Estimating mine inflow rates real time using analytical methods

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Abstract Accurately measuring mine inflow rates can sometimes be a difficult task. In the absence of being able to accurately measure mine inflow rates, pressures in the source aquifer, in conjunction with groundwater flow models, can be used to predict inflow rates. Numerical groundwater flow models are more robust than analytical groundwater flow models but require more time to set up and run. In some situations, it is desirable to have models that quickly predict mine inflow rates on a frequent to real-time basis. A spreadsheet application was developed coupling an analytical solution and numerical solver.

Key Words mine inflows, modeling, groundwater, mine seepage, mine dewatering, analytical model

Introduction

Many mines are considered "wet" and have inflow of water to some degree. Often, the inflow is only considered a nuisance and does not threaten the longevity of the mine or pose significant economic cost to control. However, in cases where significant water inflow is an issue, it is important to understand the volume of water entering the mine for designing pumping systems to ensure the mine does not flood. It is also important to track inflow rates when grouting is aimed at reducing inflow to provide a grouting success diagnostic. Moreover, when conditions are deteriorating, it is equally as important to understand magnitude and duration of inflow rate increases.

Measuring inflow rates for the purposes listed above may be simple and trivial in many mines. But sometimes, it is difficult to accurately measure mine inflow rates because (1) mine inflow occurs in abandoned workings where actual inflow point is not accessible or (2) geometry of inflow and/or mine workings (e.g., drips or trickles over large spans of workings) make it difficult to accurately measure. The aquifer supplying the fluid is obviously impacted with respect to its pressure because of the mine water inflow. The impact to the aquifer's pressure regime can be used in conjunction with groundwater flow models to predict mine inflow rates. Numerical flow models are able to simulate complex hydrogeology conditions but can be time and computationally intensive to set up and solve. At times, it is desirable to predict inflow rates as close to real time as possible for rapidly changing inflow conditions. This type of modeling is most easily achieved through analytical flow models.

A spreadsheet application was developed coupling the Theis (1935) analytical solution to a numeric solver to estimate mine water inflow rates. This application of Theis' analytical solutions is the inverse of how it is conventionally applied. Typically, pumping rates and pressures are known and used to estimate hydraulic properties of an aquifer. In this application, pressures and hydraulic properties are known and used to estimate pumping rates. While these models are simplistic with many built-in assumptions, they are nonetheless powerful and useful for quickly estimating mine inflow rates in real time.

Methods

A method was needed to quickly and frequently estimate mine water inflow changes and as close to real time as possible (i.e., daily). Numerical modeling obviously is superior in many ways but update and run time is a constraint. Estimating inflow rates via numerical models is an iterative process in that it involves perturbing simulated inflow rates, which is an input parameter, to best match predicted pressured changes to those observed. While this is certainly achievable and done with numerical models, it becomes problematic when trying to quickly and frequently estimate inflow rate changes. Because of this, a spreadsheet application incorporating analytical solutions was developed. Because analytical solutions are exact solutions, the calculations are more efficient and quicker than numerical models. Similar to the numerical models, the input parameter flow rate is perturbed to match predicted and observed pressures (i.e., water head). In the application, the flow rate perturbation to best match predicted to observed heads was automated.

The Theis (1935) solution is an industry-standard transient analytical solution for radial flow to a well. Inherent to any analytical solution is its assumptions. The Theis solution assumptions includes (1) aquifer is perfectly confined, infinite, homogeneous, isotropic, and constant thickness; (2) full or partial well screen; (3) no delay in release of stored water; (4) wellbore storage is negligible; and (5) constant pumping rate. This analytical solution uses the well function, W(u), which is an exponential integration of where r is radial distance, S is storativity, T is transmissivity, and t is time. Predicted drawdown is then a product of W(u) and where Q is constant flow rate. Because drawdown is an additive property, superposition can be used to effectively handle variable pumping rates.

The Theis (1935) solution under the condition of a constant flow rate is a relatively straightforward calculation. It becomes more of an "accounting" problem when nonconstant pumping rates and superposition are invoked. With superposition, all incremental pumping rate changes must be accounted for. In other words, each change in rate must be tracked in terms of incremental time and rate change, which is then used to predict drawdown associated with that flow change component using the Theis (1935) solution. Then for a given time, the head change components are summed. Another way to describe this process is essentially simulating a new well for every incremental flow rate change, but the new well location is in exactly the same location.

Inputs into the spreadsheet application are hydraulic properties of transmissivity and storativity, radial distance to the observation well, and observed head changes at given radial distance. The application was developed such that a specified number of flow changes occur over a given time and the number of flow rate changes effectively controls the time step—how often a flow rate is predicted. For example, assuming equidistance time steps and 60 days of data with 256 flow rate changes specified, it would result with a flow rate prediction about every 3 hours.

At the first time step, a numeric solver iteratively perturbs the initial flow rate to a value that results in best predicted to observed head match. The best fit is determined through minimization of residuals between observed and predicted. At this first time step, the incremental change in rate and magnitude also represents the total predicted changes in these parameters. At the second time step, the same process is carried out as in the first time step except superposition is incorporated for this and all future steps with respect to the prediction of total head and flow rate. This process repeats moving forward one step at a time until the last step is reached. The sequential evolution through time of this process is automated in this application. In most instances, smoothing techniques need to be implemented to prevent mathematical artifact oscillations of the predicted flow rate changes. A two-point moving average of the total predicted inflow has been found to perform reasonably well as a smoothing technique.

The spreadsheet application was verified with a synthetic dataset. This synthetic dataset was developed using artificial pumping data, hydraulic properties, and radial distance. Using this data, hydraulic heads were forward simulated with AQTESOLV (HydroSOLVE, Inc. 2006) using the Theis solution. These AQTESOLV forward-predicted heads, in addition to hydraulic properties and radial distance, were input into the spreadsheet application to inversely predict used synthetic pumping rates. Figure 1 shows synthetic forward-modeled Theis heads (thick black line) versus predicted heads from the spreadsheet application (thin gray line). The predicted heads are in excellent agreement with the forward-predicted AQTSOLV heads; however, this is expected because the purpose of the model is to force the match through manipulation of pumping rates.

Synthetic pumping rates are compared with smoothed and nonsmoothed predicted flow rates predicted with the spreadsheet application (Figure 2). The nonsmoothed predicted inflow rates (thick dark gray line) oscillate but do so about the synthetic pumping rate used to develop the heads (black line). Implementing the two-point moving average smoothing technique greatly reduces the oscillations (thin light gray line). Simple linear regression performed on cross plots of synthetic and predicted flow rates resulted in R^2 of 0.93 and 0.99 for nonsmoothed and smoothed predicted flow data, respectively.

Case Study

The Mosaic K2 potash mine has experienced brine inflows since 1985 (VanSambeek 1993). While historically there has always been a base inflow rate since 1985, there have been many transient ups and downs in total inflow rate—the ups when either a new inflow develops or a preexisting inflow increases in rate and the downs when grouting efforts are successful. Inflow changes can

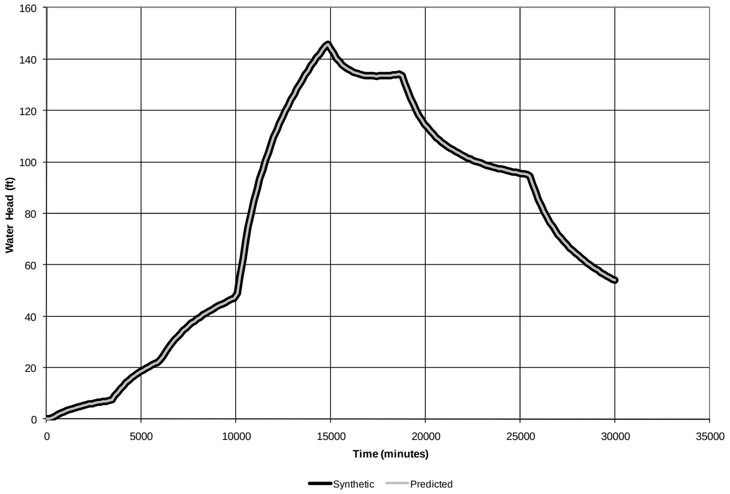

Figure 1 *Synthetic and predicted heads in feet (ft) for verification test*

occur very fast and in both directions (increasing or decreasing). Because of the difficulty accessing or accurately measuring some inflows, direct inflow measurements are not always possible or accurate. In these situations, to monitor either positive or negative flow changes, indirectly monitoring the inflow rate change with aquifer pressures is sometimes the only alternative for estimating flow rate changes. This case study details a spreadsheet application for a Mosaic K2 Potash mine inflow with large flow rate changes and where difficulty existed in getting accurate measurements.

Inflow rate estimates with a high degree of confidence were used to calibrate the spreadsheet application. Figure 3 shows an inflow estimate that was used in calibration (open circle), spreadsheet application predictions (black line), and three inflow estimates that were not used for calibration purposes (open square) but serve to show the spreadsheet application provides a reasonable inflow rate estimate.

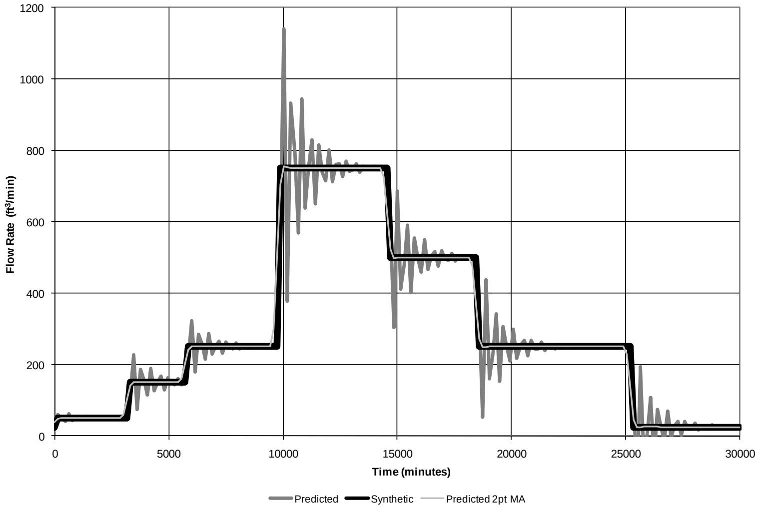

Figure 2 *Synthetic and predicted flow rates in cubic feet per minute (ft^3/min) for verification test*

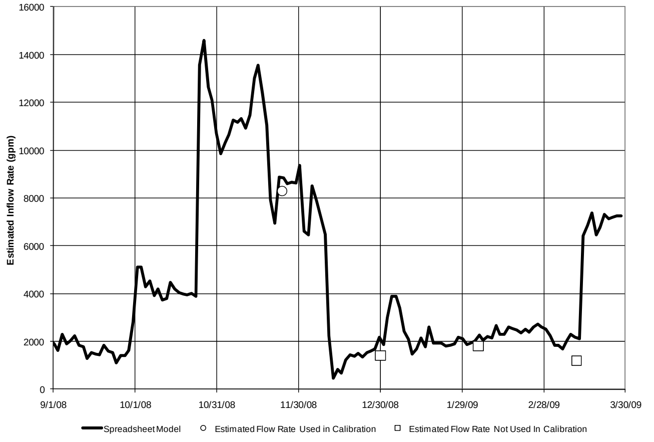

Figure 3 *Spreadsheet application-predicted inflow rates versus measured inflow estimates in gallons per minute for the case study*

Because high-quality estimates are infrequent, this application has been used as a tool for quickly predicting inflow changes. Data are updated and run on a daily basis, resulting in timely mine water inflow rate predictions. Note that the author realizes all assumptions in the analytical solution may not be fully valid, reinforcing the use of this model as a tool and may not reflect reality at all times.

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