Summary

Work package WP 5.2 "Combination of Managed Aquifer Recharge (MAR) and adjusted conventional treatment processes for an Integrated Water Resources Management" within the European Project TECHNEAU ("Technology enabled universal access to safe water") investigates bank filtration (BF) + post-treatment as a MAR technique to provide sustainable and safe drinking water supply to developing and newly industrialised countries. One of the tasks of WP 5.2 is to develop a Decision Support System (DSS) as a first qualitative tool to assess the feasibility of bank filtration for drinking water supply in developing countries.
The Bank Filtration Simulator (BFS), which is the subject of this report, is a sub-model used within the DSS to compute steady-state solutions for a two dimensional groundwater flow field in the horizontal plane for BF settings.
Input parameters are required for aquifer, bank and well characteristics to calculate the BF share analytically. In addition the minimum travel time between bank and well is computed numerically.
The sensitivity analysis yielded that the analytical calculated BF share is the most reliable output parameter, since its value is grid-independent. The most sensitive input parameters for the BF share calculation are the hydraulic conductivity of the aquifer and the clogging parameter, which both are the most uncertain ones to estimate. The accuracy of the numerically computed minimum traveltime of the BFS was cross-checked against a MODFLOW model, which produced only a very small discrepancy below 5%.
Due to the lacking time-dependency of the BFS model its application is only appropriate on a management horizon for which the system's boundary conditions (e.g. baseflow, clogging parameter and pumping rates) do not change significantly over time. In a nutshell it is therefore highly recommended to use the BFS only as a qualitative assessment tool in a first planning step to evaluate the feasibility of BF systems. Nevertheless the qualitative outputs give a valuable physically based insight of the system's behaviour for distinct operational scenarios (e.g. minimal/maximum pumping rates) in order to add transparency and reproducibility to the decision making process.

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TKI Categorisation

Classification									
Supply Chain		Process Chain		Process Chain (cont'd)		Water Quality		Water Quantity (cont'd)	
Source		**Raw water storage**		**Sludge treatment**		**Legislation/regulation**		- Leakage	
- Catchment	X	- Supply reservoir		- Settlement		- Raw water (source)		- Recycle	X
- Groundwater	X	- Bankside storage	X	- Thickening		- Treated water			
- Surface water	X	**Pretreatment**		- Dewatering		**Chemical**			
- Spring water		- Screening		- Disposal		- Organic compounds			
- Storm water		- Microstraining		**Chemical dosing**		- Inorganic compounds			
- Brackish/seawater		**Primary treatment**		- pH adjustment		- Disinfection by-products			
- Wastewater		- Sedimentation		- Coagulant		- Corrosion			
Raw water storage		- Rapid filtration		- Polyelectrolyte		- Scaling			
- Supply reservoir		- Slow sand filtration		- Disinfectant		- Chlorine decay			
- Bankside storage	X	- Bank filtration	X	- Lead/plumbosolvency		**Microbiological**			
Water treatment		- Dune infiltration		**Control/instrumentation**		- Viruses		Consumers / Risk	
- Pretreatment	X	**Secondary treatment**		- Flow		- Parasites			
- Primary treatment	X	- Coagulation/flocculation		- Pressure		- Bacteria		**Trust**	
- Secondary treatment		- Sedimentation		- pH		- Fungi		- In water safety/quality	X
- Sludge treatment		- Filtration		- Chlorine		**Aesthetic**		- In security of supply	X
Treated water storage		- Dissolved air flotation(DAF)		- Dosing		- Hardness / alkalinity		- In suppliers	X
- Service reservoir		- Ion exchange		- Telemetry		- pH		- In regulations and regulators	
Distribution		- Membrane treatment		**Analysis**		- Turbidity		**Willingness-to-pay/acceptance**	
- Pumps		- Adsorption		- Chemical		- Colour		- For safety	X
- Supply pipe / main		- Disinfection		- Microbiological		- Taste		- For improved taste/odour	X
Tap (Customer)		- Dechlorination		- Physical	X	- Odour		- For infrastructure	X
- Supply (service) pipe		**Treated water storage**						- For security of supply	X

Internal plumbing		- Service reservoir				**Water Quantity**		**Risk Communication**	
- Internal storage		**Distribution**						- Communication strategies	
		- Disinfection				**Source**		- Potential pitfalls	
		- Lead/plumbosolvency				- Source management	X	- Proven techniques	X
		- Manganese control				- Alternative source(s)	X		
		- Biofilm control				**Management**			
		Tap (Customer)				- Water balance	X		
		- Point-of-entry (POE)				- Demand/supply trend(s)			
		- Point-of-use (POU)				- Demand reduction			

TKI Categorisation (continued)

Contains		**Constraints**		**Meta data**					
Report	x	Low cost	x	*Michael Rustler, Gesche Grützmacher & Ekkehard Holzbecher*					
Database		Simple technology	x	*KompetenzZentrum Wasser Berlin*					
Spreadsheet		No/low skill requirement	x	*Michael Rustler*					
Model	x	No/low energy requirement	x	*michael.rustler@kompetenz-wasser.de*					
Research	X	No/low chemical requirement	x						
Literature review		No/low sludge production	x						
Trend analysis		Rural location	x						
Case study / demonstration		Developing world location	x						
Financial / organisational									
Methodology	X								
Legislation / regulation									

Techneau,
December 2009

WP5.2:
Combination of MAR and adjusted conventional treatment processes for an Integrated Water Resources Management

Deliverable 5.2.5
Bank Filtration Simulator - Manual

Colophon

Title
Bank Filtration Simulator - Manual

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Deliverable number
D 5.2.5

This report is: PU

Glossary

Ambient groundwater	synonymous with natural, landside-, inland-, background groundwater
Aquifer	underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, silt, or clay) from which groundwater can be extracted, e.g. by pumping wells
Baseflow	specific discharge per width unit; unit: [Length^2/Time]
Catchment area	here: synonymous with subsurface watershed; unit: [Length^2/Time]
Clogging layer	resistance of a bank to infiltrate surface water due to its lower permeability compared to the adjacent aquifer.
Confined/Unconfined	the aquifer is confined if the calculated reference head (=hydraulic head) lies above aquifer thickness, otherwise the aquifer is unconfined
Hydraulic conductivity	volumetric fluid flow rate per unit cross-sectional area for a unit hydraulic gradient at a prescribed temperature; unit: [Length/Time]
Grid extent	range between the minimum and the maximum value on both axes (x and y, respectively); unit: [Length]
Grid spacing	equidistant interval between two grid nodes; unit: [Length]
Groundwater recharge	hydrologic process during which water moves downwards from the land surface through the vadose (unsaturated) zone to the groundwater table; unit: [Length^3/Time]
Head gradient	here: synonymous with hydraulic gradient or hydraulic head gradient

Hydraulic head	here: synonymous with piezometric head, usually measured as a water surface elevation, expressed in units of length, at the entrance (or bottom) of a piezometer; unit: [Length]
Infiltration length	length of the shore, where infiltration takes place; unit: [Length]
Managed Aquifer Recharge (MAR)	umbrella term for ponded infiltration, bank filtration, well injection, aquifer storage (transfer) and recovery
Porosity	percentage of voids (empty space occupied by water and air) in the total volume of rock, which includes both solids and voids
Reference head	here: hydraulic head in the lower left corner of the model region; unit: [Length]
Reference length	here: synonymous with length (see *Figure 7*) of the subsurface catchment (from groundwater divide to drainage basin); only used if the hydrological balance is selected for baseflow calculation; unit: [Length]
Reference thickness	here: synonymous with saturated aquifer thickness, used for baseflow calculation according to Darcy's law; unit: [Length]
Share bank filtrate	portion of the total abstracted groundwater, which originates from a surface water body unit: [%]
Thickness	here: maximum thickness of the aquifer; unit: [Length]

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1 Introduction

Work package WP 5.2 “Combination of Managed Aquifer Recharge (MAR) and adjusted conventional treatment processes for an Integrated Water Resources Management“ within the European Project TECHNEAU (“Technology enabled universal access to safe water”) investigates bank filtration (BF) + post-treatment as an MAR technique to provide sustainable and safe drinking water supply to developing and newly industrialised countries. One task within WP 5.2 is to develop a Decision Support System (DSS) as a first qualitative tool to assess the feasibility of bank filtration for drinking water supply in developing countries.
The Bank Filtration Simulator (BFS), which is the subject of this report, is a sub-model used within the DSS to analytically compute steady-state solutions for a two dimensional groundwater flow field in the horizontal plane. It is capable of comparing different hydrogeological settings and well field designs. The latter can be planed according the decision maker’s goal to optimise the pumped groundwater to a predefined water quantity (portion of bank filtrate) under the constraint of maintaining water quality (minimum traveltime).

This report aims at answering the following questions:

(i) How is the BFS installed? (see Chapter 2)
(ii) What data is required as model input, what are the driving physical processes for the model simulation and which output data is generated? (see Chapters 3 - 6)
(iii) Are the simulated model results plausible in a qualitative way and which are the key model parameters? (see Chapter 7)

It is not the scope of this report to describe the functions of all sub-models of the DSS. For this purpose the reader is asked to refer to RUSTLER & BOISSERIE-LACROIX (2009). Only the BFS is addressed in this report, due to the possibility to use it within and also without the DSS (stand-alone version). Additionally it is the most complex sub-model used in the DSS which needs special attention.

It is highly recommended to use the BFS only as a qualitative assessment tool for the feasibility of BF system in a first step. Since the model is time-independent (it calculates steady-state solutions), its use is only valid if the boundary conditions (e.g. baseflow, bank clogging layer, pumping rates, etc.) do not change significantly over time. Because this is usually not the fact for highly transient well field sites with spatial and temporal changing well operation, the quantitative model results (e.g. portion of bank filtrate and the minimum traveltime towards the well) have to be evaluated cautiously (WIESE & NÜTZMANN 2009). Nevertheless the outputs can give valuable qualitative insights in the aquifer system’s behaviour for different scenarios (e.g. possible minimal/maximum pumping rates).

2 Installation

For the installation of the BFS without the TECHNEAU BF-DSS proceed with the two following steps:

Step 1: Installation of the MATLAB Runtime Component (MCR)

- Execute the ***MCRinstaller.exe*** (version 7.11) which you find in the folder **... *DSS\\ Runtime***
- Install the Matlab Runtime Component on your PC by following the instructions
- You must possess administrative rights for installation

Step 2: Installation of the BFS

- Copy all files from the following folder **... *DSS\\Bank Filtration Simulator*** in a free selectable target destination (e.g. *C:\\Programs\\Bank Filtration Simulator*) on your PC
- Run the BFS by executing the ***gw_gui5.exe*** in your above specified directory (here: *C:\\Programs\\Bank Filtration Simulator\\gw_gui5.exe)*

The installation of the BFS requires 32-bit Windows operating systems (e.g. Vista, XP, 2000) and does not support any 64-bit Windows platform. Additionally neither UNIX nor MAC operating systems are supported. Furthermore it is required to have an installed MS Excel® version on your operating system in order to use the model result export into EXCEL tables (see chapter 4). Note that the correctness of model result export is only guaranteed if '.' is selected as decimal separator under: Control Panel>Regional Settings and Language Options>Regional Options>Adapt

3 Mathematics

The mathematical calculation is based on the analytical element method. An elaborate description of the method is given by STRACK (1989).
According to HOLZBECHER (2007) this method can be divided into four steps. In a first step the 2D flowfield is visualized by using the complex potential Φ, which is connected to both - (real) potential φ and (imaginary) streamfunction Ψ - according to the following equation:

$$\Phi = \varphi + i\psi$$

where i denotes the square root of -1, the imaginary potential. Potential comprises a (real) potential and a streamfunction, so that the real and imaginary parts can be written as:

$$\varphi = \mathrm{Re}(\Phi) \ \ [L^3/T] \qquad \Psi = \mathrm{Im}(\Phi) \ \ [L^3/T]$$

The imaginary potentials for various flow patterns are shown in *Table 1*.

Table 1 Imaginary potential for various flow patterns according to (HOLZBECHER 2007)

Element	(Imaginary) Potential Φ
Baseflow	$-\bar{\mathbf{Q}}_0\mathbf{z}$
Well	$Q/_{2\pi} \log(\mathbf{z} - \mathbf{z}_{well})$

In the second step the analytical solution is computed by the superposition for the chosen potential and stream function elements of *Table 1*.
Additionally, in the presence of a clogging layer, the expression of the potential is a series of fundamental solutions, which are calculated according to the boundary conditions at the interfaces. For the exact mathematical derivation the user is referred to VAN DER VEER (1994) and VAN DER VEER (1995).

As a third step numerical post-processing for the following three tasks is conducted:

(i) Computation of hydraulic heads

$$h(x,z) = \begin{cases} \left(\varphi(\mathrm{x,y}) + 0.5 \cdot K \cdot \mathrm{H}^2 - \varphi_0\right) / (\mathrm{K} \cdot \mathrm{H}) & \text{for a confined aquifer} \\ \sqrt{2\left(\varphi(\mathrm{x,y}) - \varphi_0\right)/K} & \text{for an unconfined aquifer} \end{cases}$$

with K= hydraulic conductivity [L/T] and H = aquifer thickness [L] *(ii) Computation of flux vector components (q_x and q_y)*

$$\begin{cases} q_x(x,y) = \dfrac{\partial\varphi(x,y)}{\partial y} \\ q_y(x,y) = \dfrac{\partial\varphi(x,y)}{\partial x} \end{cases} \quad \text{or} \quad \begin{cases} q_x(x,y) = \dfrac{\partial\psi(x,y)}{\partial x} \\ q_y(x,y) = \dfrac{\partial\psi(x,y)}{\partial y} \end{cases}$$

(iii) Computation of velocity vector components (v_x and v_y)

$$v_x(x,y) = \begin{cases} q_x(x,y)/H & \text{for a confined aquifer} \\ q_x(x,y)/h(x,y) & \text{for an unconfined aquifer} \end{cases}$$

$$v_y(x,y) = \begin{cases} q_y(x,y)/H & \text{for a confined aquifer} \\ q_y(x,y)/h(x,y) & \text{for an unconfined aquifer} \end{cases}$$

Both formulae above are to be processed for groundwater flow based on the discharge potential.

(iv) Computation of average interstitial groundwater velocity ($v_{x,eff}$ and $v_{y,eff}$)

$$v_{x,eff}(x,y) = \frac{v_x(x,y)}{n_{eff}} \quad \text{or} \quad v_{y,eff}(x,y) = \frac{v_y(x,y)}{n_{eff}}$$

with:

$v_{x,eff}$, $v_{y,eff}$ = average interstital groundwater velocity [L/T] and
n_{eff} = effective porosity

It has to be noted that the computation of the global minimum is based on minimization procedure methods of golden section search and parabolic interpolation. An initial guess is improved in an iterative procedure and the end criterion depends on a maximum number of iterations and an accuracy criterion. In each iteration step the previous starting point interval is sub-divided following the golden section rule, i.e. the ratio of the smaller intervals is given by the formula:

$$I_1 / I_2 = \tfrac{1}{2}\left(1+\sqrt{5}\right) \approx 1.618$$

The golden section search is an algorithm which enables to localize the position of a global minimum, by narrowing the range of values inside which the global minimum is known to exist at each step.
The parabolic interpolation consists of approximating a function with a parabola. It is particularly efficient if the interval of interpolation is very restricted on both sides of the global minimum (hence the utility of the golden section search before). A detailed mathematical derivation for the golden section search is given e.g. in GOLDEN SEARCH TECHNIQUE (2009).

The last step is referred to as graphical post-processing with the purpose to visualize the computed results in a horizontal two dimensional groundwater flowfield. This includes the plotting of e.g. hydraulic heads, velocity vectors, streamfunctions contours and pathlines (see Chapter 6.1).

4 Graphical User Interface

The Graphical User Interface (GUI) of the BFS is divided into six sections (see *Figure 1*):

- Graphical output options (2D and 3D)
- Grid
- Aquifer
- Bank(s)
- Well(s)
- Numerical output

Furthermore there are three buttons in the bottom left corner of the GUI. Their functions are described in detail below.
By pressing the **PLOT** button a model run for the user defined model parameterisation (see Chapter 5) will be performed. After a successful model run the user can save the model results (and the corresponding initial model parameterization) by pressing the **SAVE** button. Subsequently the model data will be stored in two different EXCEL files (see *Table 2*).

Table 2 Saved parameters in the different Excel tables

Data type	Domain	Parameter	Filename	
			runlist.xls	runX.xls
Input	Aquifer	Thickness		√
		Hydraulic conductivity		√
		Baseflow		√
		Reference head		√
		Porosity		√
	Bank	Orientation		√
		Clogging parameter		√
	Well	Coordinates		√
		Pumping rate	√ (total)	√ (single)
Output	Total well field	Share bank filtrate	√	
	Total well field	Minimum traveltime	√	
	Bank	Infiltration length	√	

The first EXCEL file is called 'runlist.xls' and stores one model input parameter (total pumping rate of user defined wells) and four output parameters (number of the saved model run, share bank filtrate, minimum traveltime and infiltration length). Each time you click on the **SAVE** button the data will be stored in a new row in the same EXCEL table 'runlist.xls'. It was implemented so that the model results can be easily loaded into the DSS.

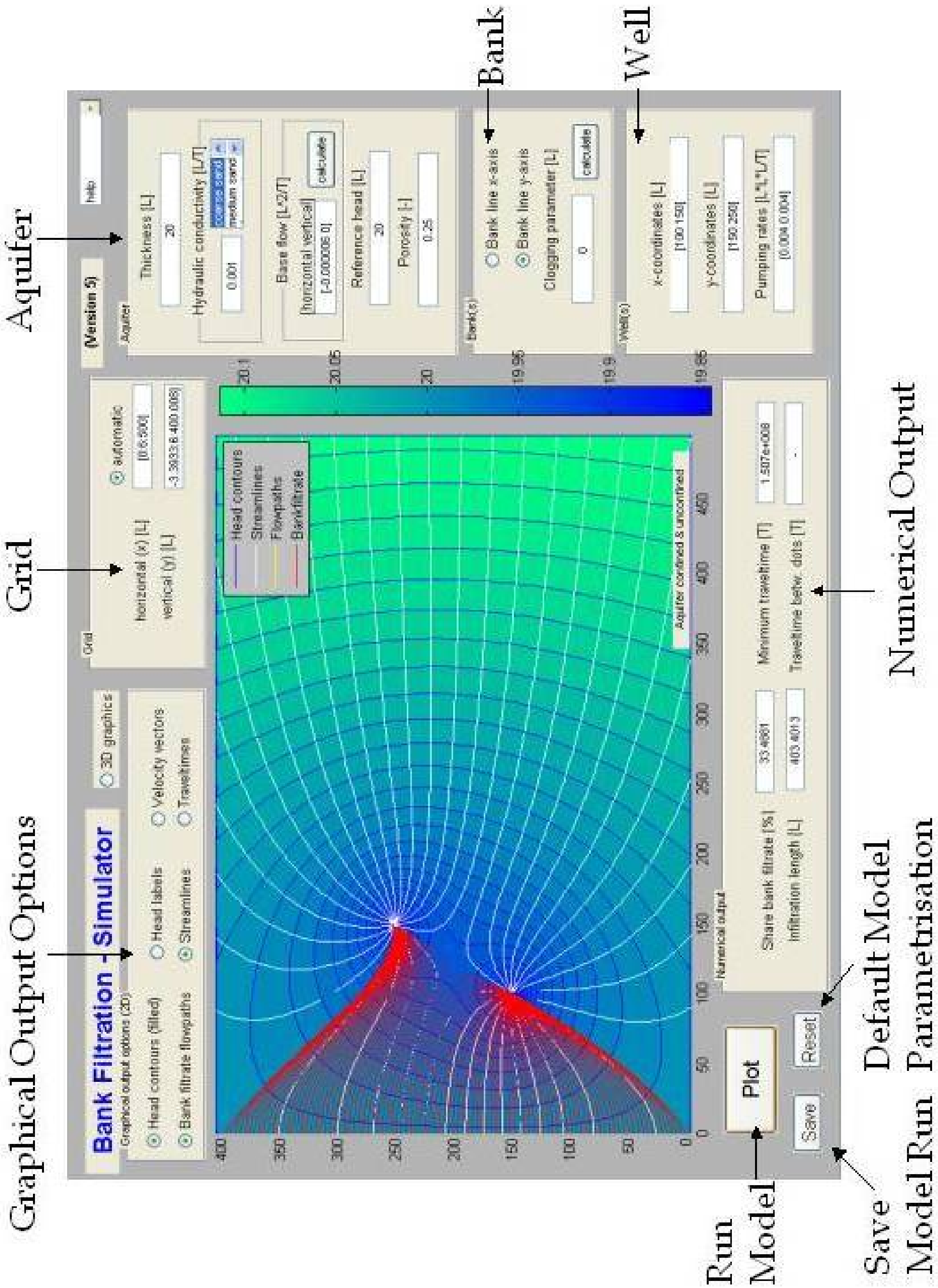


Figure 1 *GUI of the BFS after a model run with the default parameterisation*

The second output file, called 'runX.xls' contains the complete model parameterisation but without the numerical model output (see Chapter 6.2). The data storage differs significantly from the above mentioned 'runlist.xls' file due to the number of parameters it contains (see *Table 2*). With every click on the **SAVE** button the whole input data of a model run will be saved in different EXCEL tables called 'run**X**.xls'. The **X** indicates the number of times you have clicked on the **SAVE** button. For example if you click twice on the **SAVE** button, two EXCEL table files ('run1.xls', 'run2.xls') will be created. These are saved under the main folder of the BFS (here: *C:\Programs\Bank Filtration Simulator\...).*
Note that you have to delete (i) the runlist.xls and (ii) all runX.xls files if the results of a new model run need to be saved in EXCEL tables that start with the run number one in the 'runlist.xls' and 'run1.xls', respectively.

The third button is the **RESET** button, which restores the default model parameterisation.

5 Model Parameterisation

5.1 Physical units

Concerning physical units, the user inputs need to be consistent. Once one value is given in a certain unit, this unit has to be used in all input data. The output is given in the same unit. Letters in brackets symbolize physical units:

L = length, T = time

<u>Example:</u> *If the aquifer thickness is given in meters, and hydraulic conductivity in meter/second, the input for baseflow is in square meter/second and the reference head in meters.*

5.2 Grid characteristics

The grid section is placed in the left corner in the GUI (see *Figure 2*). The grid is needed for graphical outputs: values of variables are calculated at grid points only. Small grid-spacing provides smooth output curves. The field extension, represented in the graphical output window, is given here.

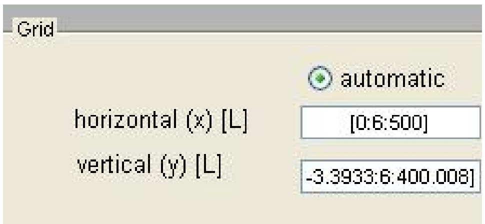


Figure 2 Grid section of the BFS

5.2.1 Automatic gridding

An automatic gridding can be chosen by the user under the grid section. If the automatic gridding is active, the grid spacing and the extension of the grid along the bank are selected automatically. The region represented in the graphical output window is extended to capture the entire region in which the bank filtration takes place.
Additionally an automatic gridding will be performed only for the coordinates on the x- and y- axes which are bank lines. The scales in the vertical and horizontal direction may become quite different. If that is not wished by the user, the coordinate scale can be adjusted manually by deactivating the green dot left to the automatic gridding. Furthermore an automatic gridding is performed only when there is a change between the groundwater outflow and the bank filtrate inflow on the bank. In situations where there is only a bankfiltrate either flowing to the wells or migrating further in the aquifer, the automatic gridding is not performed. Then the former limits of the graphics on the display remain unchanged.

5.2.2 Manual gridding

A rectangular grid is specified by the two vectors for x- and y-coordinates of the grid nodes. These input parameters are to be specified under the grid section. Both coordinates have to be given in two edit boxes in **[ ]** brackets. It is convenient to use the double-dot option for equidistant grids, as shown by the following example.

Example: *[0:6:400] gives nodes between 0 as minimum value and 400, and grid spacing 6: 0, 6, 12, 18....396.*

The user has to take care that the wells do not coincide with the grid nodes. Otherwise the program may calculate heads near to negative infinity, which may cause severe problems of the program. In any case the colour bar scaling is effected and may show an unrealistic scale.

5.3 Aquifer characteristics

Under the aquifer section (see *Figure 3*) the user can change basic hydrogeological characteristics of the aquifer such as the thickness [L], the hydraulic conductivity [L/T], the baseflow [L²/T], the reference head [L] and the porosity. All parameters mentioned above are described in detail in the following sub-chapters.

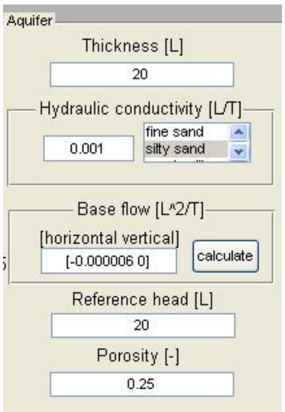


Figure 3 Aquifer properties section of the BFS

5.3.1 Hydraulic conductivity

To set a value for the hydraulic conductivity, the user can choose between direct (text box on the left hand side) or indirect input (list box on the right hand side). If the latter is selected the user only has to specify the desired aquifer matrix and the hydraulic conductivity will be set automatically according to *Table 3*. This is a strongly simplified assumption and it should only be used if no further information is available.

Table 3 Aquifer matrix and corresponding hydraulic conductivity [m/s] which are implemented as default values in the BFS

Aquifer matrix	Hydraulic conductivity [m/s]
Coarse gravel	5.0e-3
Gravel	1.5e-3
Coarse sand	1.0e-3
Medium sand	6.0e-4
Fine sand	1.0e-4
Silty sand	1.0e-5
Sandy silts	1.0e-6
Clay	1.0e-8

Note that all hydraulic conductivity values in the table above are given in meters/second. Subsequently they are only valid if all values for the model simulation are in the same SI units (International System of Units). Additionally it is assumed that the hydraulic conductivity is constant over time and space. Due the hydraulic conductivity in every real-world aquifer being more or less heterogeneous (because of different sedimentation and geological processes) a quantitative application of the BFS should be avoided. Therefore it is recommended to use the BFS only as a first qualitative assessment tool.

5.3.2 Thickness and reference head

It is assumed that for the generic situations for which the BFS is designed the aquifer thickness is constant. If the reference head lies above the aquifer thickness, the aquifer is confined. Otherwise the aquifer is unconfined. The values are given in length units [L] above the aquifer basis.

5.3.3 Porosity

The porosity (=effective porosity) has no influence on hydraulic (or: piezometric) heads, on streamlines, on bank filtration share etc. An overview of the total and effective (minimum, average, maximum) measured porosity values for different unconsolidated sediments is given in *Figure 4*.
The effective porosity has only an influence on the computation of the minimum traveltime by alternating the average interstitial groundwater velocity (see Chapter 3). Consequently the lower the porosity is set, the higher the effective groundwater velocity resulting in a lower the minimum traveltime between bank and production well.

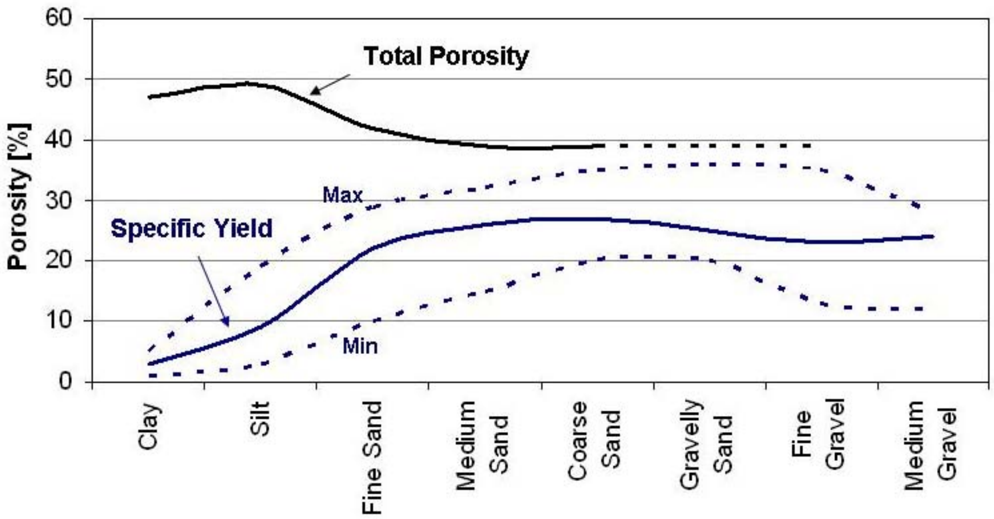


Figure 4 *Total porosity versus specific yield (effective porosity) of unconsolidated sediments modified from* K*RESIC (2007), specific yield values from* J*OHNSON (1967)*

5.3.4 Baseflow

The user has three options to define the baseflow in the BFS:

(1) Direct input
(2) Darcy's law
(3) Hydrological balance

For direct input (1) the baseflow is characterized by two input parameters which the user can specify in the baseflow textbox under the aquifer section. Both values have to be specified within **[ ]** brackets. The first value is the baseflow in x-direction, the second in y-direction. The positive x-direction on the display is from left to right; the positive y-direction is from bottom to top.
Alternatively one can calculate the baseflow using (2) Darcy's Law or the (3) hydrological balance, by clicking on the **CALCULATE** button on the right hand side of the baseflow section (see *Figure 3*).
Additionally it is assumed that for the generic situations for which the BFS is designed the baseflow is constant.
A non-zero baseflow value in x-direction can only be given, if there is a hydraulic gradient along the y-axis (even if there are no wells in operation). Analogously a non-zero baseflow value in y-direction can only be given, if there is a hydraulic gradient along the x-axis even in case of no active wells.

The baseflow calculation, initiated by the **CALCULATE** button (see *Figure 5*), depends not only upon the saturated aquifer thickness (=reference thickness) and the hydraulic gradient (=head gradient) but also on the hydraulic conductivity that the user specified under the aquifer section (see *Figure 3*). Thus if the user changes the hydrologic conductivity after performing the baseflow calculation with Darcy's law, he has to recalculate the baseflow by clicking the **CALCULATE** button a second time.

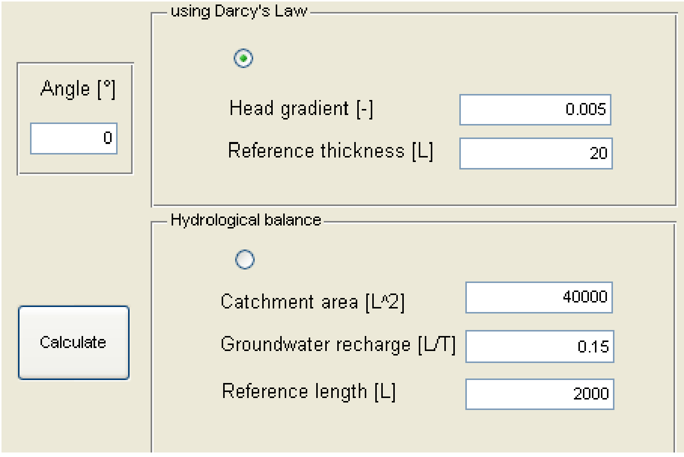
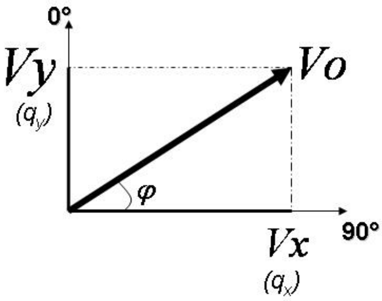


Figure 5 *Baseflow calculation section of the BFS*

In addition the parameter **'angle'** is used as input if the baseflow is calculated either by using Darcy's law or the hydrological balance of the (subsurface) watershed. Subsequently it is important to know that 0° corresponds to the positive x-axis and 90° to the positive y-axis (*Figure 6)*. In addition every angle e.g. 45° can be computed as a baseflow vector consisting of two components (qx and qx) by using the Pythagorean theorem (*Figure 6*).



$$Vx = Vo * \cos(\varphi)$$
$$Vy = Vo * \sin(\varphi)$$

$$\sin(45°) = \cos(45°) = \sqrt{2}/2 \approx 0{,}07011$$

Figure 6 *Baseflow (q_x, q_y) and velocity (V_x, V_y) vector components for an angle (φ) of 45°*

5.3.4.1 *Darcy's law*

The x and y components of the baseflow vector can be calculated using Darcy's law by clicking on the corresponding **CALCULATE** button. In order to calculate the baseflow according to that law, the user has to enter the head gradient I (=hydraulic gradient) of ambient groundwater and the reference thickness H (=saturated aquifer thickness) [L].
The baseflow B [L^2/T] – which is the specific discharge per unit width - is then calculated according to the following equation:

$$B = K*I*H \quad [L^2/T]$$

where K denotes the hydraulic conductivity [L/T], which the user has to define under the aquifer section (see Chapter 5.3.1).

5.3.4.2 Hydrological balance

There is the option to calculate the baseflow by the hydrological balance of the subsurface watershed of the modelled aquifer. For this three parameters are required:

- Subsurface catchment area A [L^2]
- Groundwater recharge R [L/T]
- Reference length L [L]

The baseflow B [L^2/T] is then calculated by using the following equation:

$$B = A*R/L \qquad [L^2/T]$$

It is assumed that the (subsurface) catchment area is known to be independent from the pumping regime. The groundwater recharge [L/T] is the average portion of precipitation volume in the whole subsurface catchment area that reaches the water table of the aquifer in a user-defined time scale (e.g. winter, summer, year, decade). The reference length must not coincide with the dimension of the model area, as illustrated in *Figure 7*. It is only an important parameter when calculating the baseflow.

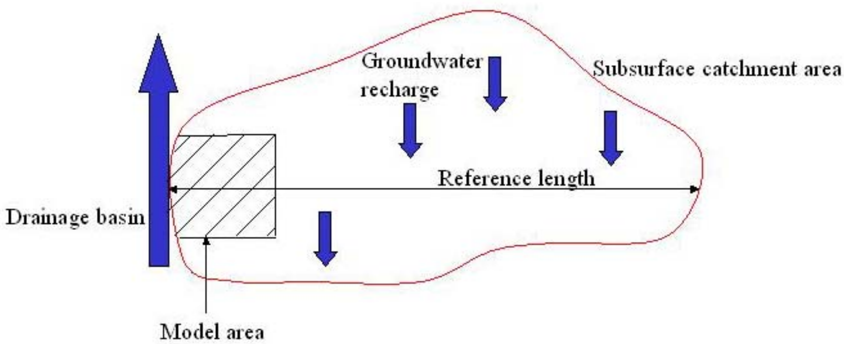


Figure 7 *Components of the hydrological balance: subsurface catchment area (red lines), groundwater recharge (small blue arrows) and reference length (black line). Note that the model area (black square with crossed lines) depends only on the user defined grid extent (Chapter 5.2) and has no influence on the baseflow calculation.*

5.4 Bank characteristics

Under the bank section (see *Figure 8*) the user can specify the orientation (see Chapter 5.4.1) and the clogging parameter (see Chapter 5.4.2) of the bank.

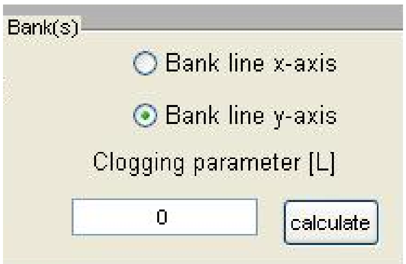


Figure 8 *Bank properties section of the BFS*

5.4.1 *Orientation*

In the BFS the bank line can be placed either along the x-axis, the y-axis or both as shown in *Figure 9*. The user can choose between these alternatives by activating or deactivating the two checkboxes under the bank(s) section (see *Figure 8*). The bank is assumed to be a straight line or the combination of straight lines. The optional cases are:

- the bank is identical with the x-axis
- the bank is identical with the y-axis
- the bank is located along x- and y-axis

In addition the flow reducing effect of a clogging layer (hydraulic conductivity of the bank is less than the hydraulic conductivity of the aquifer) can be taken into account by specifying a clogging parameter.

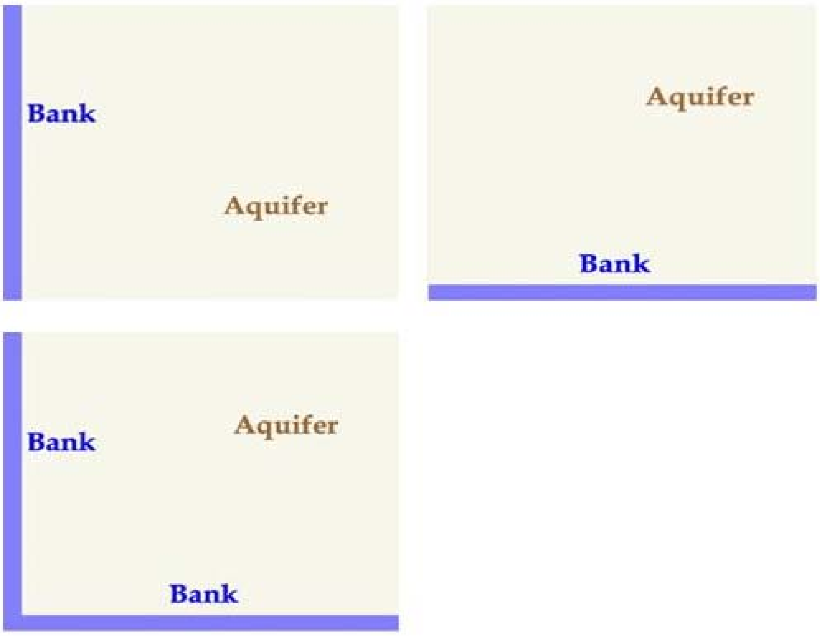


Figure 9 *Bank orientation options: y-axis (upper left), x-axis (upper right) and both (lower left)*

5.4.2 *Clogging parameter*

The clogging layer is assumed to be homogeneous and constant along the bank. The clogging parameter ($Clog_{Parameter}$) is the product of the clogging layer thickness ($Clog_{Thickness}$) and its relative hydraulic conductivity compared with the aquifer ($K_{Clog}/K_{Aquifer}$):

$$C\log_{Parameter} = C\log_{Thickness} \cdot \frac{K_{C\log}}{K_{Aquifer}} \quad [L]$$

If there is no clogging layer, the value of the clogging parameter is zero.
There are two possibilities to define a clogging parameter in the BFS. On the one hand one can specify the value directly in the textbox. On the other hand it is also possible to calculate the clogging parameter automatically (according to the equation above). Therefore one has to click on the **CALCULATE** button under the bank section (see *Figure 8*) in a first step. Subsequently a new clogging layer properties section (see *Figure 10*) window is opened. After defining the required input parameters (thickness and hydraulic conductivity of the clogging layer) one has to click on the corresponding **CALCULATE** button in a second step and the clogging parameter calculation will be performed automatically.

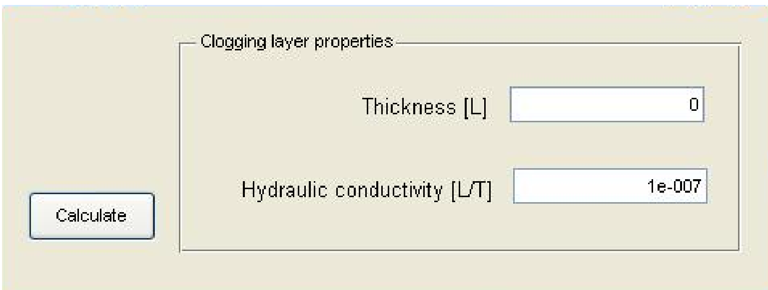


Figure 10 Clogging layer calculation section

Note that the clogging parameter calculation has to be performed every time the hydraulic conductivity of the aquifer is changed under the aquifer section (see *Figure 3*). Subsequently the user has to click on the **CALCULATE** button again.

Example: *If the clogging layer is 1 meter thick and 100 times less permeable than the aquifer, the clogging parameter is 100 meter in the SI physical unit system.*

5.5 Well characteristics

Under the well(s) properties section (see *Figure 11*) it is possible to define groundwater abstractions or injections through a single well or multiple wells. Therefore the user has to specify the x- and y-coordinates and an average pumping rate [L^3/T] for each well. Positive pumping rates are used for discharge wells (sinks) and negative for injection wells (sources). Well diameters are not considered in the well implementation.

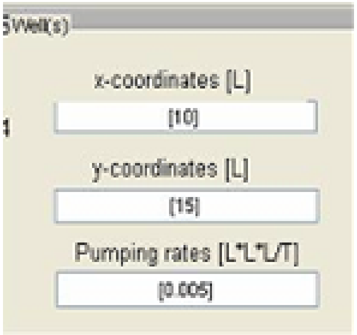


Figure 11 Well(s) properties section

5.5.1 Coordinates

The well coordinates are given in two edit boxes in **[ ]** brackets. The user may specify several wells by introducing several x- and y-coordinates separated by blanks. One may even give numerical vector operations. Note that the BFS will give an error message if the number of x- and y-coordinates does not coincide.

Example: *50*[1 2 3 4 7 8 9 10] gives positions 50, 100, 150, 200, 350, 400, 450 and 500.*

5.5.2 Pumping rate

Negative values denote aquifer recharge, positive values water withdrawal. Pumping rates are given in an edit box in **[ ]** brackets. Note that the pumping rate is assumed to be independent of the recent water table in the BFS. The user may specify several pumping and/or recharge rates by introducing several values, separated by blanks. One may even give numerical vector operations.
The BFS will give an error message if the numbers of coordinates and pumping rates do not coincide.

Example: *0.001*[1 1 1 2 2 1 1 1] gives 8 pumping wells, among which the two medium wells pump at a double rate than the outer wells.*

6 Model Output

6.1 Graphical output

The graphical output is defined by selecting the desired parameters under the graphical output options section (see *Figure 12*). There are seven parameters that all can be enabled or disabled:

- Head contours
- Head labels
- Velocity vectors
- Streamlines
- Bank filtrate flowpaths
- Traveltimes
- 3-D graphics

The user's parameter selection does not affect the model calculations, since it has only an effect for the visual output. The only exception is that without enabling the parameter **'traveltimes'** no numerical output for **'traveltime between dots'** is calculated (see *Figure 14*).

Figure 12 Graphical output options section

6.1.1 Head contours

The distribution of the (hydraulic) heads represents the two dimensional flow field in the horizontal plane. It also illustrates the drawdown or the rise of the water table due to groundwater abstraction or aquifer recharge, respectively. The BFS visualizes the head distribution with a map of blue contours, filled by a green/blue colour-distribution. The relation between colour and value is given in the colour bar on the right of the graphical figure. Head contours for the situation, specified by the user, are given after pressing the **PLOT** button. If the head contour output is selected, the head contours in the graphical output are labelled.

6.1.2 Velocity vectors

Velocity contours are visualized as small arrows. The length of the arrows is proportional to the velocity. The number of arrows plotted depends on the grid spacing: the smaller it is, the more arrows are plotted and the shorter they are. Subsequently, due to the different scales of the velocity near and far from wells, the arrows may become too big in the close vicinity of wells.

6.1.3 Streamlines

Streamlines provide valuable information concerning the flowfield. A pattern of streamlines for the calculated situation is given in the graphical output, after pressing the **PLOT** button. The white lines indicate that ambient groundwater flows towards the bank and/or the well(s).
The flow of a water particle can be envisaged by following the streamlines. In addition the flow velocity in different parts of the modelled area can be compared. This is due to the fact that there is the same volume of water flow between neighbouring streamlines in every part of the modelled area. Thus if streamlines converge, there are higher flow velocities, whereas if flow velocities are low, there is a wider space between streamlines. The spacing of the streamfunction is set automatically as the 20th part of the pumping rate of well number 1, if that is non-zero.
Note that straight lines from the well positions to the left towards the y-axis are not streamlines, but side-effects of the analytical element method, as the complex logarithm is not a unique function in the complex plane.

6.1.4 Bank filtrate flowpaths

Bank filtrate flowpaths are calculated and given in the 2-D plot, if the parameter **'bank filtrate flowpaths'** is activated by the user under the graphical output options section (see *Figure 12*). Bank filtrate flowpaths are given in red. Starting positions for the bank filtrate are chosen automatically along the bank lines. The calculation is based on a flow path tracing algorithm which works correctly if the grid spacing is identical in the x- and y-axis. If the spacing in both directions does not coincide a message box appears on the screen. The user may adjust the grid spacing manually.
It is important to know that the bank filtrate flowpaths are calculated only for starting positions on the bank within the chosen spatial extension of the graphic output. Thus not the entire region of bank filtrate may be captured if the minimum or maximum value of the grid is not appropriately selected. If the user selects the automatic gridding, the window is automatically chosen wide enough. An exception is the situation in which the bank filtrate infiltrates everywhere along the axes. Such a situation is given when there is no baseflow across a bank line. In that case the share of bank filtrate in pumped water is 100%.
If the baseflow is from the bank towards the aquifer (positive value on x- or y-axis) then there is no distinction between the bank filtrate flowing towards the wells or migrating further within the aquifer. Additionally flowpaths can coincide with streamlines, if their starting positions coincide with a streamline passing through the bank.

6.1.5 *Traveltimes*

If the '**traveltimes'** option is set under the graphical output options section (see *Figure 12*) another set of flowlines is created with dots indicating the traveltimes. The distance between the dots indicates a constant time-step. Thus wide distances between dots indicate fast flow (=high velocity) whereas small distances between dots indicate slow flow (=low velocity). Moreover traveltimes depend on the effective porosity. The smaller the effective porosity, the higher is the average interstitial groundwater velocity (see Chapter 3 for the mathematical background).
In addition it does not matter whether the '**traveltimes'** option is enabled or not, since the minimum traveltime is calculated anyway.

6.1.6 *3D graphics*

By activating the **'3D graphics'** button in the upper right of the graphical output section a 3D-visualisation of the steady state groundwater flowfield will be created in a new window (see *Figure 13*) in addition to the standard 2D-plot.

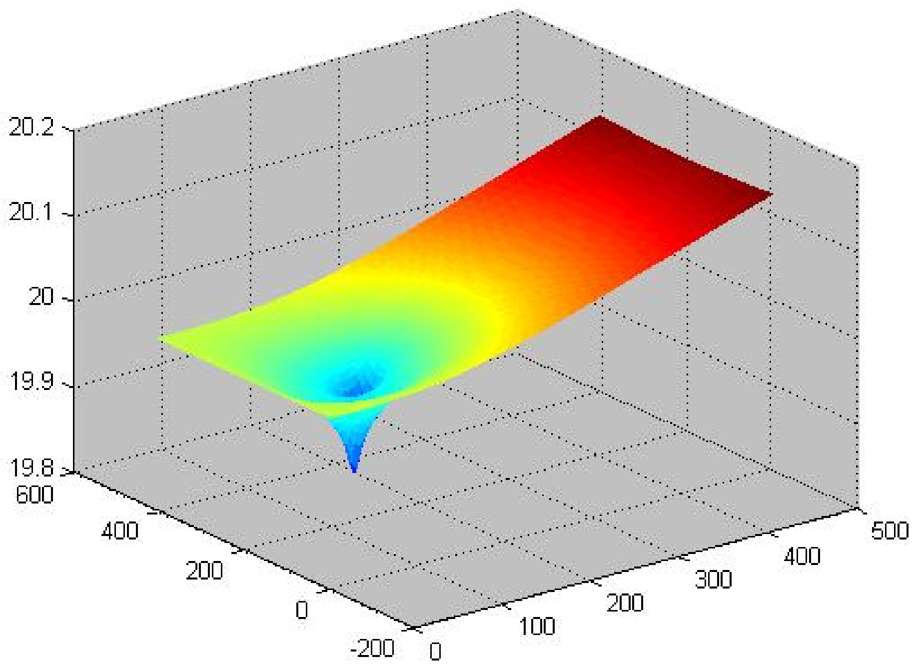


Figure 13 *3D-visualisation of the hydraulic head distribution for the default model parameterisation*

6.2 Numerical output

Under the numerical output section (see *Figure 14*) there are four parameters which are printed in the bottom of the GUI:

- Share bank filtrate (%)
- Minimum traveltime [T]
- Infiltration length [L]
- Traveltime between dots [T]

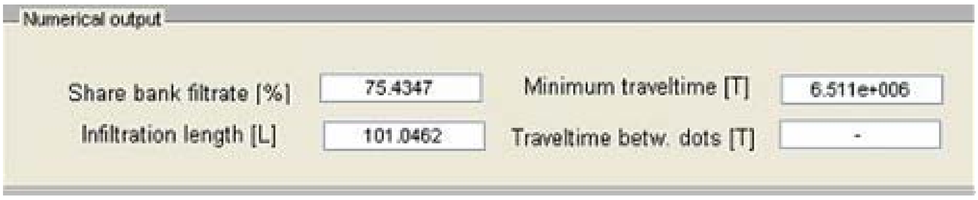


Figure 14 Numerical output section of the BFS

6.2.1 Share bank filtrate

The portion of bank filtrate in the water pumped from the extraction wells is calculated by the BFS after pressing the **PLOT** button. The ratio of bank filtrate is valid for the pumping of the entire set-up, and does not distinguish single wells. If there is no baseflow across a bank line, neither on the x-axis nor on the y-axis, bank filtrate enters along the entire bank line (only theoretically). In that case the share bank filtrate in pumped water is 100%.

6.2.2 Minimum traveltime and traveltime between dots

Minimum traveltime for flowpaths with starting points on the bank, in the interval selected by the user as grid nodes (see Chapter 5.2), is computed in any case. The determination of the traveltime depends on the discrete velocity field, i.e. the grid spacing has an influence on the results.
Note that the traveltime between dots is only computed if the **'traveltimes'** parameter under the graphical output section is enabled (see *Figure 1* and Chapter 6.1.5).

6.2.3 Infiltration length

The infiltration length [L] is the scope of the bank where infiltration due to groundwater abstraction through pumping wells appears.

7 Sensitivity Analysis

A sensitivity analysis is performed by varying the different initial model parameters of the BFS (*Table 4*) one by one by several orders of magnitude to verify that the model code is implemented correctly. This means that the plausibility of the model outputs is checked in a qualitative way. Only the minimum traveltime is also compared quantitatively against a numerical MODFLOW model by using the same model parameteristion but slightly different boundary conditions (see Chapter 7.5).

Table 4 Initial model parameterisation of the sensitivity analysis (seconds and meters are used as time and spatial units, respectively)

Parameter	**Value**
Grid characteristics	***manually***
horizontal (x-axis)	[0 : 1 : 400]
vertical (y-axis)	[-200 : 1 : 200]
Aquifer characteristics	***unconfined***
aquifer thickness [m]	85
reference head [m]	80
reference thickness [m]	80
porosity [/]	0.2
hydraulic gradient [/]	0.001
hydraulic conductivity [m/s]	0.00012
baseflow angle [°]	0
baseflow component in x- and y-direction [m^2/s , m^2/s]	[-0.0000096 , 0] (calculated using Darcy's law)
Bank characteristics	
Orientation [x-,y-axis or both]	y-axis
Clogging parameter [m]	0
Well(s) characteristics	
Distance to bank [m]	63
Pumping rate [m^3/s]	0.044
Number of abstraction wells	1
Position in grid [x,y]	[63 0]

7.1 Grid characteristics

For every grid node the hydraulic head is calculated. Therefore the accuracy of both analytical computation of hydraulic heads and numerical computation of minimum traveltime – which depends on the calculated hydraulic head distribution (see Chapter 3) - is constrained by the total amount of grid nodes calculated according the following formula:

Total amount of grid nodes = Grid extent (xaxis*yaxis) / Grid spacing^2

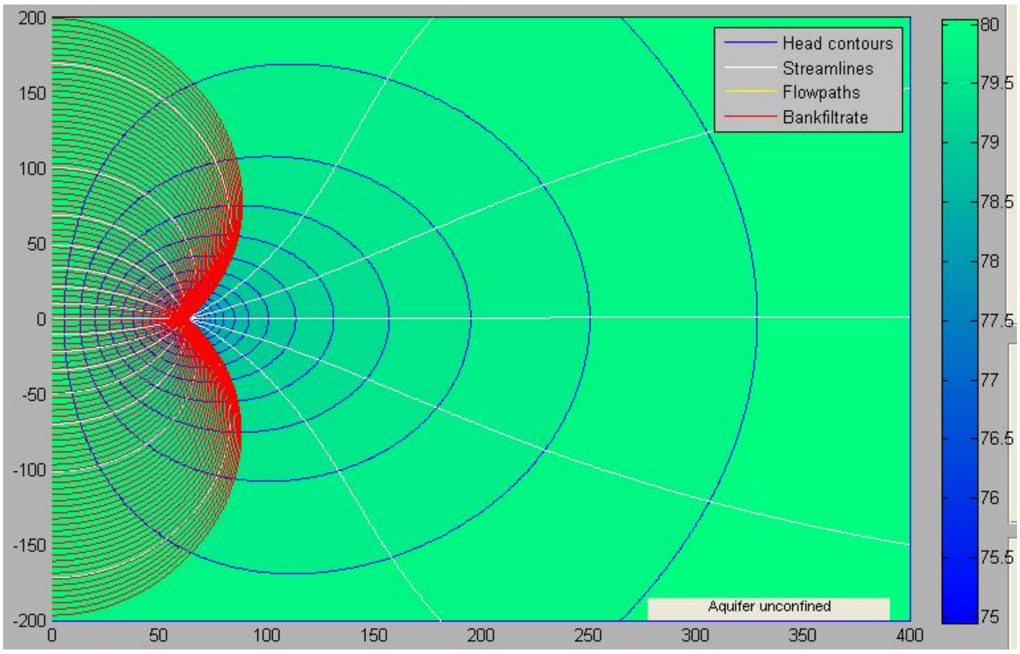
with:
Grid extent (xaxis), Grid extent (yaxis) = range between the minimum and the maximum value for each axis (x and y, respectively); unit: [L]
Grid spacing = equidistant interval between two grid nodes; unit: [L]

Therefore the layout of the grid concerning both, extent and spacing (see Chapter 5.2) can have an effect on the model result accuracy, which is analysed in detail below.
The grid extent is the range between the minimum and the maximum value on both axes (x- and y-axis, respectively) for a given grid spacing. Subsequently the bigger the extent is chosen, the more grid nodes are taken into account, resulting in a higher accuracy of the model representation for the groundwater flow field distribution near the model boundary (*Figure 15*).
The opposite is the case for a too small grid extent (*Figure 16*), leading to an inadequate representation of the flow field distribution at the model boundary and thus erroneous result for the minimum traveltime calculation. But this error is only of minor importance since it only contributes to approximately 20% derivation for the minimum traveltime (*Figure 18*) and has no significant effect on the depression cone results (*Figure* 17).
In addition the grid spacing (equidistant interval between two grid nodes) for a given grid extent determines how many hydraulic heads are calculated. Subsequently the coarser the grid spacing is chosen, the fewer hydraulic heads are calculated and vice versa (*Figure 19* and *Figure 20,* respectively). On the one hand the dependency between grid spacing and depression cone is non-linear (*Figure 21*), leading to a nonlinear increasing inaccuracy, the coarser the grid spacing is chosen. On the other hand the dependency between grid spacing and minimum traveltime is linear (*Figure 22*). However, if the grid spacing is only varied between 10m and 0.1m the calculated minimum travelime varied between 3.1 years and 10 days, respectively. As a result the grid spacing is identified as most sensitive parameter for the grid layout, which the user has to specify with caution.
In a next step various model runs are performed and analysed in order to derivate a rule-of-thumb which may help the user to avoid qualitative erroneous model results due to an inadequate grid parameterisation (see Appendix B). As a conclusion it is recommended to define the grid layout at least according to the following rules-of-thumb:

Grid spacing < Distance (Bank-Well) / 10
Distance (Bank-Well) < Extent of the Grids < 8 * Distance (Bank-Well)

The first rule of thumb states that grid spacing must be chosen at least ten times smaller than the distance from the bank to the well. The second one states that the maximum grid extent for both x- and y-axis should be less than eight times the distance between the bank and production well. In addition the minimum grid extent has to be at least above the distance of the well to the bank.

In a nutshell the impact of a wrongly chosen grid extent on the model results for the depression cone can be neglected compared to the highly non-linear effect of different grid spacings. Nevertheless it is highly recommended to perform a first model run by using the automatic gridding option (see Chapter 5.2.1), so that the whole flowfield is captured by the grid extent. In a next step this grid layout can be further improved by shifting the model boundary further away from the bank (increase grid extent) and subsequent refinement of the grid spacing. The above stated empirical rules-of-thumb are highly recommended to accomplish this task, since they help the user to avoid errors due to an inadequate grid layout.



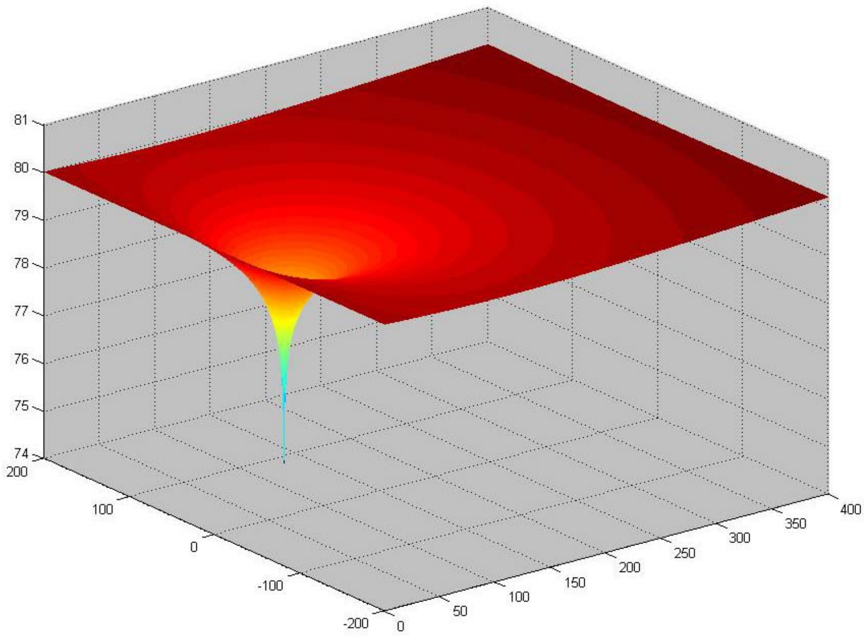
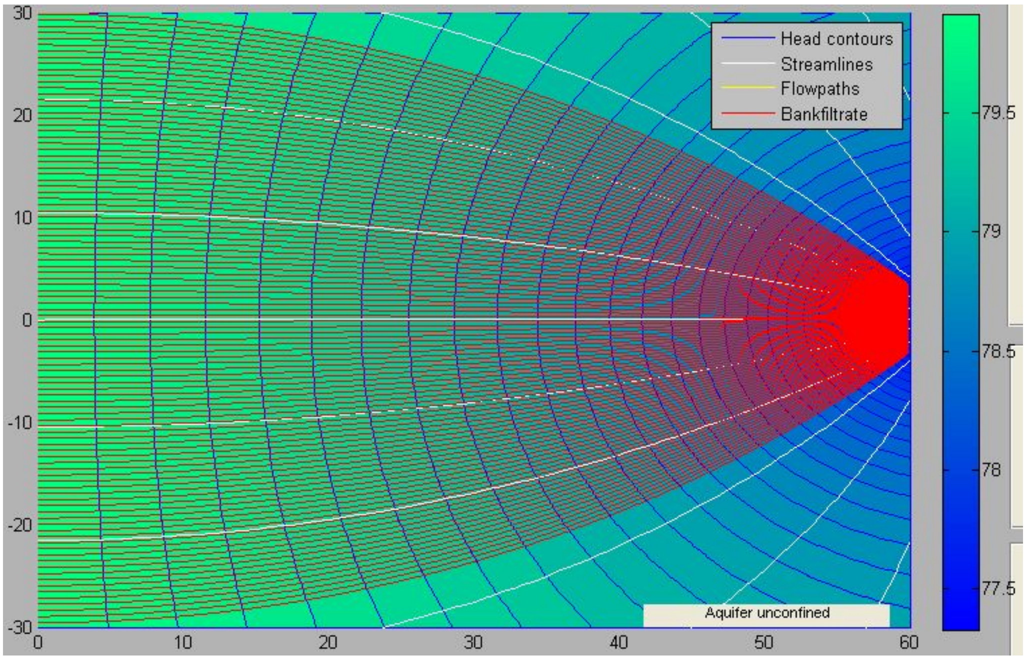


Figure 15 *Influence of the grid extent (400 m for x-axis and y-axis) on the 2D-flow field (upper figure) and the 3D-depression cone (lower figure). Note that the total amount of grid nodes is 160000.*



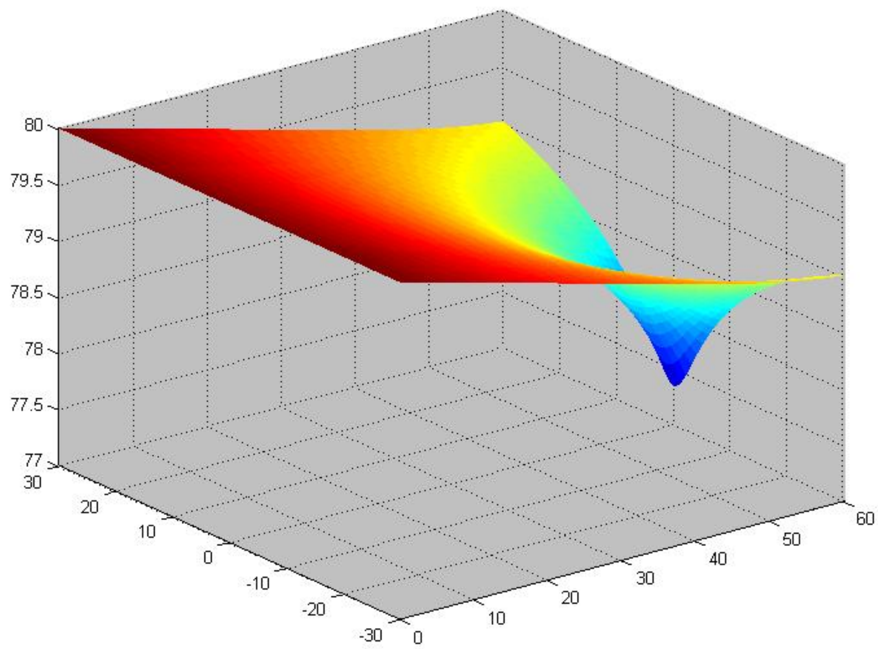


Figure 16 *Influence of the grid extent (60 m for x-axis and y-axis) on the 2D-flow field (upper figure) and the 3D-depression cone (lower figure). Note that the total amount of grid nodes is 3600.*

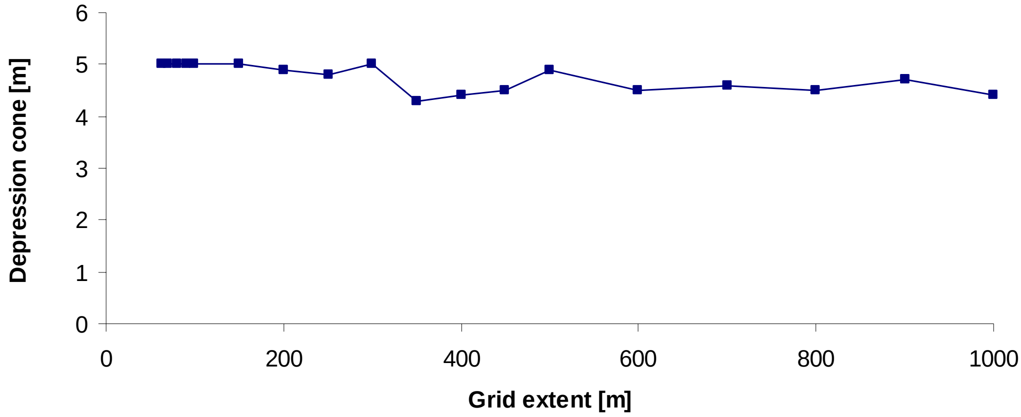


Figure 17 *Influence of the grid extent on the depression cone calculation*

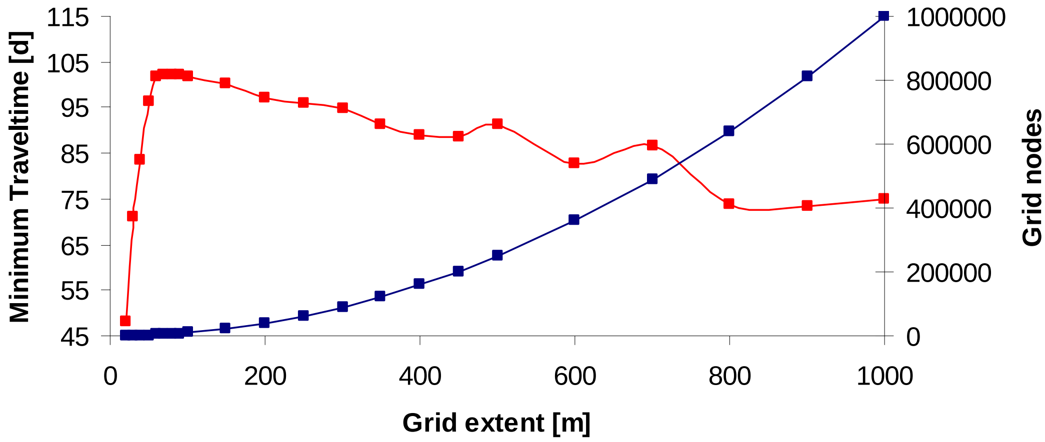


Figure 18 *Influence of the grid extent on the minimum traveltime (red) and the number of grid nodes (blue) calculation. Note that the rule-of-thumb is not valid below 63m (distance of the well to the bank) and above 500m (minimum traveltime oscillates).*

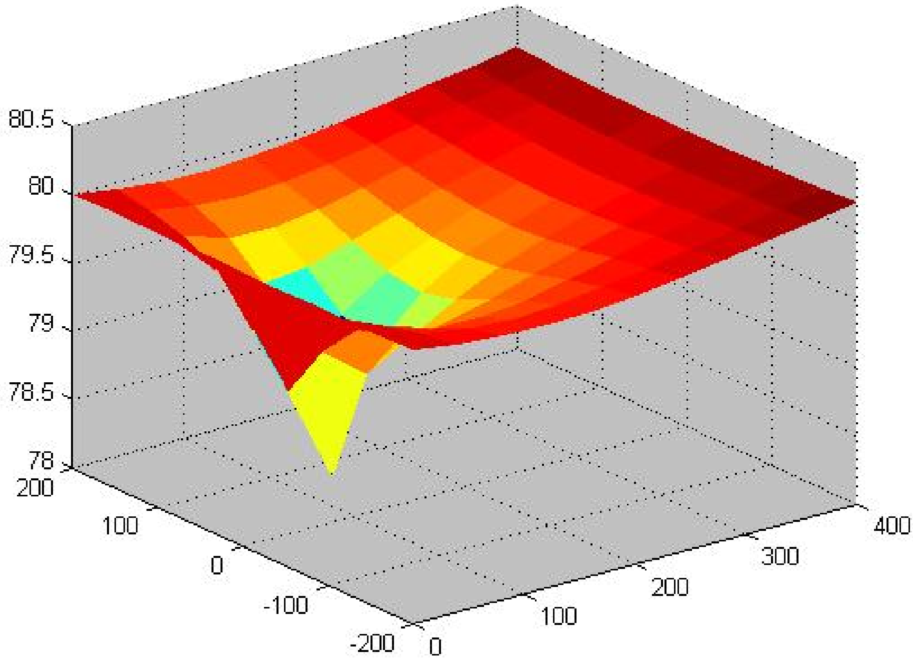


Figure 19 *3D plot of the hydraulic head distribution with a grid spacing of 40 m and a grid extent of [0:400] and [-200:200] for x-axis and y-axis, respectively. Note that the total amount of grid nodes is 100 and the corresponding depression cone is 1.6m.*

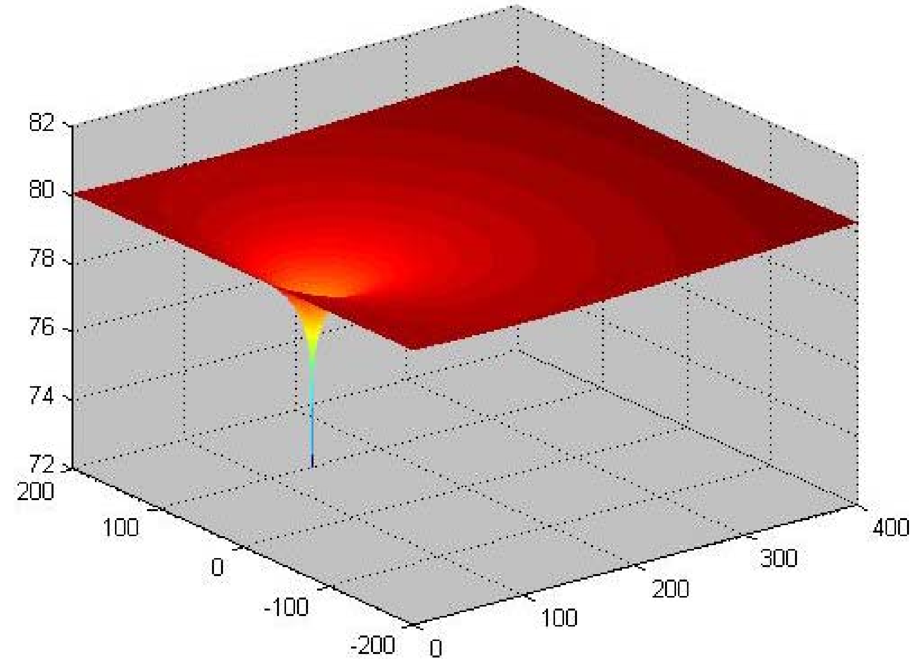


Figure 20 *3D plot of the hydraulic head distribution with a grid spacing of 0.2m and a grid extent of [0:400] and [-200:200] for x-axis and y-axis, respectively. Note that the total amount of grid nodes is 4000000 and the corresponding depression cone is 6.2 m.*

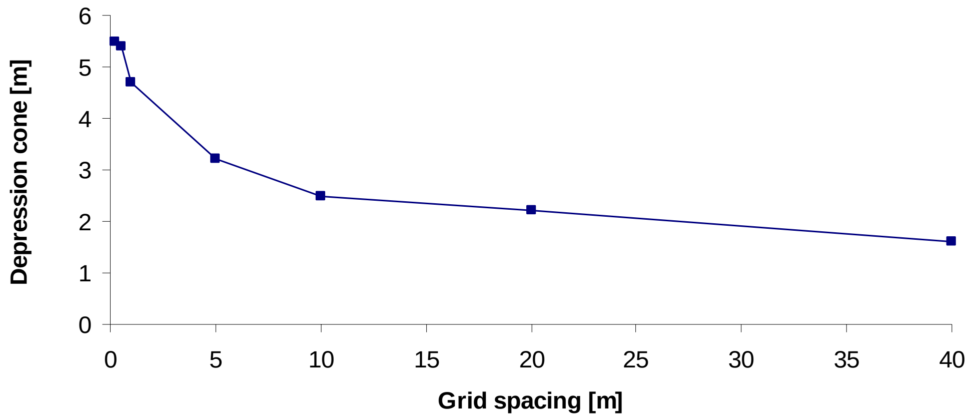


Figure 21 *Influence of the grid spacing on the depression cone calculation*

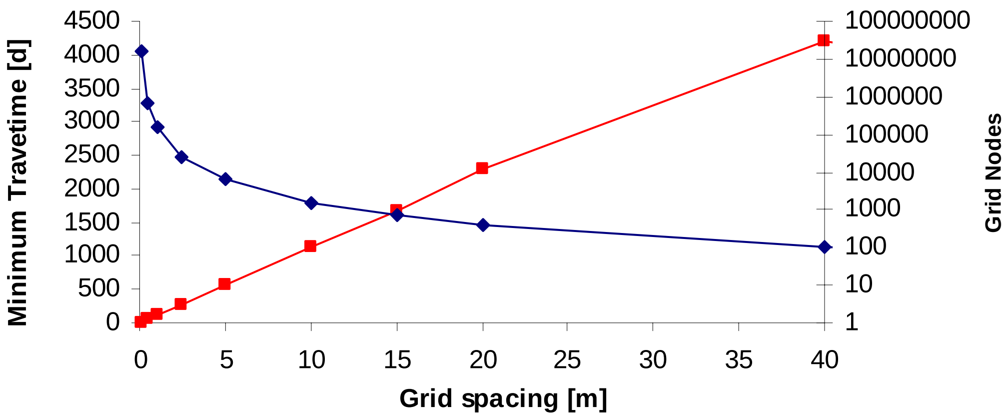


Figure 22 *Influence of the grid spacing on the calculated minimum traveltime (red) and the number of grid nodes (blue). Note that the scale on the right y-axis for the grid nodes is logarithmic, showing the non-linear dependency between grid spacing and the number of grid nodes!*

7.2 Aquifer characteristics

7.2.1 Baseflow

The BFS offers two options for calculating the baseflow component by using either the hydrological balance (Chapter 5.3.4.2) or Darcy's law (Chapter 5.3.4.1). Only for the latter one the sensitivity analysis is performed by varying each parameter (hydraulic conductivity, hydraulic gradient and reference thickness) one by another, which is explained in detail in the following sub-chapters.

7.2.1.1 Hydraulic conductivity

At first the model pre-defined aquifer matrixes (coarse gravel to clay) and their corresponding hydraulic conductivity are chosen as input parameters (see *Table 3*). The baseflow is calculated according to Darcy's law and is recalculated every time the aquifer matrix was varied (see Chapter 5.3.4.1). As a result, the lower the hydraulic conductivity of the aquifer matrix, the higher is the share bank filtrate (see *Figure 23*). At first this might be surprising but is plausible since the baseflow of ambient groundwater towards the bank decreases as the hydraulic conductivity of the aquifer matrix decreases.

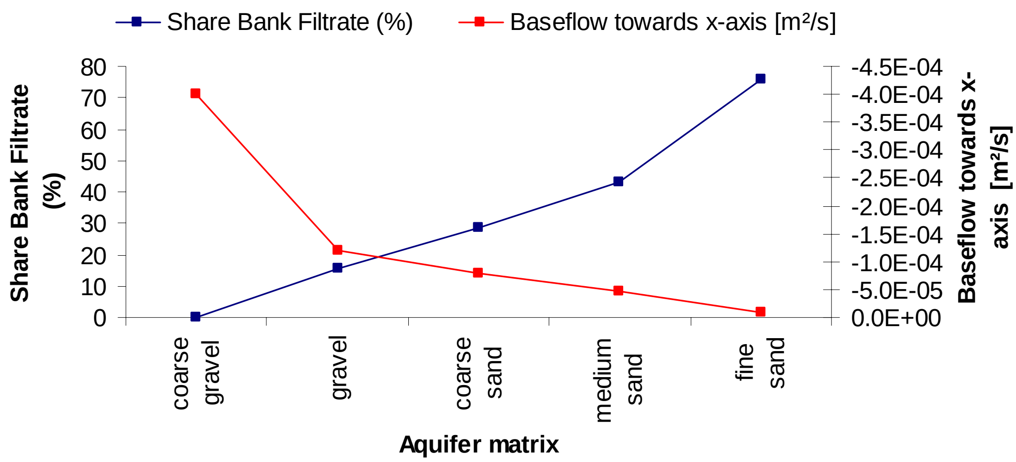


Figure 23 *Influence of the hydraulic conductivity on the share bank filtrate (blue line) and baseflow (red line); no values are given for sandy silt and clay because the aquifer is partially running dry.*

Varying the hydraulic conductivity does not only change the portions of bank filtrate and baseflow but also the minimum traveltime (see *Figure 24*). This is due to the fact that the calculation of the average interstitial groundwater velocity depends on the hydraulic conductivity as well (see Chapter 3 for the mathematical background). Subsequently it is plausible that the minimum traveltime is lowered as the share bank filtrate increases.

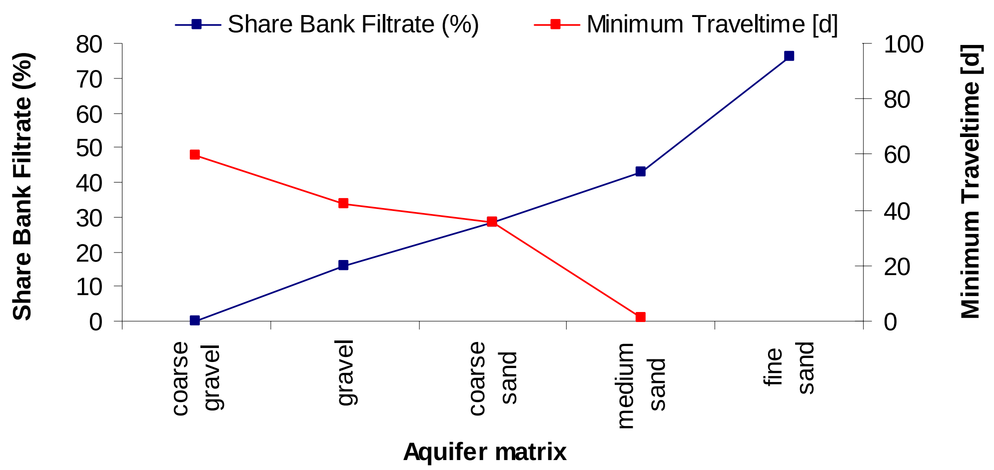


Figure 24 *Influence of the hydraulic conductivity on the share bank filtrate (blue line) and the minimum traveltime (red line); no values are given for sandy silt and clay because aquifer is partially running dry.*

7.2.1.2 Hydraulic gradient

The hydraulic gradient is directly related to the baseflow. The lower the hydraulic gradient of the ambient groundwater towards the bank, the higher the share bank filtrate and vice versa. According to *Figure 25* the share bank filtrate in the pumped groundwater increases with decreasing hydraulic gradient. The opposite result is observed for the minimum traveltime.

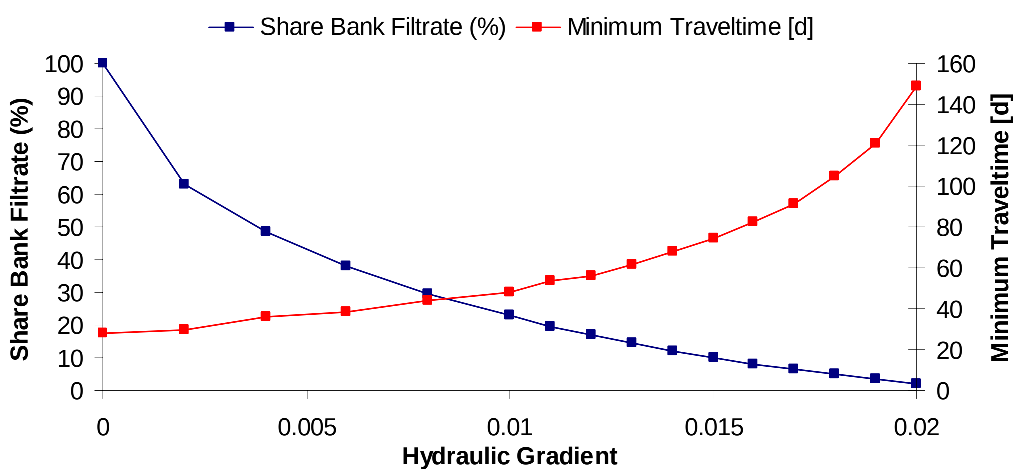


Figure 25 *Influence of the hydraulic gradient on share bank filtrate and minimum traveltime. Grid parameters: [0:1:200] [-100:1:100]*

7.2.1.3 Reference thickness

The reference thickness (= saturated aquifer thickness) is an important parameter if one calculates the baseflow with Darcy's law. As shown in *Figure 26*, the higher the reference thickness, the lower the bank filtration share and the greater the minimum traveltime.

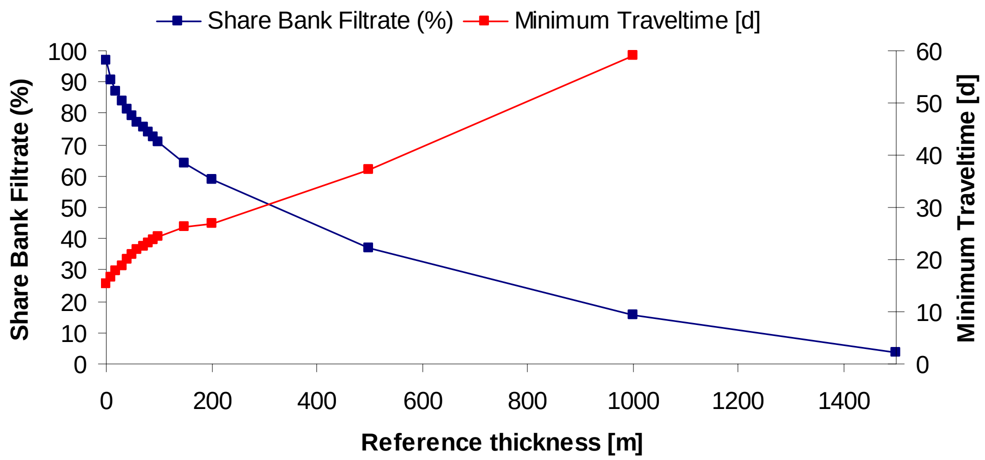


Figure 26 Influence of reference thickness on bank filtration share and minimum traveltime calculation

7.2.2 Porosity

Due to the parameterisation of the model, the porosity only has an effect on the computed minimum traveltime. The lower the porosity, the lower the computed minimum traveltime. As shown in *Figure 27*, the computed minimum traveltime linearly depends on the porosity, which fits perfectly with the underlying physical based equation for the average interstitial groundwater velocity (see Chapter 3).

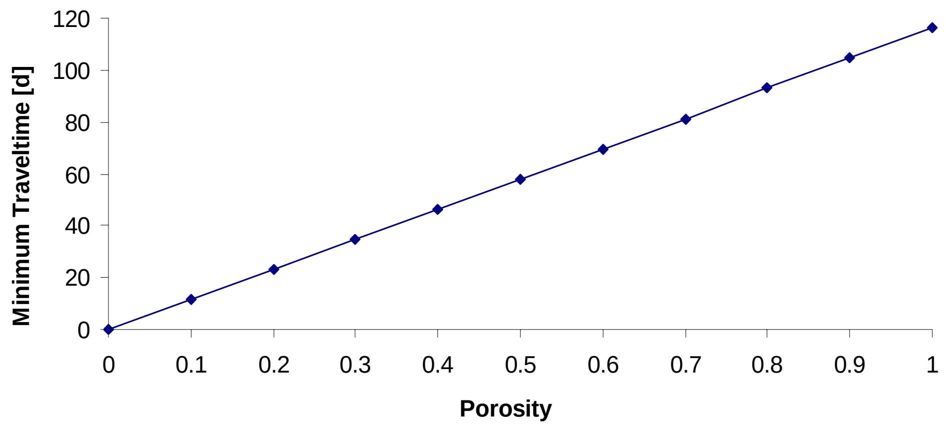


Figure 27 Influence of effective porosity on minimum traveltime calculation

7.3 Bank characteristics

7.3.1 Orientation

The orientation of the bank either on the x- or y-axis has no effect on the outputs (see *Figure 28*), provided one takes care to modify the appropriate parameters before. Those parameters are: the grids (the extent for each axis must be inverted when the axes are inverted), the baseflow (its coordinates must be inverted when the axes are inverted, by choosing a 90° angle when defining the parameters for the baseflow), and the well position (the x and y coordinates must be inverted).
Moreover one must not study one well at the zero abscissa, since the BFS crashes in this case. In fact the deviation of the minimum traveltime between both bank orientations is below 2% and therefore not visible in *Figure 28* since it is very small. In addition the deviation for the share bank filtrate remain below 1% (see Appendix A, *Table 14*). As a conclusion the influence of the bank orientation on both, share bank filtrate and minimum traveltime can be neglected.

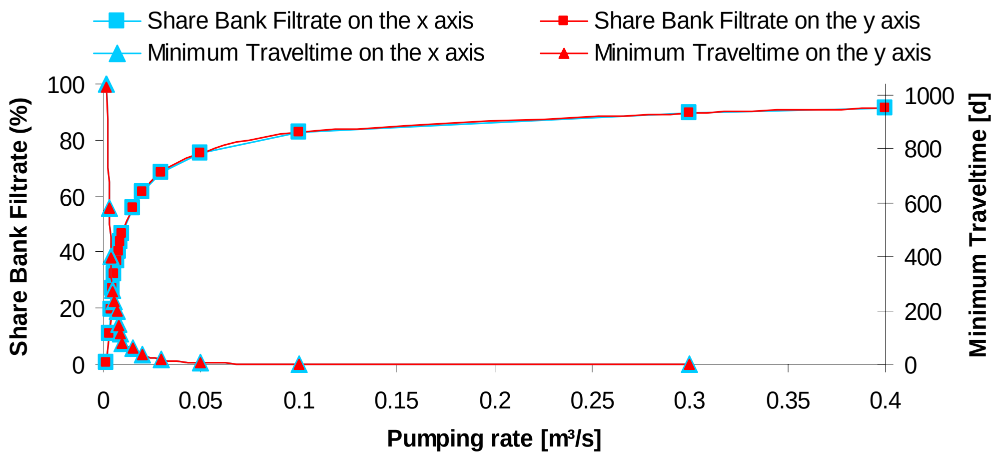


Figure 28 *Influence of the orientation of the bank on the share bank filtrate and the minimum traveltime calculation*

7.3.2 Clogging parameter

The clogging parameter has an effect on both, share bank filtrate and minimum traveltime, as shown in *Figure 29*. The share bank filtrate decreases with an increasing clogging parameter because the water volume exchanged between the bank and the aquifer is reduced. As a result the depression cone around the pumping well is greater if a clogging layer is present.

In addition, a higher clogging parameter results in a greater minimum traveltime of the bank filtrate towards the pumping well, which may have a positive effect on the quality of the abstracted water.

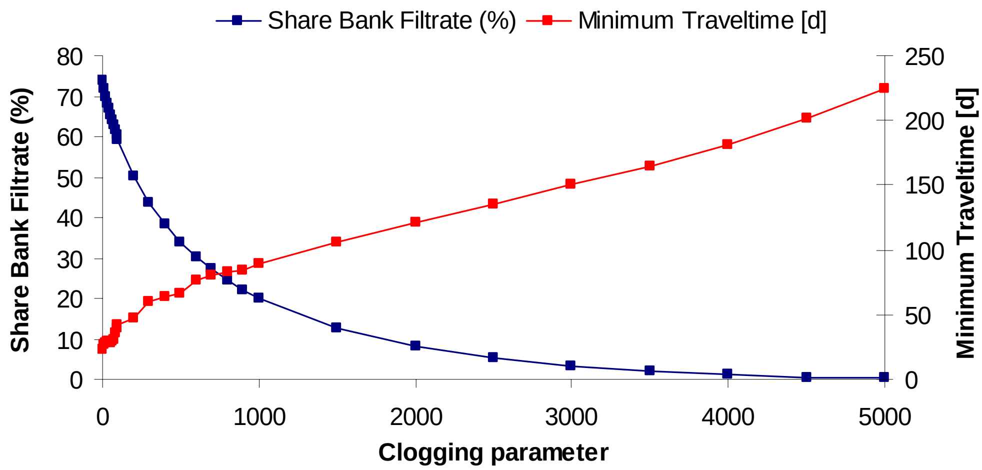


Figure 29 *Influence of the clogging parameter on the share bank filtrate and the minimum traveltime*

7.4 Well characteristics

7.4.1 Pumping rate

The pumping rate is varied between 0.002 m^3/s (=7.2 m^3/h) and 0.3 m^3/s (=1080 m^3/h). The effects on both, bank filtration share and minimum traveltime are analysed in *Figure* 30. The higher the pumping rate, the higher the portion of bank filtrate and the lower the minimum traveltime. Thus the pumping rate is a crucial operational parameter, which has a big impact on both, bank filtration share and minimum travel time.

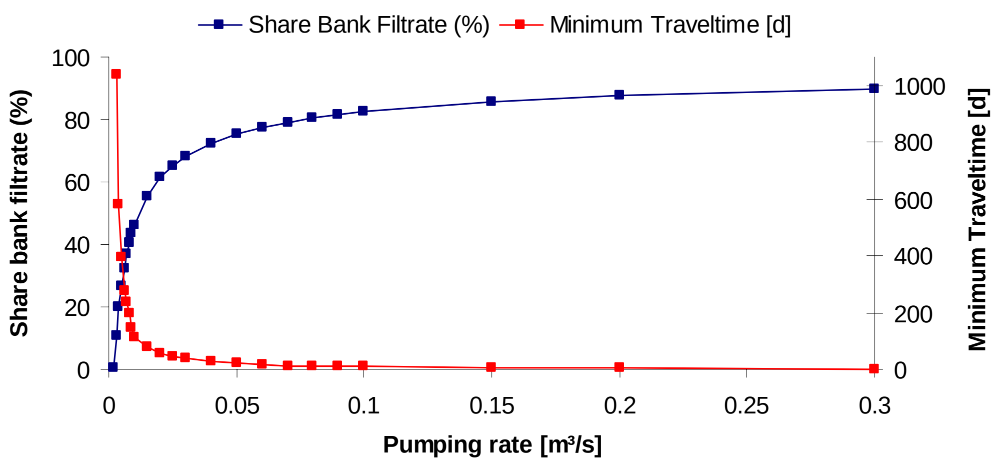


Figure 30 *Influence of varying pumping rates on bank filtration share and minimum traveltime. The distance between the bank and the well is 63 meters. Note that below a pumping rate of 0.002m³/s, the minimum traveltime becomes infinite, since the hydraulic gradient between bank and well is too low*

7.4.2 *Distance to bank*

The distance between the well and the bank is varied, as shown in *Figure 31*. The bank filtration share decreases and the minimum traveltime increases with greater distances to the bank. Because the distance between bank and well has an adverse effect either on the quantity (low share bank filtrate) or the quality (low the minimum traveltime) it requires a trade-off strategy. The user has to 'optimise' the well operation to a predefined purpose (e.g. highest quantity of bank filtrate, under the constraint of conservation of a pre-defined minimum traveltime).
Moreover the depression cone depth increases as the well is located further and further away from the bank, so that the bank filtration share becomes less efficient (*Figure 32*).

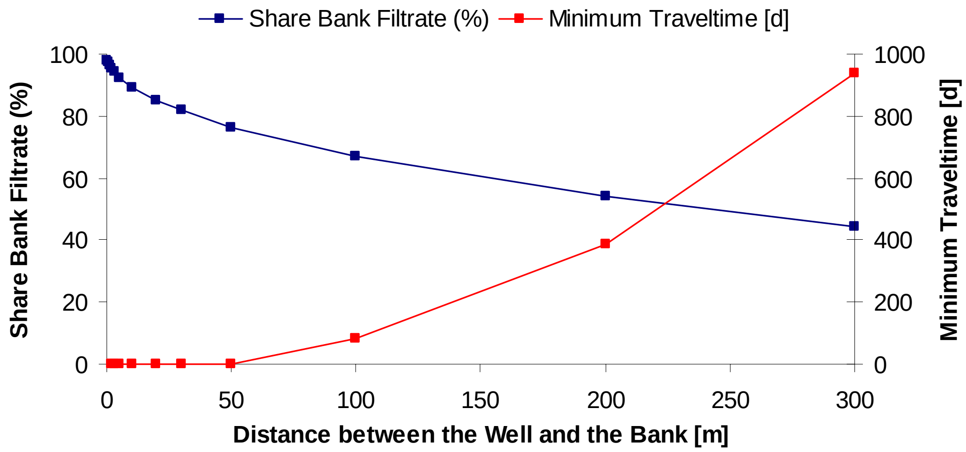


Figure 31 *Influence of varying production well distances to the bank for a constant pumping rate of 0.044 m³/s*

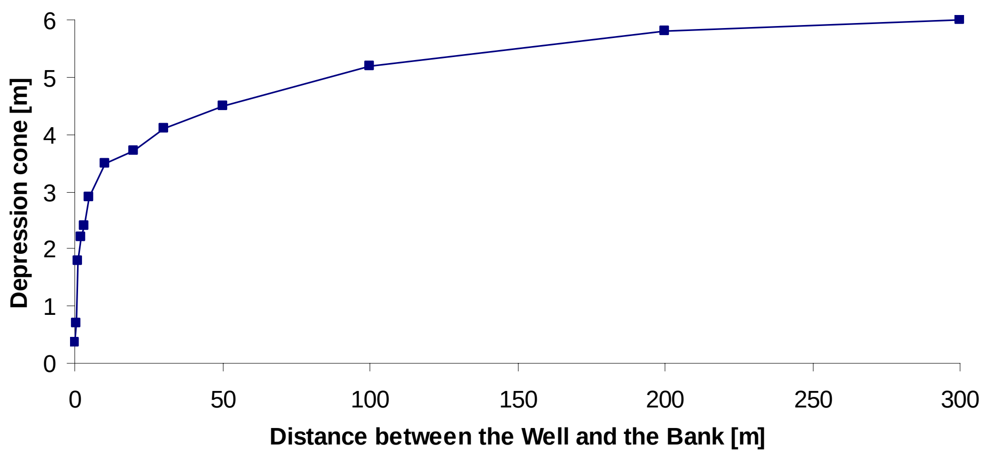


Figure 32 *Influence of the distance between one well and the bank on the depression cone depth*

In addition *Figure 33* illustrates that the maximum distance with a non-zero bank filtration share strongly depends on the well's pumping rate. For example at a distance of 400 m from the bank, the share bank filtrate is nearly zero for a pumping rate of 0.011 m^3/s, whereas with the double pumping rate the portion of bank filtrate increases to about 20%. This shows that higher pumping rates can easily improve the share bank filtrate at a location that would not benefit of the (additional) surface water source with a lower pumping rate.

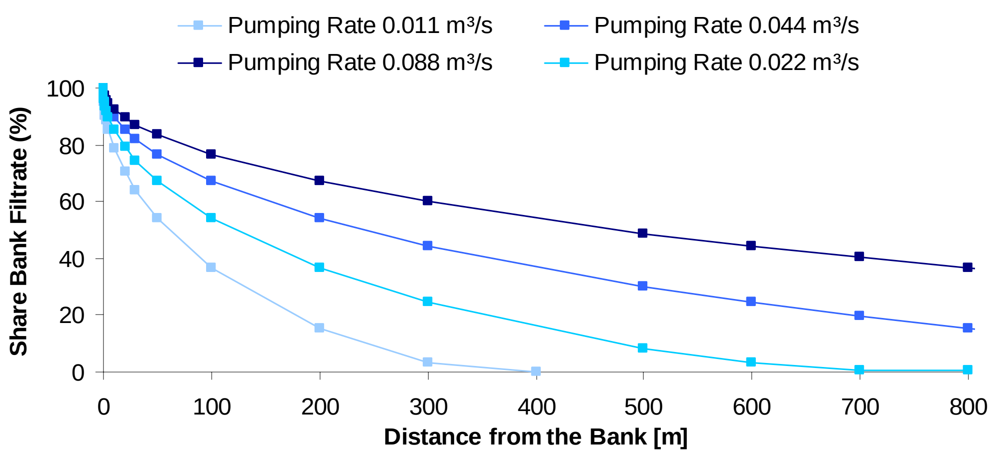


Figure 33 *Influence of varying pumping rates (coloured lines) and different well distances to the bank (squares) on the share of bank filtrate*

7.4.3 Well spacing

To analyse the effect of two competing wells a second well is placed in the model, at the same distance from the bank. Model runs are carried out with well spacing (distance between the wells) ranging from 50 to 150 m (*Figure 34*). It can be deduced that the distance between the two pumping wells should be big enough so that their depression cones do not overlap and subsequently influence each other. This is only the case if the well spacing is at least 150 m. Otherwise (e.g. well spacing of 50 m, see the top of *Figure 34*) this would lead to a well's performance decrease under field conditions (due to a lowered aquifer transmissivity) because the wells would compete for the same groundwater source (but not in this model because the well pumping rates are assumed to be independent of the recent water level!).

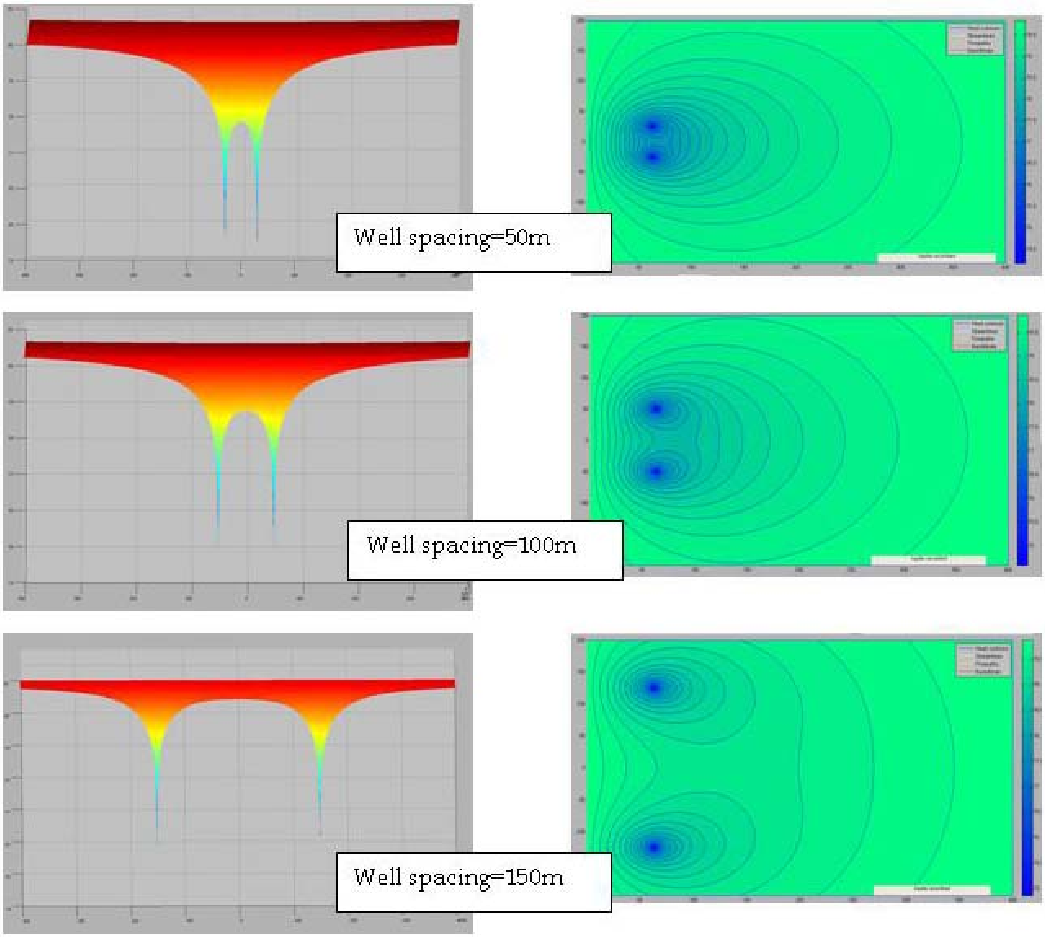


Figure 34 *Influence of varying well spacing on the depression cones overlapping (left column) and on the head gradient (right column). The pumping rate for each well is 0.044 m^3/s. It is recommended that for this hypothetical hydrogeological setting and well configuration (distance from bank, pumping rate) the distance between both wells should be more than 150 m so that their depression cones do not overlap. The latter would lead to a lower well performance in field situation (due to a decrease in transmissivity in the case of an unconfined aquifer) but not in the BFS, since the pumping rate is assumed to be independent of the recent water table*

7.5 Accuracy of minimum traveltime calculation

In order to check if the numerical BFS algorithm for the minimum traveltime is not only qualitatively but also quantitatively plausible, it is compared against results gained by the well-known MODFLOW model (HARBAUGH et al. 2000). The graphical user interface PMWIN (CHIANG & KINZELBACH 2005) is used as pre- and postprocessor.
The site specific steady state groundwater model consists of 400 rows and columns, respectively. In addition each grid cell has a length and width of 1m, respectively. The boundary conditions were defined as constant head (western boundary), specific flux (eastern boundary) and no-flow (northern and southern boundary), which is illustrated in Appendix A, Figure 36. Thus the MODFLOW model uses exactly the same parameters as the BFS (see Table 4). However, since MODFLOW is a numerical groundwater model it requires an explicit definition of the boundary conditions to calculate the groundwater flow field. The initial hydraulic heads at the western and eastern boundary is specified at 80m and 80.4m, respectively. For the minimum traveltime calculation the advective transport model MODPATH (POLLOCK 1994) was used, which is based on a semi-analytical particle tracking scheme. The time step for the particle tracking algorithm is set at 0.1 days.
The minimum traveltime results for different pumping rates are shown in Figure 35. It is easily visible that the biggest deviations of approximately 40% for the minimum traveltime occur between MOFLOW/MODPATH and the BFS version 1.0. Note that BFS version 1.0 has been used to perform the qualitative sensitivity analysis (see chapter 7.1 - 7.4)! Since the updated BFS version 1.01 uses a ten times higher accuracy for the minimum traveltime calculation, the resulting deviation from the MODFLOW/MODPATH results are very low (<5%). A detailed numerical comparison of these results is given in Appendix A, Table 20.

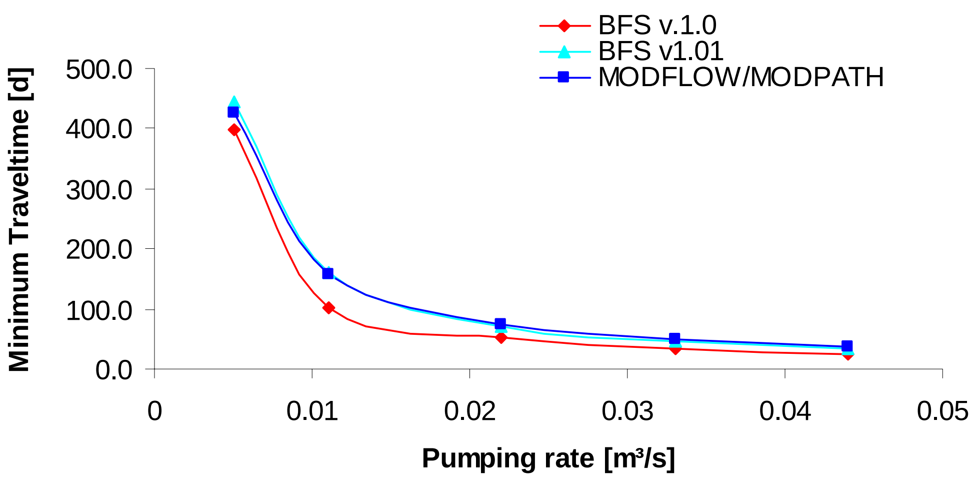


Figure 35 *Accuracy of the minium traveltime output for the two BFS versions (1.0 and 1.01) compared to the MODFLOW/MODPATH results for different pumping rates*

7.6 Conclusion

The sensitivity analysis yielded that the analytically calculated BF share is the most reliable output parameter, since its value is only affected by the parameterisation of bank, aquifer and well characteristics and independent of the grid characteristics. In addition the most sensitive parameters are the hydraulic conductivity of the aquifer (see chapter 7.2.1.1) and the clogging parameter (see chapter 7.3.2), which are both the most uncertain ones. Moreover they are assumed to be homogenous within the BFS but can vary (depending on the scale!) up to several logarithmical orders of magnitude under field conditions (CALVER 2001, KRESIC 2007).
The numerical computation of the minimum traveltime is a less reliable model output parameter since it is not only dependent upon the above described parameterisation (bank, aquifer and well characteristics) but also requires an adequate grid layout (see chapter 7.1) and the (effective) porosity of the aquifer as additional input parameter. The former is the most sensitive one, due to the strong non-linear dependence between grid spacing and calculated grid nodes. Thus, empirical rules-of-thumb based on model simulations may help the user in avoiding errors associated with an inadequate grid layout (see chapter 7.1). Nevertheless the quantitative accuracy check of the minimum traveltime calculation against the MODFLOW/MODPATH model yielded that the deviation between both is very small for the updated BFS version 1.01 (see chapter 7.5). Subsequently the resulting uncertainty of the minimum traveltime algorithm can be neglected since the selection of the grid characteristics has a much higher impact on the minimum traveltime calculation (see chapter 7.1).

As a conclusion an easy steady-state model like the BFS cannot replace more sophisticated numerical groundwater models such as e.g. MODFLOW (HARBAUGH et al. 2000) if quantitative robust results are required. Only the latter are capable of simulating transient (time-dependent) and heterogeneous groundwater flow, which is usually the case at BF sites (WIESE & NÜTZMANN 2009). However the BFS can be used as a first qualitative assessment tool to check the feasibility of BF systems for drinking water supply. Firstly, the BFS is capable of simulating the effect of different aquifer, bank and well characteristics for an area of interest in a physically based way in order to add transparency and reproducibility to the decision making process. Secondly its application requires only low effort concerning time, money, and manpower. Therefore the application of the BFS is recommended to accompany decision making processes especially in developing and newly industrialised countries where data availability and low financial budgets are usually the major burden for the application of the more adequate transient numerical groundwater models stated above.

8 References

CALVER, A. (2001): Riverbed permeabilities: Information from pooled data Ground Water 39(4): 546-553

CHIANG, W.-H. & KINZELBACH, W. (2005): 3D-groundwater modeling with PMWIN. Berlin, New York, Springer.

GOLDEN SEARCH TECHNIQUE (2009): Golden Search Technique. http://pages.intnet.mu/cueboy/education/notes/algebra/goldensectionsearch.pdf

HARBAUGH, A. W.; BANTA, E. R.; HILL, M. C. & MCDONALD, M. G. (2000): MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model - User Guide to Modularization Concepts and the Ground-Water Flow Process. Open-File Report, U. S. Geological Survey. 2000-92: 121, http://water.usgs.gov/nrp/gwsoftware/modflow2000/ofr00-92.pdf

HOLZBECHER, E. (2007): Environmental modeling. Berlin, Springer.

JOHNSON, A. I. (1967): Specific yield - compilation of specific yields for various materials. Water Supply Paper, U. S. Geological Survey. 1662-D, http://pubs.er.usgs.gov/djvu/WSP/wsp_1662-D.djvu

KRESIC, N. (2007): Hydrogeology and groundwater modeling. Boca Raton, Fla., CRC Press.

POLLOCK, D. W. (1994): User's guide for MODPATH/MODPATH-PLOT, Version 3; a particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model. Open-File Report, U. S. Geological Survey. 94-464: 248 p., http://water.usgs.gov/nrp/gwsoftware/modpath5/modpath5.html

RUSTLER, M. & BOISSERIE-LACROIX, C. (2009): Developement of a Decision Support System. TECHNEAU Integrated Project. D5.2.11

STRACK, O. D. L. (1989): Groundwater mechanics. Englewood Cliffs, NJ, Prentice Hall.

VAN DER VEER, P. (1994): Exact solutions for two-dimensional groundwater flow in a semiconfined aquifer Journal of Hydrology 156(1): 91-99

VAN DER VEER, P. (1995): Exact solutions for two-dimensional groundwater flow in a semiconfined aquifer Journal of Hydrology 171(1): 213-214

WIESE, B. & NÜTZMANN, G. (2009): Transient leakance and infiltration characteristics during lake bank filtration Ground Water 47(1): 57-68

Appendix A

Grid characteristics

Table 5 Grid extent and depression cone (data for *Figure 17*)

Grid extent [m]	Depression cone [m]
63	5
70	5
80	5
90	5
100	5
150	5
200	4.9
250	4.8
300	5
350	4.3
400	4.4
450	4.5
500	4.9
600	4.5
700	4.6
800	4.5
900	4.7
1000	4.4

Table 6 Grid extent (data for *Figure 18*)

Grid extent [m]	Minimum traveltime [d]	Number of grid nodes
20	48.2	400
30	71.1	900
40	83.7	1600
50	96.2	2500
60	102	3600
70	102	4900
80	102	6400
90	102	8100
100	102	10000
150	100	22500
200	97.1	40000
250	96.1	62500
300	94.8	90000
350	91.3	122500
400	89.1	160000
450	88.6	202500
500	91.2	250000
600	82.8	360000
700	86.6	490000
800	73.7	640000
900	73.4	810000
1000	74.9	1000000

Table 7 Grid spacing and depression cone (data for *Figure 21*)

Grid spacing [m]	Depression cone [m]
0.2	5.5
0.5	5.4
1	4.7
5	3.2
10	2.5
20	2.2
40	1.6
50	1.3
60	1.3
70	1.7
90	1.2
100	1.3
110	0.5
120	0.6
150	0.5

Table 8 Grid spacing *(*data for *Figure 22)*

Grid spacing [m]	Minimum traveltime [d]	Number of grid nodes
0.1	10.4	16000000
0.5	55.4	640000
1	111	160000
2.5	281	25600
5	577	6400
10	1129	1600
15	1673	711
20	2299	400
40	4215	100
80	2706	25
100	31565	16

Aquifer characteristics

Table 9 Aquifer matrix (data for *Figure 23* and *Figure 24*)

Aquifer matrix	Share bank filtrate (%)	Minimum traveltime [d]	Baseflow [m²/s]
coarse gravel	0	Inf	-4.00E-04
gravel	15.7	59.9	-0.00012
coarse sand	28.4	42.2	-8.00E-05
medium sand	43.0	35.4	-4.80E-05
fine sand	76.0	0.99	-8.00E-06

Table 10 Hydraulic gradient (data for *Figure* 25)

Hydraulic gradient	Share bank filtrate (%)	Minimum traveltime [d]
0	100	28.4
0.002	63.1	29.5
0.004	48.6	35.7
0.006	38.1	38.3
0.008	29.7	44.4
0.01	22.8	48.0
0.011	19.8	53.6
0.012	17.0	55.9
0.013	14.4	61.5
0.014	12.1	67.8
0.015	9.99	74.3
0.016	8.06	82.2
0.017	6.32	90.8
0.018	4.76	105
0.019	3.38	121
0.02	2.20	149

Table 11 Reference thickness (data for *Figure 26*)

Reference thickness [m]	Share bank filtrate (%)	Minimum traveltime [d]
1	97.0	15.4
10	90.7	16.5
20	86.8	17.7
30	83.8	18.9
40	81.3	19.9
50	79.2	20.9
60	77.2	21.7
70	75.4	22.5
80	73.7	23.2
90	72.1	23.9
100	70.7	24.4
150	64.2	26.3
200	58.9	26.9
500	36.9	37.2
1000	15.7	59.1
1500	3.7	Inf

Table 12 Porosity (data for *Figure 27*)

Porosity	Minimum traveltime [d]
0	0
0.1	11.6
0.2	23.2
0.3	34.8
0.4	46.5
0.5	58.1
0.6	69.7
0.7	81.3
0.8	92.9
0.9	104.5
1	116.1

Bank characteristics

Table 13 Bank orientation (data for *Figure 28*)

Pumping Rate [m³/s]	Bank (x-axis)		Bank (y-axis)	
	Share bank filtrate (%)	Minimum traveltime [d]	Share bank filtrate (%)	Minimum traveltime [d]
0.002	0.46	Inf	0.48	Inf
0.003	10.7	1039.4	10.7	1029
0.004	19.8	580.5	19.8	579
0.005	26.8	397.7	26.8	396
0.006	32.3	276.0	32.3	270
0.007	36.8	235.3	36.8	235
0.008	40.5	195.8	40.5	195
0.009	43.6	148.3	43.6	146
0.01	46.3	111.2	46.3	111
0.015	55.6	79.2	55.7	79.1
0.02	61.4	59.0	61.4	58.8
0.03	68.3	37.0	68.3	36.8
0.05	75.3	19.7	75.3	19.5
0.1	82.5	8.51	82.5	8.37
0.3	89.9	2.66	89.9	2.62
0.4	91.2	2.06	91.2	2.03

Table 14 *Deviation of the minimum traveltime and the share bank filtrate between the two bank orientations according to the pumping rate*

Pumping Rate [m³/s]	Minimum traveltime deviation (%)	Share bank filtrate deviation (%)
0.003	1.02	0.46
0.004	0.33	0.25
0.005	0.36	0.18
0.006	2.29	0.15

0.007	0.29	0.12
0.008	0.58	0.11
0.009	1.40	0.09
0.01	0.09	0.09
0.015	0.21	0.06
0.02	0.35	0.05
0.03	0.61	0.04
0.05	1.03	0.03
0.1	1.64	0.02
0.3	1.62	0.01
0.4	1.63	0.01
MEAN VALUES	*0.90*	*0.11*

Table 15 Clogging parameter (data for *Figure 29*)

Clogging parameter	Share bank filtrate (%)	Minimum traveltime [d]
0	73.7	23.2
10	71.8	27.3
20	70.0	28.5
30	68.3	28.8
40	66.8	28.8
50	65.3	28.6
60	63.9	29.4
70	62.7	30.3
80	61.4	36.3
90	60.3	40.0
100	59.2	42.4
200	50.1	47.4
300	43.5	60.5
400	38.3	64.2
500	34.0	66.0
600	30.3	77.1
700	27.2	80.50
800	24.5	82.4
900	22.2	84.3
1000	20.1	89.1
1500	12.6	105
2000	8.03	121
2500	5.12	135
3000	3.22	151
3500	1.96	165
4000	1.13	182
4500	0.59	202
5000	0.25	224

Well characteristics

Table 16 Pumping rate (data for *Figure 30*)

Pumping rate [m³/s]	Share bank filtrate (%)	Minimum traveltime [d]
0.002	0.46	Inf
0.003	10.7	1040
0.004	19.8	580
0.005	26.8	398
0.006	32.3	275
0.007	36.8	235
0.008	40.5	196
0.009	43.6	150
0.01	46.3	116
0.015	55.6	79.1
0.02	61.4	59.02
0.025	65.3	46.0
0.03	68.3	37.1
0.04	72.5	26.1
0.05	75.3	19.8
0.06	77.5	15.9
0.07	79.1	13.2
0.08	80.4	11.2
0.09	81.6	9.75
0.1	82.5	8.6
0.15	85.7	5.49
0.2	87.6	4.07
0.3	89.9	2.75

Table 17 Distance of well to the bank (data for *Figure 31*)

Distance well-bank [m]	Share bank filtrate (%)	Minimum traveltime [d]
0.2	98.1	Inf
0.5	97.4	Inf
1	96.5	Inf
2	95.2	0.79
3	94.1	0.92
5	92.5	0.97
10	89.4	1.10
20	85.1	1.28
30	81.8	1.39
50	76.5	1.23
100	67.0	82.1
200	54.0	385
300	44.3	936

Table 18 Pumping rate and distance of the well to the bank (data for *Figure 33*)

Share bank filtrate (%)	Pumping rate [m³/s]			
Distance well-bank [m]	**0.088**	**0.044**	**0.022**	**0.011**
0	100	100	100	100
0.2	98.7	98.1	97.4	96.3
0.5	98.2	97.4	96.3	94.8
1	97.5	96.5	95.1	93.0
2	96.6	95.2	93.2	90.4
3	95.9	94.1	91.7	88.3
5	94.7	92.5	89.4	85.0
10	92.5	89.4	85.1	78.9
20	89.4	85.1	79.0	70.4
30	87.1	81.8	74.3	63.9
50	83.4	76.5	67.0	53.9
100	76.6	67.0	53.9	36.5
200	67.0	54.0	36.5	15.2
300	59.9	44.3	24.3	3.35
500	48.8	30.0	8.3	0
600	44.3	24.30	3.4	
700	40.2	19.5	0.35	
800	36.5	15.2	0.35	
900	33.1	11.5		
1000	30.0	8.34		
1100	27.1	5.62		
1200	24.4	3.36		
1300	21.8	1.58		
1400	19.5	0.35		
1500	17.3	0.35		
2000	8.3			
2500	0			

Table 19 Distance of well to the bank (data for *Figure 32*)

Distance well-bank [m]	Depression cone [m]
0.2	0.35
0.5	0.7
1	1.8
2	2.2
3	2.4
5	2.9
10	3.5
20	3.7
30	4.1
50	4.5
100	5.2
200	5.8
300	6

Accuracy of minimum traveltime calculation

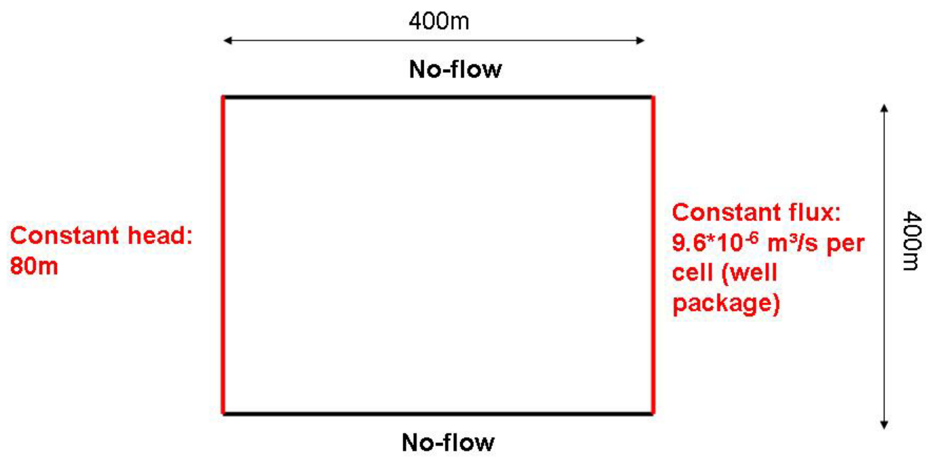


Figure 36 Boundary conditions for the site specific MODFLOW-2000 model; Note that each cell is a length and width of 1m, respectively!

Table 20 Calculated minimum traveltimes using the two BFS versions compared to site specific MODFLOW/MODPATH model

Parameter	Model	Pumping rate				
		0.044	**0.033**	**0.022**	**0.011**	**0.005**
Minimum Traveltime [d]	**BFS v.1.0**	23.2	33.1	53.1	103.4	397.6
	BFS v1.01	34.7	46.5	72.2	159.2	443.9
	MODFLOW/MODPATH	35.6	48.1	73.4	158.2	425.8
Deviation of model results [%]	**BFS v1.0 - Modflow**	34.7	31.2	27.6	34.7	6.6
	BFS v1.01 - Modflow	2.4	3.3	1.7	-0.6	-4.2

Appendix B

I / OPTIMISATION OF THE GRID SPACING

Taking the same parameters as in **Chapter 7** (63m between the well and the bank), we study the influence of the hydraulic gradient on the minimum traveltime with different grid spacings ranging from 1m up to 100m (see *Figure 37*). We only focus on the hydraulic gradient because this parameter is the most affected when the grid spacing is varied. If the spacing between the grid nodes is too high (above 6m), the minimum traveltime becomes far too high to be correct and the evolution with the hydraulic gradient is not the expected one. For a smaller grid spacing (below 6m) the evolution of the minimum traveltime becomes correct.
In a second model run we choose a distance between the bank and the well of 20m and we vary the grid spacing between 0.1m and 10m (see *Figure 38*).

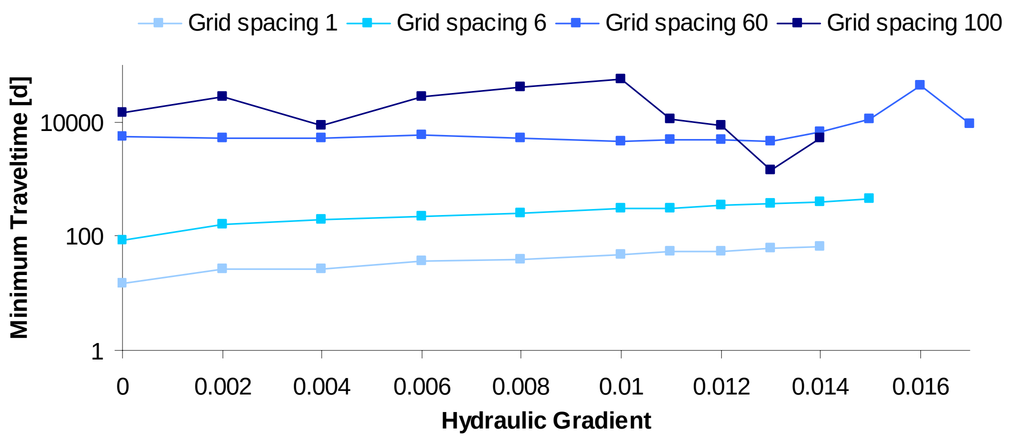


Figure 37 *Influence of the grid spacing on the minimum traveltime for a pumping well at 63m from the bank*

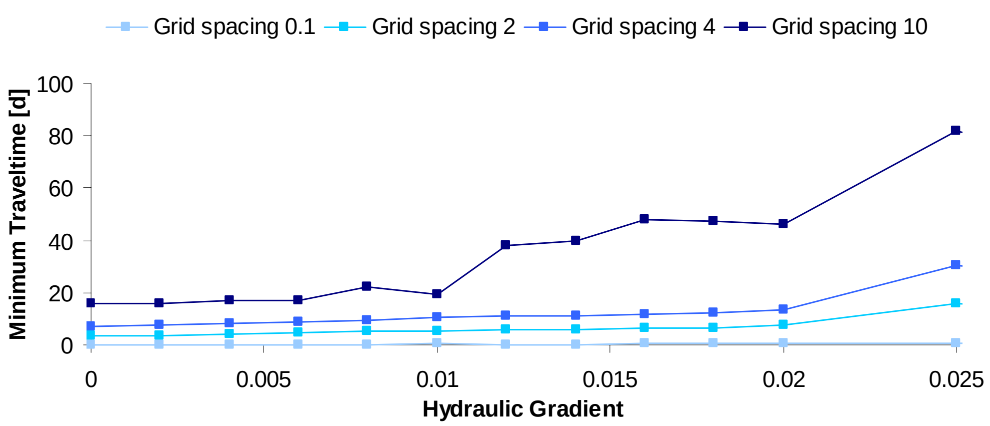


Figure 38 *Influence of the grid spacing on the minimum traveltime for a pumping well at 20m from the bank*

As previously the qualitative evolution of the minimum traveltime is only correct for grid spacings smaller than 2m. The same conclusion can be drawn with a distance well-bank of 200m (data not shown). For a grid spacing coarser than 20m, the evolution of the minimum traveltime is no longer correct. As a result we can deduce the following rule-of-thumb:
Grid spacing < Distance (Bank-Well) / 10

II / OPTIMISATION OF THE GRID EXTENT

We choose the same parameters as in the **Chapter 7** to study the influence of the hydraulic gradient on the minimum traveltime. This time the grid spacing is kept constant (1m), but the extent of the axis is varied. In a first step we choose a distance between the well and the bank of 63m. The simulations are made for the following values of the extent of the grid: 200 / 400 / 500 / 800 / 1000 / 2000 m (see *Figure 39*). The evolution of the minimum traveltime is correct for a grid extent under 500 m, which is 8 times the distance between the well and the bank (63 m).
Subsequently we choose a distance between the well and the bank of 200 m. The simulations are made for the following values of the extent of the grid: 1000 / 1200 / 1400 / 1600 / 2000 m (see *Figure 40*). In this case above 1600 m the evolution of the minimum traveltime is no longer correct, which is above 8 times the distance from the well to the bank.
At last we choose a distance between the well and the bank of 20 m. The simulations are made for the following values of the extent of the grid: 20 / 40 / 80 / 160 / 200/ 400 m (see Figure 41). The results are no longer correct when the extent of the grid is above 160 m. Subsequently we can deduce a second rule-of-thumb concerning the grid extent:
Extent of the Grid < 8 * Distance (Bank-Well)

Note that of course the extent of the grid must be superior to the distance of the well to the bank.

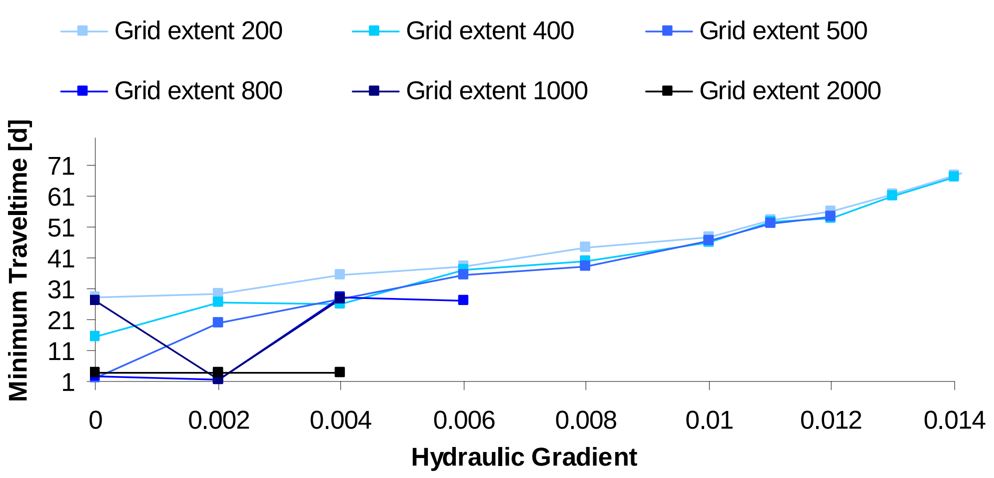


Figure 39 *Influence of the grid extent on the minimum traveltime for a distance between the well and the bank of 63 m*

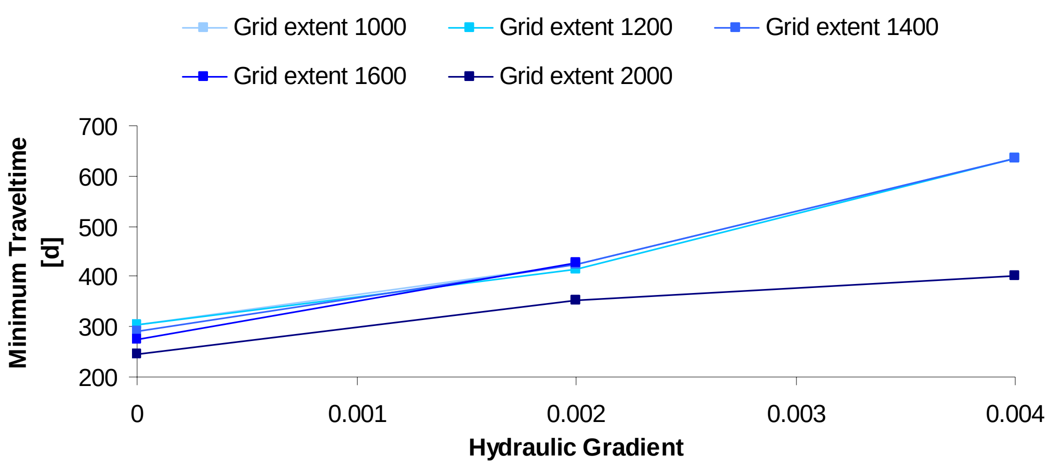


Figure 40 *Influence of the grid extent on the minimum traveltime for a distance between the well and the bank of 200 m*

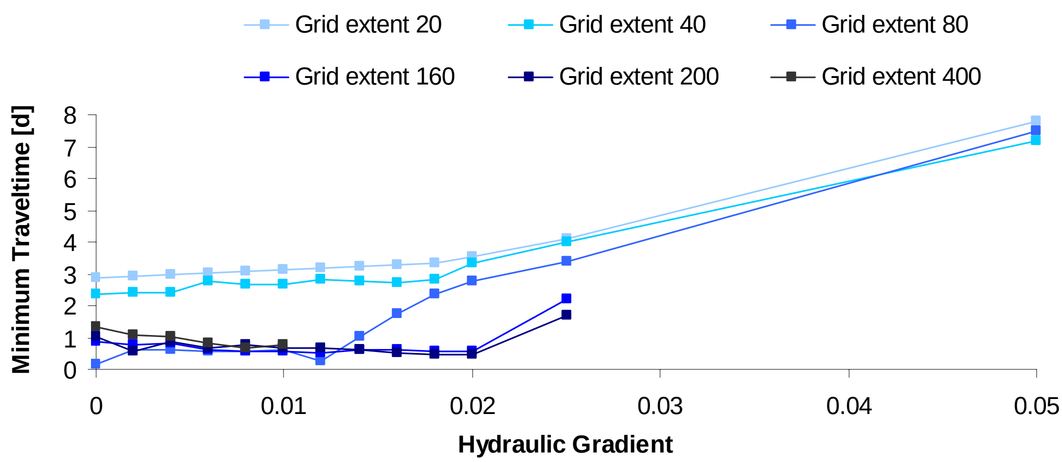


Figure 41 *Influence of the grid extent on the minimum traveltime for a distance between the well and the bank of 20 m*