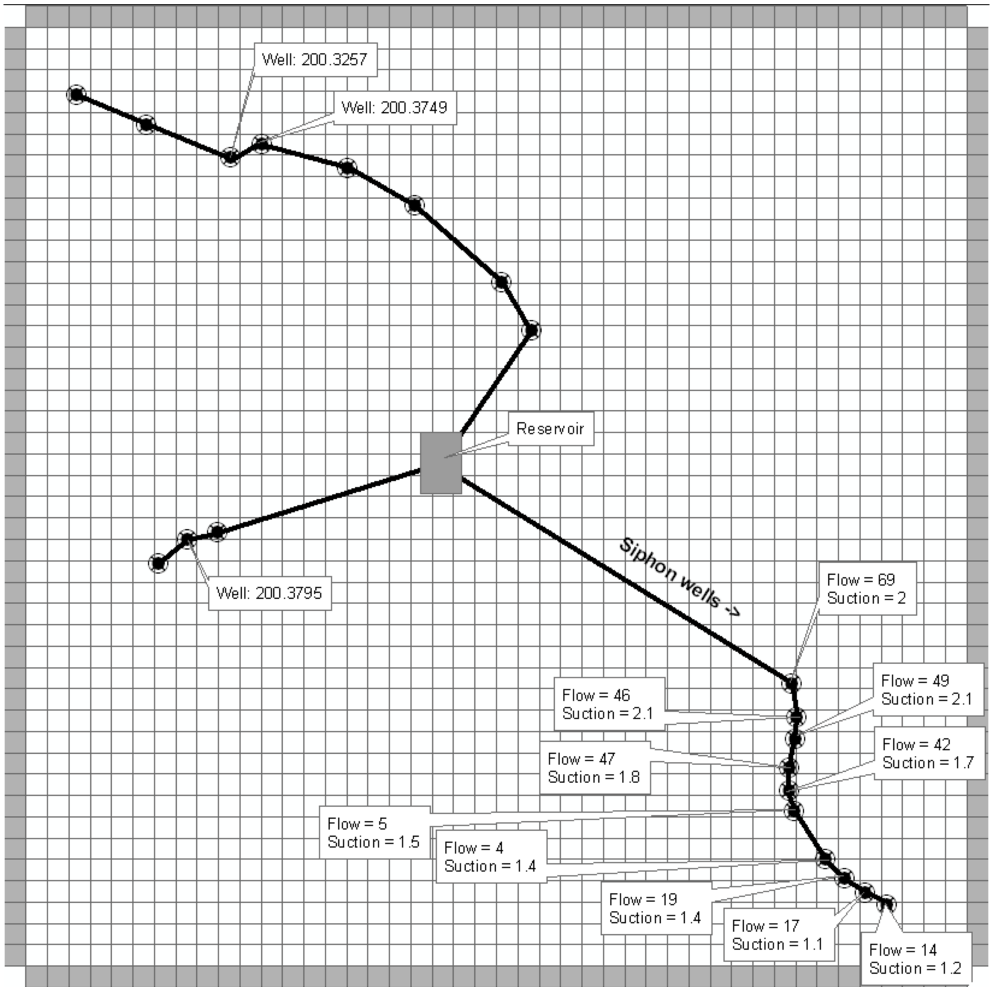

Figure 1. Model setup. Grids represent the cells in the groundwater model, circles represent the wells, and the lines represent the pipes. Data from the pump test on the siphon wells are shown in labels.

A test of the siphon wells has been performed where flow and suction were measured in the individual wells. The pipe network has been calibrated by setting the inflows at the well-nodes in the EPANET setup and running the model decoupled to steady-state. Subsequently, the EPANET model has been connected to the well field model and a joint calibration of the groundwater and well model has been performed. In the calibration a global hydraulic conductivity of the groundwater model and the skin factors of the individual wells were adjusted to match the differences between the wells. Two wells were significantly different with a much smaller flow than the other wells. This difference has been accounted for by increasing the skin value with a factor of 100 for these two wells.

It is currently being considered to renovate the two wells with poor performance. To evaluate the effect of that a model run was performed where the skin factor for these two wells has been set equal to that of the remaining wells. This results in a 400 % increase in flow from these two wells. However, the total flow from all the wells only increases by 0.1%, because the flows from the other wells are reduced correspondingly. This reduction occurs because the wells lower the groundwater table, thereby affecting the wells nearby. The effect on the energy consumption is also negligible (energy consumption is here calculated by using a constant efficiency rate of the pump of 0.75). Interestingly, the flow from the well farthest away from the pumping station actually increases in this model run, illustrating how unexpected a coupled system may react.

A similar analysis was performed for one of the wells with a submersible pump installed. All other pumps were turned off and two simulations were run where the skin factor was 10 and 0.1, respectively. Selected results are shown in Table 1. With the high skin factor the head in the well is 1 m lower than with the low skin factor. Consequently, more energy is required to pump the water. The total flow rate and the head in the aquifer are not significantly affected and therefore these changes will not influence the other wells. Assuming that the skin factor of a well can be reduced by a factor 100 by renovation these results can then be used to compare the reduction in energy costs with the costs of well renovation for a decision maker.

Skin factor	Head in well [m]	Head in aquifer [m]	Flow rate [m^3/hour]	Energy [kW]
0.1	9.05	9.56	79.3	2.39
10	8.00	9.57	78.1	2.64

Table 1. Steady state results of simulation with one well using different skin factors.

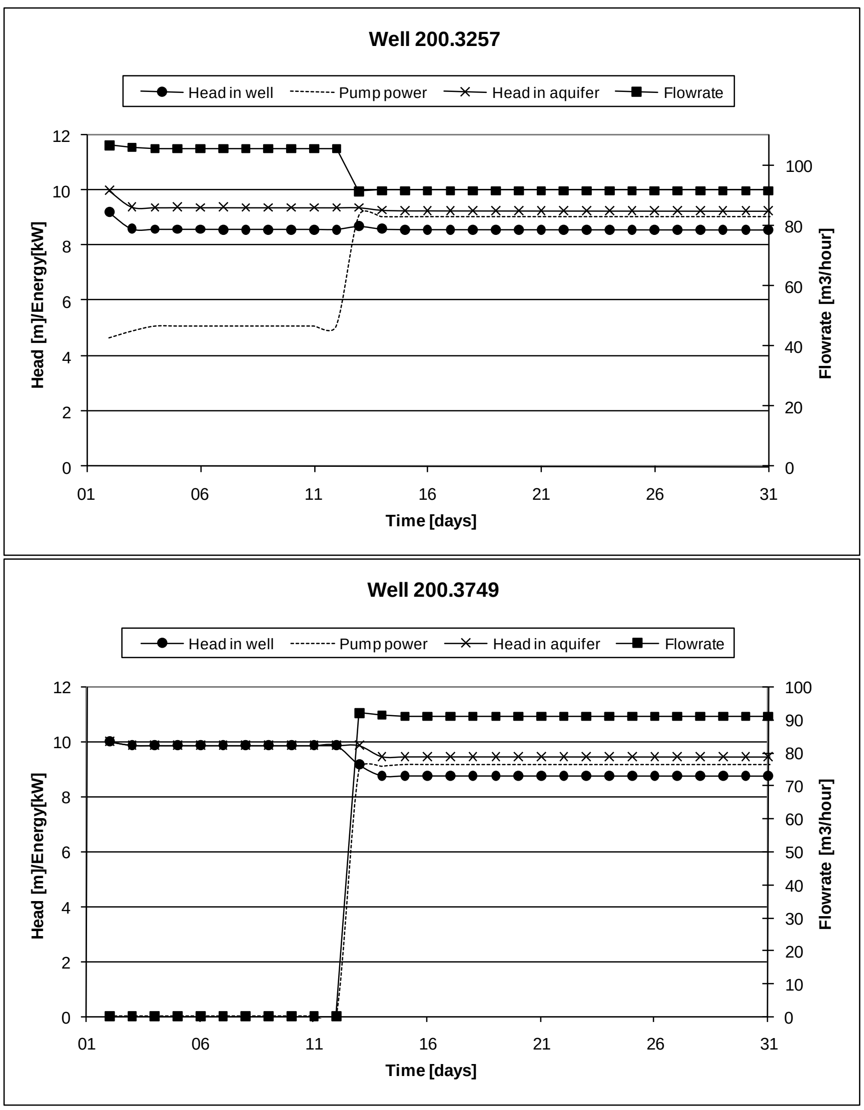

Figure 2. Simulation results for two wells.

Another simulation was performed for the wells with submersible pumps where only 5 of the pumps were active for the first 10 days, followed by 20 days where all 11 pumps were active. Figure 2 show the results for two of the wells. Well 200.3813 is active for the entire period with a flow rate close to 100 m^3/hour. The head in the aquifer is slightly higher than the head in the well. Well 200.3782 is inactive for the first 10 days. In this period the head decreases slightly due to the pumping in the nearby wells. There is no difference between the head in the well and the head in the aquifer. When pumping starts, the head decreases and, as expected, there is a drawdown in the well. When pumping starts in all wells, the flow rate decreases slightly in 200.3813. However, the energy used to maintain this flow is almost doubled. The primary cause of this is not the decrease of the water level in the aquifer but the increase of pressure in the pipe network due to the increase in flow.

CONCLUDING REMARKS

To simulate different operation strategies for pump scheduling and water withdrawal at well-fields an integrated, dynamically coupled hydrological and hydraulic modeling system has been developed. The well-field model is based on a generic shell that combines a groundwater model, a well model and a pipe network model. To simulate the drawdown near the well in more details a well model based on the MNW package from MODFLOW with an improved iteration scheme has been included in the shell. Presently the well field model includes the MIKE SHE hydrological model and the EPANET pipe network model. The paper has illustrated the potential of the developed modeling system on a well-field test case for analyzing different pumping schedules and investigating the effect of pump renovation. The results of the model can be used to optimize the operation of existing or new well-fields by minimizing operation and maintenance costs conditioned on different constraints such as system reliability and environmental impacts.

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