The Bank Filtration Simulator – a MATLAB GUI

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Abstract
The Bank Filtration Simulator is a groundwater modelling software that is especially designed for simple bank filtration simulations. The advantage of its user-friendly graphical user interface (GUI) is that it can be applied by users, which are not familiar with the common modelling software, but are interested only in the bank filtration application. The study shows, how MATLAB can be applied to implement specialized tools for specific environmental problems. Two examples of application are given.

Keywords
Bank Filtration, Analytical Solutions, MATLAB, Graphical User Interface

1. Introduction
At many locations in all parts of the world water supply is, at least partially, based on bank filtration systems. In the vicinity of a freshwater body, a river or a lake, water is pumped by a single well or a well gallery and fed into the water supply network. Such systems are not only important from the quantitative point of view (as they prevent groundwater over-exploitation), but also from the qualitative perspective. In many cases they deliver purified water, as the surface water interacts with the porous matrix during the aquifer passage, and various natural attenuation processes occur. In Germany urban areas on all major rivers rely on this technology (e.g., Berlin on the Spree and Havel rivers, Dresden at the Elbe river, Cologne and Mannheim at the Rhine river etc.).

The Bank Filtration Simulator software is designed to assist during the design and operation of such facilities. The program was mainly developed within the NASRI project on 'Natural and Artificial Systems for Recharge and Infiltration', supported by the Berlin Centre of Competence for Water and sponsored by the Berliner Wasserbetriebe and Veolia Water.

The program is designed with a graphical user interface (GUI) that allows user-friendly input of parameters and visual output of results. The details are described below. The program is implemented in MATLAB (2007). It can be used directly from MATLAB, but its main envisaged application is as a stand-alone executable.

The program is designed as a software tool for education, demonstration and a first assessment of conditions and feasibility. It can be used in classes for students and by students themselves in exercises. It is suitable as part of a demonstration task to convince laymen about the feasibility of the bank filtration technology. Last not least it can be used as a first check at a specific site to determine if conditions are appropriate or not for such a technology. The tool may assist the decision maker, who has to compare several

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alternative sites; or the technician in the field as well, who aims to find the optimal position of a well or well gallery.

To use the Bank Filtration Simulator requires less skill, than using a groundwater program – which is the common technique to be applied for such a purpose. For that reason it can be applied not only by groundwater specialists, but also by technicians in the field on a laptop, or by decision makers in non-technical departments of concerned companies.

The description of the Bank Filtration Simulator can be considered as an example of how specialized software tools can be implemented by MATLAB or other comparable packages. The aim is to produce tools for a very specialized field of application, for which more sophisticated modelling software is used in common practical work nowadays. Such specialized tools are of course not competitive with commercial groundwater programs that allow the modelling of a greater number of diverse situations.

2. Differential Equations and Analytical Solutions

The mathematical algorithms within the computations are implemented using analytical solutions based on potential theory. We give a brief outline of the details. Darcy’s Law,

\[ \mathbf{v} = -K \nabla h \]  

(1)

an empirical relationship, is well established for groundwater flow (Holzbecher 1997). Equation (1) states the proportionality between filtration (or Darcy-) velocity \( \mathbf{v} \) and dynamic pressure, here represented by hydraulic head \( h \). The proportionality constant is the material parameter \( K \), the so called hydraulic conductivity.

Two types of aquifers can be distinguished concerning the upper surface of the water bearing pore space, which may be either free or confined by an impermeable layer. The hydrogeologist speaks of an unconfined or phreatic aquifer in the first situation and of a confined aquifer in the second. The principle of mass conservation leads to variants of the continuity equation

\[ \begin{align*}
\nabla H \mathbf{v} &= 0 \quad \text{for} \quad \text{confined situations} \\
\nabla h \mathbf{v} &= 0 \quad \text{for} \quad \text{unconfined situations}
\end{align*} \]

(2)

where \( H \) denotes the aquifer thickness of the confined aquifer. Moreover it should be noted that hydraulic head is measured with respect to the aquifer basis. Equations (1) and (2) can be combined to

\[ \begin{align*}
\nabla H K \nabla h &= 0 \quad \text{for} \quad \text{confined situations} \\
\n\nabla h K \nabla h &= 0 \quad \text{for} \quad \text{unconfined situations}
\end{align*} \]

(3)

Aquifer modeling in 2D is usually based on these differential equations or variants. The differential equation (3) is formulated in terms of hydraulic head. An alternative formulation is based on the hydraulic potential \( \varphi \)

\[ \varphi = \begin{cases} 
K \cdot H \cdot h - \frac{1}{2} K \cdot H^2 + \phi_0 & \text{for} \quad \text{confined situations} \\
\frac{1}{2} K \cdot h^2 + \phi_0 & \text{for} \quad \text{unconfined situations}
\end{cases} \]

(4)

for which the classical potential equation (or Laplace equation) holds

\[ \nabla^2 \varphi = 0, \quad \text{in 2D:} \quad \frac{\partial^2 \varphi(x,y)}{\partial x^2} + \frac{\partial^2 \varphi(x,y)}{\partial y^2} = 0 \]

(5)
The potential \( \phi \) has the physical unit of \( [m^3/s] \). The constant \( \phi_0 \) has to be chosen appropriately. In the BF-Simulator it is chosen to fulfill a point condition. In the implementation we utilize the complex potential \( \Phi = \phi + i\psi \) with imaginary unit \( i \) and streamfunction \( \psi \). Streamline patterns are visualized as contour lines of the streamfunction \( \psi \). For that purpose we identify the model region with a part of the complex plane, represented by the variable \( z=x+iy \) (Holzbecher 2007).

Two solutions of the potential \( \Phi \) are implemented in the Bankfiltration Simulator. The analytic solution for a regional 1D flow field is:

\[
\Phi = Q_0 z
\]

with baseflow discharge vector \( Q_0 \), given by a complex number. The solution for a well with pumping rate \( Q_{\text{well}} \) at the position \( z_{\text{well}} \) is given by:

\[
\Phi = \frac{Q_{\text{well}}}{2\pi} \log(z - z_{\text{well}})
\]

According to the principle of superposition, solutions for generic situations can be summed up as analytical elements, to obtain a solution for a specific situation. In the MATLAB model we take the base flow element (6) and add two or four functions of type (7) for each well. The additional mirror wells have to be considered to fulfill the potential boundary condition at the coordinate axes. The procedure is described in many textbooks on the subject (Strack 1989).

Clogging layer effects can be considered by using the analytical solution of van der Veer (1978) for flow in the vicinity of a semipermeable layer. Although van der Veer is of interest in a completely different set-up (vertical cross-section) and application field, the solution can be adopted to horizontal cross-sections and bank-filtration. For brevity we omit details here.

The use of the analytical solution has several advantages, in comparison to numerical solutions that are given the preference in commercial codes. The solutions, as given in equations (6) and (7) are grid independent. They can thus be computed quickly for the visualization (for which a mesh is needed again). Moreover there is no need to identify a boundary of the model region with specific characteristics in order to define a boundary condition - except for the condition along the straight bank line. The disadvantage of the latter is that a specific boundary can not be considered by the simple code, as it is implemented.

As mentioned above the code is by purpose implemented for the special situation of wells located in the vicinity of a straight bank line and can not be used for other situations. Groundwater modelling codes allow irregular boundaries, general boundary conditions, inhomogeneties, transient effects, and 3D patterns – just to mention a few points.

3. Implementation

The purpose of the software is the evaluation of generic situations of bank filtration facilities. The user has to provide basic characteristics of the aquifer (thickness, hydraulic conductivity, base flow and reference head value at the bank), of the bank (straight horizontal line or straight lines, meeting at an angle of 90°, clogging parameter) and of the well gallery (position and pumping or recharge rates of single wells). The user may also specify the spatial extension of the model region and the grid spacing used for graphical output. Moreover several options concerning the graphical output can be specified: there are options to visualize head contours, streamlines, flow paths and/or velocity arrow fields. The graphical user interface (GUI) of the Bank Filtration Simulator is depicted in Figure 1.

After the specification of input data, computations are initiated by a click on the 'Plot' button. The variables of the flow field are calculated at the grid points and visualized at the graphic panel. Moreover the
share of bank filtrate within the pumped water is calculated and displayed in the corresponding output field.

Fig. 1: Graphical User Interface for the Bank Filtration Simulator

The output for the default settings of the program is shown in Figure 2. The coordinate axis on the left hand side represents the shoreline between surface water body and aquifer. Depicted is the groundwater flow pattern in the aquifer from a top view. Flow paths of bank filtrate (i.e., the water originating from the surface water), entering from the bank boundary on the left side of the panel, leading to the two wells, are traced in red colour. The streamline pattern for the entire model region is depicted by white lines; pristine groundwater is entering from the right.

There are further output options. The distribution of piezometric head in the model region is shown by blue contours and a green-blue fill pattern. Not shown is the field of velocity vectors that also provide an illustrative representation of the flow pattern. Arrows indicate the flow direction. The lengths of the arrows, i.e. velocity vectors, indicate the 'speed' at different locations within the aquifer. Also not shown are travel time markers along the streamlines. These are also speed-indicators: long distances between successive markers show a high velocity, short distances low velocities.

Aside from graphical output, one numerical output value appears on the display: that is the share of bank filtration in pumped water for the specified set-up. That is a crucial parameter for the design of well galleries, as it is most relevant for the mixing of surface water on one side and groundwater on the other side.
A very convenient option for the practitioner is enabled by automatic gridding. Aside from the grid spacing, the spatial extension of the model region can be calculated by the program. As the length of that part of the bank, along which bank filtration occurs, is not known beforehand, it is of great help for the user if that length does not have to be determined by several trial and error runs. For the run shown in Figure 2, that option was enabled, and in the displayed region the range of the vertical axis coincides with the shore part of interest for bank filtration.

4. Application Examples

The NASRI Bank Filtration Simulator was used in two feasibility studies, carried out by UNESCO-IHE, that were aimed at assessing the relevance of river bank filtration at different field sites in Malawi and Kenya (Chaweza 2006 and Bosuben, 2007). Facing water quality issues in surface water and rising water demand in urban areas the studies intended to clarify if river bank filtration would be an option with respect to water availability and water quality.

At five different field sites, data on the hydrogeological setting (depth and geometry of the aquifer, hydraulic conductivities), on water availability (minimum and maximum flow, hydraulic heads) on water quality (surface water and ground water) as well as on the prognostic water demand were collected. In a first step, the well numbers and positions were optimized using the programs MODFLOW setting as a target a minimum travel time of 10 days and a maximum draw down of 10 m. The developed setting was
then introduced to the NASRI Bank Filtration Simulator in order to easily calculate the bank filtration share, which was aimed at being as high as possible. Mixing calculations were then carried out in order to forecast the water quality of the pumped raw water, combined with published elimination rates for problematic substances.

The feasibility at the investigated sites was limited by the hydraulic conductivity of the alluvial aquifer, which could not be determined exactly (the $K$-values ranged from $10^{-7}$ m/s to $10^{-4}$ m/s). Therefore three different settings were modelled: maximum, average and minimum hydraulic conductivity. For the minimum hydraulic conductivity the draw down of the wells could not be limited to $< 10$ m for the targeted yield, an application of bank filtration would not seem feasible under these conditions. Maximum and average hydraulic conductivity, however, did show realistic values in all cases.

The NASRI Bank Filtration Simulator was used to optimize the share of bank filtrate by varying well spacing, distance from river and pumping rates. The final water quality prediction showed for all investigated sites that the drinking water standards would probably be met, with exception of flood events, during which a post-treatment might be necessary.

Fig. 3: Sample NASRI BF output display for Eldoret town in Kenya (4 wells, 100 m from bank, 50 m well spacing, hydraulic conductivity $6 \times 10^{-3}$ m/s) (Bosuben, 2007).
5. Discussion

The Bank Filtration Simulator is an example of how MATLAB can be used for computations in applied environmental science and technology. MATLAB ideally combines powerful tools for mathematical calculations, outstanding tools for graphical output, and the ability to put these together in a graphical user interface. One further example would be a software tool for the simulation and exploration of transport, sorption and degradation processes in 1D.

As MATLAB is available at almost all academic institutions nowadays, the programs can be used by students within and in exercises or homework after courses. The MATLAB compiler provides the option, to produce stand-alone versions of the programs, which can be applied by users for which the MATLAB software itself is not available. In that way a much larger user community can be addressed and the programs, installed on laptops, can be taken into the field.

As the application example showed, the NASRI BF Simulator can support feasibility studies for river bank filtration in regions with limited data. For scientific purposes there is, however, some limitation that needs to be mentioned: As it is a 2D model, a possible groundwater flow beneath the river is not included. Many investigations, however, have shown that this is possible at bank filtration sites currently in operation (Massmann et al. 2007). It has to be clear, therefore, that this tool can give a first rough estimate of the feasibility of bank filtration – it can not replace a detailed hydrogeological investigational study.

References

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