Techneau, February 2011

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

Deliverable 5.2.11

Decision Support System for Bank Filtration Systems

TECHNEAU is an Integrated Project Funded by the European Commission under the Sixth Framework Programme, Sustainable Development, Global Change and Ecosystems Thematic Priority Area (contractnumber 018320).

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 within the project is the development of a Decision Support System (DSS) to assess the feasibility of BF systems under varying boundary conditions such as: (i) quality of surface and ambient groundwater, (ii) local hydrological and hydrogeological properties (e.g. clogging layer) and (iii) well field design (distance to bank) and operation (pumping rates). Since the successful, cost-effective implementation of BF systems requires the optimization of different objectives such as (i) optimizing the BF share in order to maintain a predefined raw water quality or (ii) maintaining a predefined minimum travel time between bank and production well, both aspects are addressed within the DSS.

As an example for a practical application the DSS is tested with data from the Palla well field in Delhi/India. As a result optimal shares of bank filtrate were calculated for the monsoon and non-monsoon season. By simulating different pumping and clogging scenarios with the BF Simulator optimal pumping rates were derived. The DSS proved to be a good qualitative tool to identify and learn about the trade-offs a decision maker has to make due to the (i) inherently competing nature of different objectives (e.g. high BF share and minimum travel time > 50 d) and the (ii) inherent uncertainty due to the large natural variability of boundary conditions (e.g. clogging layer). Since both characteristics can be addressed within the DSS it helps to add transparency and reproducibility to the decision making process. An additional advantage is that its application requires only low effort concerning time, money, and manpower. Thus the application of the DSS 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 more complex, data-demanding decision support tools. However, it needs to be considered that in practice additional parameters like water availability, energy efficiency and cost-benefit need to be taken into account.

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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*					
Database	X	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	X	Developing world location	x						
Financial / organisational									
Methodology	X								
Legislation / regulation									

Colophon

Title
Decision Support System for Bank Filtration Systems

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Deliverable number
D 5.2.11

This report is: PU (for public)

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1 Introduction

1.1 Background

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 within the project is the development of a decision support system (DSS) to assess the feasibility of BF systems under varying boundary conditions such as:

(i) quality of surface and ambient groundwater
(ii) local hydrological and hydrogeological properties
(iii) well field design and operation

1.2 Aim and Scope of the Report

As the implementation of BF systems requires the evaluation of multiple boundary conditions, which all can have an impact on the performance of BF systems (GRISCHEK et al. 2007), the planning of BF systems is a rather complex task. Thus a DSS, which takes all the above stated boundary conditions into account, was developed as a tool to r assist planners, engineers or decision makers in assessing the feasibility of BF systems.

The present report is aimed at the documentation of the DSS developed (Chapter 2), concerning installation, programming concept, implementation of the different sub-models and its limitations. In addition the DSS was tested with data for the Palla well field of northern Delhi, India (Chapter 3). First, water quality assessment was performed with the objective to identify an 'optimal' BF share range, which guarantees that the raw water has drinking water quality.

Subsequently, well field operation (pumping rate per well) was optimized in a trial-and-error approach with the BF Simulator for two distinct well field design scenarios in order to achieve a BF share, which lies within the above defined 'optimal' BF share range. In addition the impact of the natural boundary condition 'bank clogging' on the 'optimal' well field operation was assessed, since it is spatiotemporal and highly variable.

Finally the DSS results for the hypothetic Palla well field optimization case study were evaluated in the light of the model limitations and recommendations are made, for using the DSS efficiently (Chapter 4).

2 Documentation

2.1 Information required for using the BF-DSS

Before installing the BF-DSS be aware that you have at least the input data available listed in Table 1 below.

Table 1 Minimum input data requirements for the application of the BF-DSS

Domain	Input parameters
Water quality assessment	Surface water quality samples
	Ambient groundwater quality samples
Hydrogeology	**Aquifer type** (required parameters: aquifer thickness, saturated aquifer thickness)
	Ambient baseflow Option 1: Calculation with Darcy's law (required parameters: saturated aquifer thickness, hydraulic aquifer conductivity, natural hydraulic gradient of ambient GW without pumping Option 2: calculation with water budget (required parameters: groundwater recharge rate, areal extent of subsurface catchment)
	Porosity (parameter only required for minimum travel time calculation between bank and production well but not for share of BF calculation!)
Hydrology	**Colmation of the river/lake bank?** Option 1: no (> no additional parameter required) Option 2: yes (additional parameters: hydraulic conductivity of the river/lake, river/lake bank thickness)
Well field	**Design** (required parameters: x, y-coordinates for specification of distance between bank and production well and location along the bank)
	Operation (required parameters: pumping rate of each production well)

2.2 Installation

For the installation of the BF-DSS proceed according to the following steps:

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

- If the MCR is not installed on your computer, run the self-extracting executable MCRInstaller.exe, located in: \DSS\MATLAB\Runtime for DSS\. Its installation is required for execution of the DSS
- Note that you must possess administrative rights for installation of the MATLAB Runtime Components!
- Install the MATLAB Runtime Components on your PC as follows:
  - On the target machine, add the MCR directory to the system path specified by the target system's environment variable. NOTE: On Windows, the environment variable syntax utilizes backslashes (\), delimited by semi-colons (;)

    i. Locate the name of the environment variable 'Path' (under Windows)

    ii. Set the path by doing one of the following:

    NOTE: <mcr_root> is the directory where MCR is installed on the target machine.

    1) Add the MCR directory to the environment variable by opening a command prompt and issuing the DOS command:
    set PATH=<mcr_root>\v711\runtime\win32;%PATH%

    2) Alternately, add the following pathname:
    <mcr_root>\v711\runtime\win32
    to the PATH environment variable, by doing the following:

    1. Select the **My Computer** icon on your desktop.
    2. Right-click the icon and select **Properties** from the menu.
    3. Select the **Advanced** tab.
    4. Click **Environment Variables**.

Step 2: Installation of the DSS

- Copy all files from the following folder ...\DSS in a free selectable directory on your target machine (e.g. C:\Programs\DSS\)
- Run the DSS by executing the dss.exe in your above specified directory (here: C:\Programs\DSS\dss.exe)
- When a info box with the text **'Please select an option'** pops up choose **'Set DSS Directory'** and select the folder where you installed the DSS (here: C:\Programs\DSS\). To confirm your input click **'Ok'** and the DSS GUI will be started.
- If the DSS does not start the DSS folder selected in the last step was wrong. Subsequently you can try again by clicking the **'Set DSS Directory'** button or skip the program by pushing the **'Quit'** button.
- Note: the absolute path of the DSS is saved automatically in the file dss_absolutepath.txt in the folder ***<userdefined>\DSS*** and read out by the DSS in the start up process.

Note that the execution of the DSS requires a 32-bit Windows operating system (e.g. Vista, XP, 2000) and does not support any 64-bit Windows platform. In addition neither UNIX nor MAC operating systems are supported!
Furthermore for complete functionality an installed version of Microsoft EXCEL is required on the target machine. Note that the correctness of the DSS is only guaranteed if '.' is selected as decimal separator under: Control Panel>Regional Settings and Language Options>Regional Options>Adapt

2.3 Programming Concept and Implementation

The Decision Support System (DSS) is programmed with the software MATLAB® (THE MATHWORKS 2009a) and compiled as stand-alone version by using the MATLAB® Compiler™ (THE MATHWORKS 2009b). As shown in Figure 1 and Figure 2 the structure of the DSS is divided into four steps. The first three steps (water quality data, hazard calculation, mixing calculation) are needed for the water quality assessment in order to identify an 'optimal' BF share range. During the fourth step well field design and operation is interactively optimized in a trial-and-error approach through simulation modelling to achieve the 'optimal' BF share identified above. The function of each of the sub-models (purple ellipses, Figure 1) is described in detail in section 2.4.
Note that the DSS is developed according the proposal of BUYTAERT et al. (2008) as modular software under the Lesser General Public License (GNU PROJECT 1999) to trigger its development, including bug-fixing and quality control as well as adding transparency to the decision making process. However, this is not true for the BF simulator programmed by HOLZBECHER (2009).

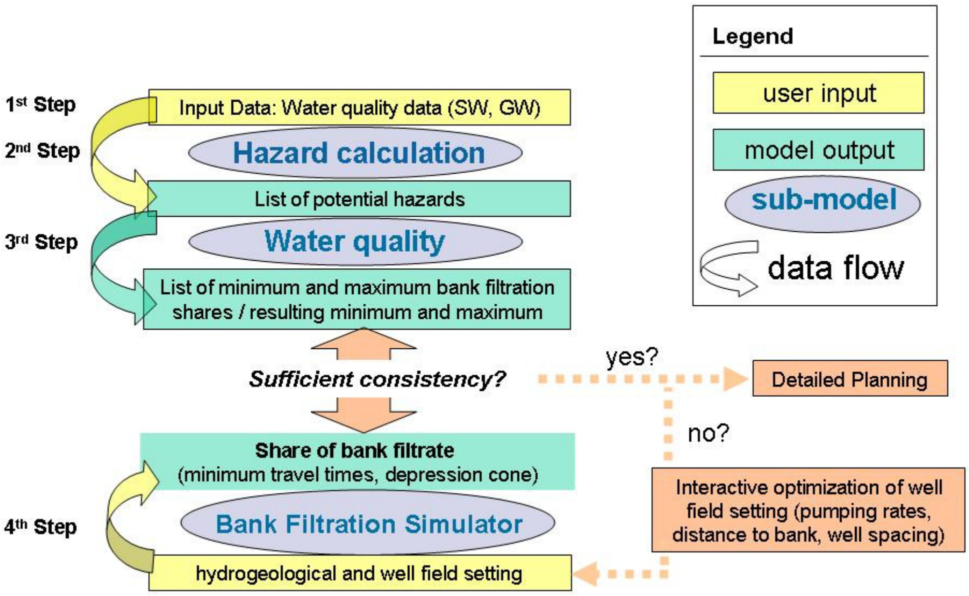
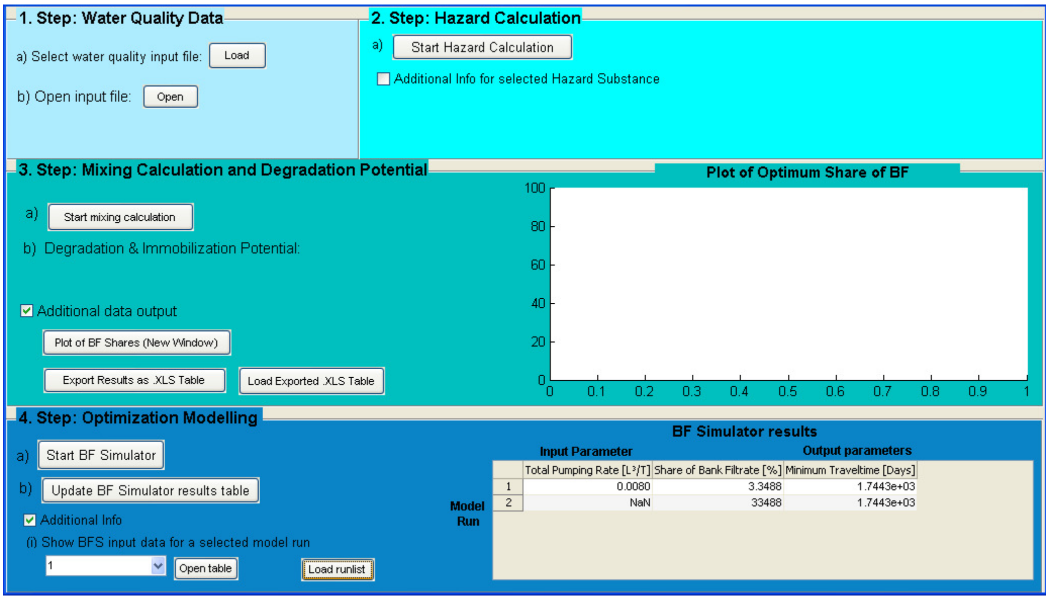


Figure 1 *Conceptual flow chart of the DSS for bank filtration*



BF Simulator results

Model Run	Input Parameter	Output parameters	
	Total Pumping Rate [L³/T]	Share of Bank Filtrate [%]	Minimum Traveltime [Days]
1	0.0080	3.3488	1.7443e+03
2	NaN	33488	1.7443e+03

Figure 2 *Screenshot of the DSS Graphical User Interface*

2.4 Sub-Models

2.4.1 *Water quality assessment*

2.4.1.1 *Input data (1. Step)*

The user has to specify a water quality input file by clicking the **'Load'** button and selection of an EXCEL file in a first step. It is important that the structure of the input file has to be exactly the same as given in Appendix A, Table 7 and Table 8 or in ***<userdefined>\DSS\data\userinput\userinput_dummy.xls***. Subsequently one has to specify the surface water and ambient groundwater concentrations for each substance that are to be considered within the DSS in the EXCEL file. It is further required to delete all rows for which no concentrations are specified. In addition the user should be aware that any change of the numbers in the column 'SubstanceID' leads to an erroneous hazard calculation, since this parameter is used as reference to compare each input substance against the concerning threshold value specified under: ***<userdefined>\DSS\data\helpdata\t_SubstHelpDat.xls***
The DSS offers the possibility to open the above selected EXCEL file by pressing the **'Open'** button. If the user makes modifications and saves this new EXCEL file version by clicking on **'Save'** or **'Save under'** button in the EXCEL program, one has to click on the **'Input'** button again, to adapt the modified EXCEL input file into the DSS. Note that the above described functionality only works if Microsoft EXCEL is installed on your PC.

2.4.1.2 *Hazard calculation (2. Step)*

Input:

In the second step surface- and ambient groundwater concentrations for each substance (specified under Step 1, see chapter 2.4.1.1) are compared to the corresponding threshold concentration derived from either the Drinking Water Guideline of the World Health Organization (WHO 2008) or – if not specified in the WHO guidelines – in the German Drinking Water Ordinance (TRINKWV 2001). The threshold values are saved under the following folder and filename:
<userdefined>\DSS\data\helpdata\t_SubstHelpDat.xls and can be easily adapted if the threshold value has changed or other guidelines apply.

Implementation:

The potential hazard calculation is implemented in the DSS according to the following equations:

if (c_{SW}(substance)>$c_{threshold}$(substance))or (c_{GWr}(substance) > $c_{threshold}$(substance)
then: substance = potential hazard

Subsequently if the threshold concentration of the input substance either in surface water (c_{SW}) or ambient groundwater (c_{GW}) is exceeded, it is identified as potential hazard.

Output:

If a quality parameter exceeds the pre-defined threshold a list of potential hazards is produced and visualized in the GUI output. In addition the user can select a potential hazard substance by clicking the **'Select'** button and check if surface water, ambient groundwater concentration or both exceeded the threshold value.
Further information for the selected substance is available after enabling the **'Additional Info'** button. Depending on the user's choice detailed information concerning either the substance itself (**'Substance Info'** button) or the substance group (**'Group Info'** button) is shown in a new window within the DSS. The given information was compiled in a literature review and is also documented in HÜLSHOFF et al. (2009)

2.4.1.3 Mixing calculation and degradation potential (3. Step)

Input:

For each potentially hazardous substance (calculated under Step 2 of the DSS, see *Chapter 2.4.1.2*) the surface water and the ambient groundwater concentrations (specified in user input file) as well as the threshold concentration defined in the file ***<userdefined>\DSS\data\helpdata \t_SubstHelpDat.xls*** are used for the conservative mixing calculation.

Implementation:

To quantify the possible dilution for all identified potentially hazardous substances a conservative mixing model is implemented in the DSS. The objectives and constraints of this model are defined according the following equations:

$$(1)\quad a \cdot c_{SW} + (b \cdot c_{GW}) \leq 0.9 \cdot c_{threshold}$$

$$(2)\quad a + b = 1$$

$$(3)\quad a, b \geq 0$$

where:

a = share of bank filtrate (surface water) (%)
b = share of ambient groundwater [%]
c_{SW}, c_{GW} = hazard concentration in surface water and groundwater, respectively
$c_{threshold}$ = threshold concentration of the specific hazard

Equation (1) states that the threshold limit for each substance is reduced by 10% to ensure a security margin, since the dilution is dependent on the BF share, which itself is strongly dependent upon the complex interrelationship between multiple and highly uncertain parameters (e.g. clogging layer, hydraulic conductivity). In addition equation (2) describes that only two sources of water (surface water and ambient groundwater) are considered in the mixing calculation. Note that only under the constraint of equation (3), that both, surface water and ambient groundwater shares in abstracted water are non-negative, the solution of equation (2) makes physical sense and is well defined. Subsequently by inserting equation (2) in (1) and converting to **a** the optimization problem can be simplified to equation (1.1):

$$a \cdot c_{SW} + (1-a) \cdot c_{GW} \leq 0.9 \cdot c_{threshold}$$

$$a \cdot c_{SW} + c_{GW} - a \cdot c_{GW} \leq 0.9 \cdot c_{threshold}$$

$$a \cdot (c_{SW} - c_{GW}) + c_{GW} \leq 0.9 \cdot c_{threshold}$$

$$a \leq \frac{0.9 \cdot c_{threshold} - c_{GW}}{(c_{SW} - c_{GW})} \tag{1.1}$$

In literature this modelling technique is often called constrained optimization (or mathematical programming) model.

Output:

For each potential hazard an optimum minimum and maximum bank filtration share is computed. Three cases can be distinguished:

if $c_{SW} > c_{GW}$ then : Minimum BF Share = 0 & Maximum BF Share = a
if $c_{SW} < c_{GW}$ then : Minimum BF Share = a & Maximum BF Share = 1
if $c_{SW} = c_{GW}$ or c_{SW}>0.9*threshold & c_{GW}>0.9*threshold then:
Minimum BF Share = 0 & Maximum BF Share= 0

In the first case the surface water concentration for the hazardous substance lies above the ambient groundwater concentration. Subsequently the solution of the computed parameter **a** is the maximum, whereas zero is the minimum (physical possible) bank filtration share for which all constraints are satisfied. For the second case it is exactly vice versa. Finally, if both surface water and ambient groundwater have exactly the same concentration or both lie above their threshold concentration multiplied by 0.9, no dilution can be computed. Subsequently both minimum and maximum BF share are set to zero.
If there is a global optimum bank filtration share (concerning all potential hazard substances) it is plotted with dashed lines in the figure **'Plot of Optimal BF Share'** on the right hand side of the DSS GUI. The purple colour indicates the maximum and the light blue colour the minimum boundary of the optimal BF share.

Literature Study of Degradation and Immobilization Potential

As dilution (conservative mixing) is only one out of many processes taking place during bank filtration a literature review of observed degradation and immobilization potential for each water quality parameter (listed in: ***<userdefined>\DSS\data\helpdata\t_SubstHelpDat.xls***) was performed. The summarized results are optionally shown in a new window if the user has chosen a hazard substance and push the ***Select*** button under ***Step 3b***.
Note that additional information for each hazard output parameter (including pathogens and viruses) is given in (HÜLSHOFF et al. 2009), including a reference list of the cited literature used for this study (see Chapter 4).

2.4.2 *Optimization of well field design and operation (4. Step)*

In a 4th step a simple, steady-state model (BF Simulator) is used to optimize either well field (i) design (distance to bank), (ii) operation (pumping rates) or (iii) both under given conditions (aquifer and bank characteristics), so that the previously identified 'optimal' BF share (see Chapter 2.4.1.3) can be achieved.
A detailed documentation how to use the BF Simulator supplemented with a qualitative sensitivity analysis is given in (RUSTLER et al. 2009).

To start the BF Simulator (BFS) the user has to press the **'Start BF Simulator'** button. Model results can be obtained by clicking on the 'Update table' button. Subsequently one (lumped) input and two output parameters of the BFS (saved under: ***<userdefined>\DSS\BankFiltrationSimulator*\runlist.xls**) are loaded into the table on the right hand side of Step 4. These are in detail:

- Input Parameter
    - Total pumping rate [L^3/T]: sum of the pumping rates of all production wells
- Output Parameters
    - Bank filtration share [%]: average percentage of surface water in the pumped groundwater for the whole well field
    - Minimum travel time [Days]: lowest travel time between bank and production well (no average value for the whole wellfield but local or global minimum, depending upon the grid layout)

In addition, further information on the model parameterisation is available if the user enables the **'Additional Info'** button. Subsequently the user can open an Excel file containing whole model parameterisation (input data for aquifer, bank and well) for a desired model run by choosing a model run number and pressing the **'Select'** button afterwards. Note that the above described functionality only works if Microsoft EXCEL is installed on your PC.

2.5 Limitations

BF is inherently coupled with complex physical, biological, chemical processes (*Figure 3*). These are often strongly transient and vary in time and space due to the natural variability of meteorological (evaporation, precipitation, groundwater recharge), hydrological (flow regime: floods, droughts) and hydrogeological (baseflow) conditions (MASSMANN et al. 2007a, MASSMANN et al. 2007b, MASSMANN et al. 2008, WIESE & NÜTZMANN 2009, LORENZEN et al. 2010).

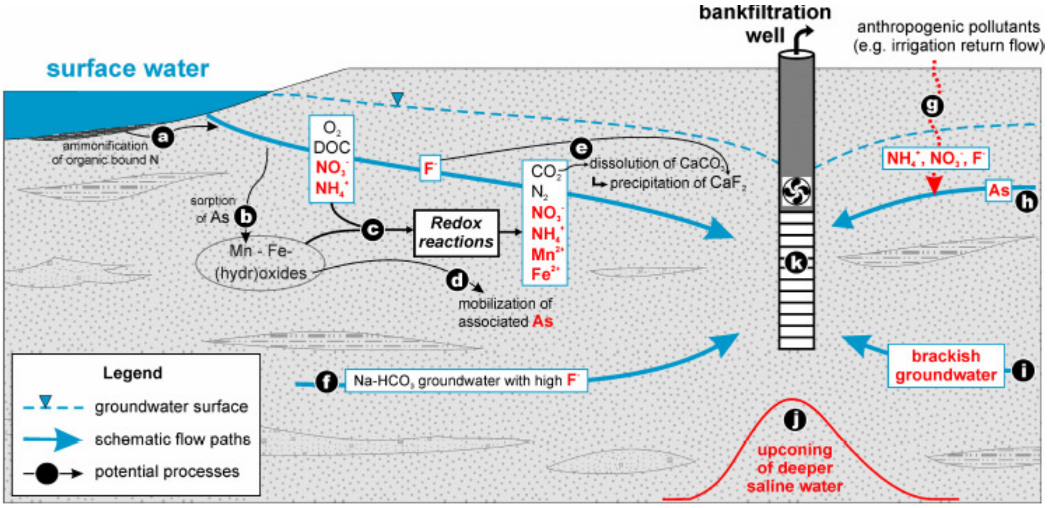


Figure 3 *Processes during bank filtration (LORENZEN et al. 2010) observed at TECHNEAU field sites in Delhi (India): (a) Mineralisation of solid organic material and ammonification of organic bound N (and nitrification); (b) Sorption of As on Fe/Mn-(hydr)oxides; (c) Redox reactions, including the oxidation of organic carbon, the reduction of NO_3 - and the reductive dissolution of Mn/Fe-hydroxides; (d) Mobilisation of As during the dissolution of Mn/Fe-(hydr)oxides; (e) Formation of CO_2, leading to a pH-decrease, dissolution of $CaCO_3$ and the precipitation of CaF_2; (f) Deep fresh groundwater resources (Na-HCO_3- type) with high geogenic F- concentrations; (g) Leaching of anthropogenic pollutants (i.e. agrochemicals); (h) Ambient groundwater with high As concentrations; (i) Brackish groundwater; (j) Upconing of deep saline water; (k) Attenuation of peak concentrations through mixing of water from different sources (bank filtrate, ambient groundwater and deep groundwater),*

However, the DSS is only able to:

- Simulate steady-state conditions for an aquifer (e.g. hydraulic conductivity) and bank (clogging layer) with spatial homogeneous properties. Consequently it is highly recommended to use the DSS only on a management timescale for which steady-state conditions can be assumed (e.g. hydrologic year) and not in a strictly quantitative way since it is unable to take the heterogeneity and temporal variability of parameters into account.

- Consider two water sources (surface water and ambient groundwater) for both water quality assessment (Chapter 2.4.1) and well field optimization (Chapter 2.4.2). Thus, water availability which is simulated by using the BF Simulator is only valid if there are no additional water sources (or if these can be neglected) such as:
  - Multi-aquifer system: upconing saline groundwater from deeper aquifer (Figure 3, j)
  - Groundwater underflow: additional groundwater input from adjacent groundwater basins (e.g. horizontal extent of the subsurface catchment is not limited by a surface water body that acts as an hydraulically boundary)

- Simulate raw water quality concentrations by using conservative mixing calculation between surface water and ambient groundwater but does not consider additional degradation processes (e.g redox conditions). Subsequently the complex biological, physical and chemical degradation processes taking place at the river-aquifer interface (hyporheic zone) and within the aquifer are not addressed, which is a common constraint for all recently available management tools (TELLAM & LERNER 2009). However, neglecting the hyporheic zone and the aquifer as a filter and bio-reactor, results in an underestimation of substance removal, thus falsely implying the need for additional post-treatment. Moreover dissolution (Figure 3, c) or mobilization processes (Figure 3, d) in the aquifer, which can take place under anoxic/anaerobic conditions are not addressed. Each of these processes can lead to an increase of inorganic trace element concentrations (e.g. Mn/Fe/As). Thus, a permanent warning message is implemented in the DSS which reminds the user to be aware of this drawback.

- Simulate the share of bank filtrate with the BF simulator for steady-state conditions and under the assumption that the pumping rates of the production wells are independent of the current water table. Consequently the effect of yield loss due to an overlapping of depression cones between two adjacent production wells is not addressed (see RUSTLER et al. 2009).

- Give site specific information on the degradation and immobilization potential for substances during BF through a literature study. Thus an extrapolation is only valid if the field site of interest has similar boundary conditions considering hydrology, hydrogeology and well field operation. At least the latter is lacking if a BF well field site is planned at an undeveloped groundwater basin. In this case it is highly recommended to conduct detailed water quality monitoring during the hydrogeological exploration investigation.

In a nutshell it is recommended to use the DSS only as a qualitative assessment tool in a first planning step for the design and operation of BF systems. In a next step if quantitative 'robust' results are needed, it is inevitable to accompany the planning with thorough field investigations and a sound monitoring program regarding both quantity and quality of surface water and groundwater through a dense network in an adequate temporal (depending on the groundwater dynamics) and spatial (depending on the aquifer heterogeneity) resolution. This is a precondition for a meaningful application of more sophisticated numerical model approaches like e.g. MODFLOW (HARBAUGH et al. 2000), which are capable of simulating transient groundwater flow dynamics but are highly data demanding concerning model parameterisation and calibration.

3 Test Application

3.1 Palla Well Field

3.1.1 *Site Description*

The Palla well field is located north of the urbanized parts of Delhi , India (*Figure 4*). It lies mainly on the western hydrological floodplain of the Yamuna River, which is about 300m wide and regularly flooded during monsoon (LORENZEN et al. 2010). To the west and the east the Palla well field is limited by hydrological barriers – the Western Yamuna Canal (WYC) and the Yamuna River, respectively. The former lies on a surface level of 225m a.s.l. and the latter on 210 m a.s.l. (JARVIS et al. 2008, see Table 2).. Subsequently the average surface elevation slope direction is from west to east and very low (0.1 %, see Table 2).
In total the well field consists of approximately 90 production wells which are used for drinking water supply (*Figure 5*). Due to the pumping of the production wells adjacent to the Yamuna River the water table in the aquifer is lowered below the river stage. As a consequence the Yamuna River looses water to the unconfined aquifer by a process known as induced infiltration or bank filtration (LORENZEN et al. 2010).

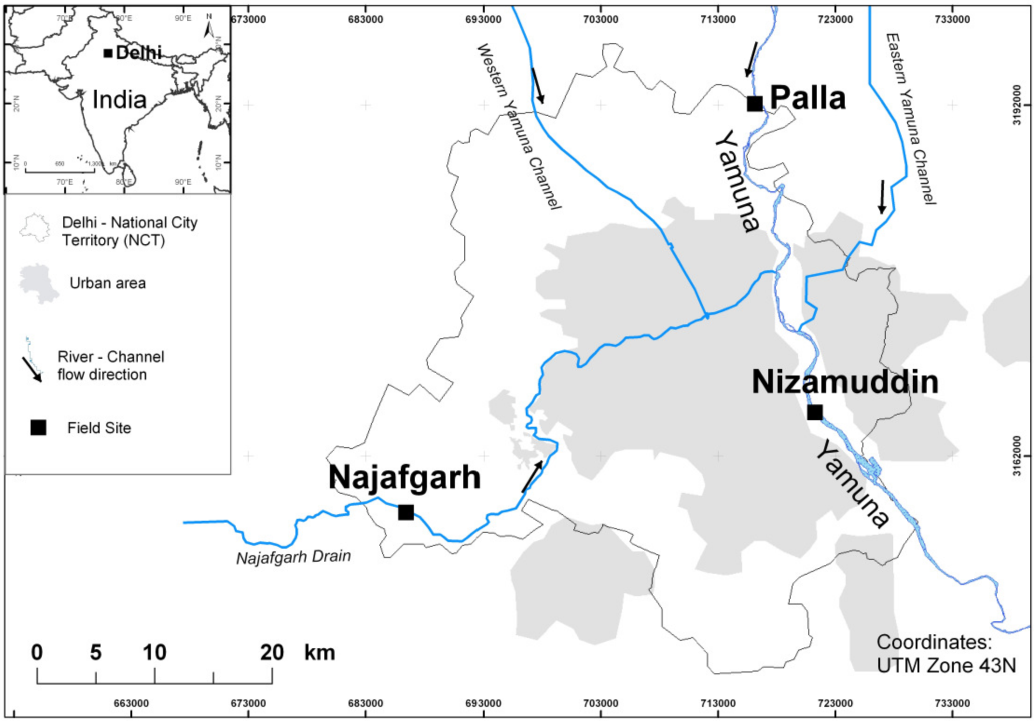


Figure 4 *Location of the Palla well field along the Yamuna River, northern of the mega-city Delhi, India (PEKDEGER et al. 2006)*

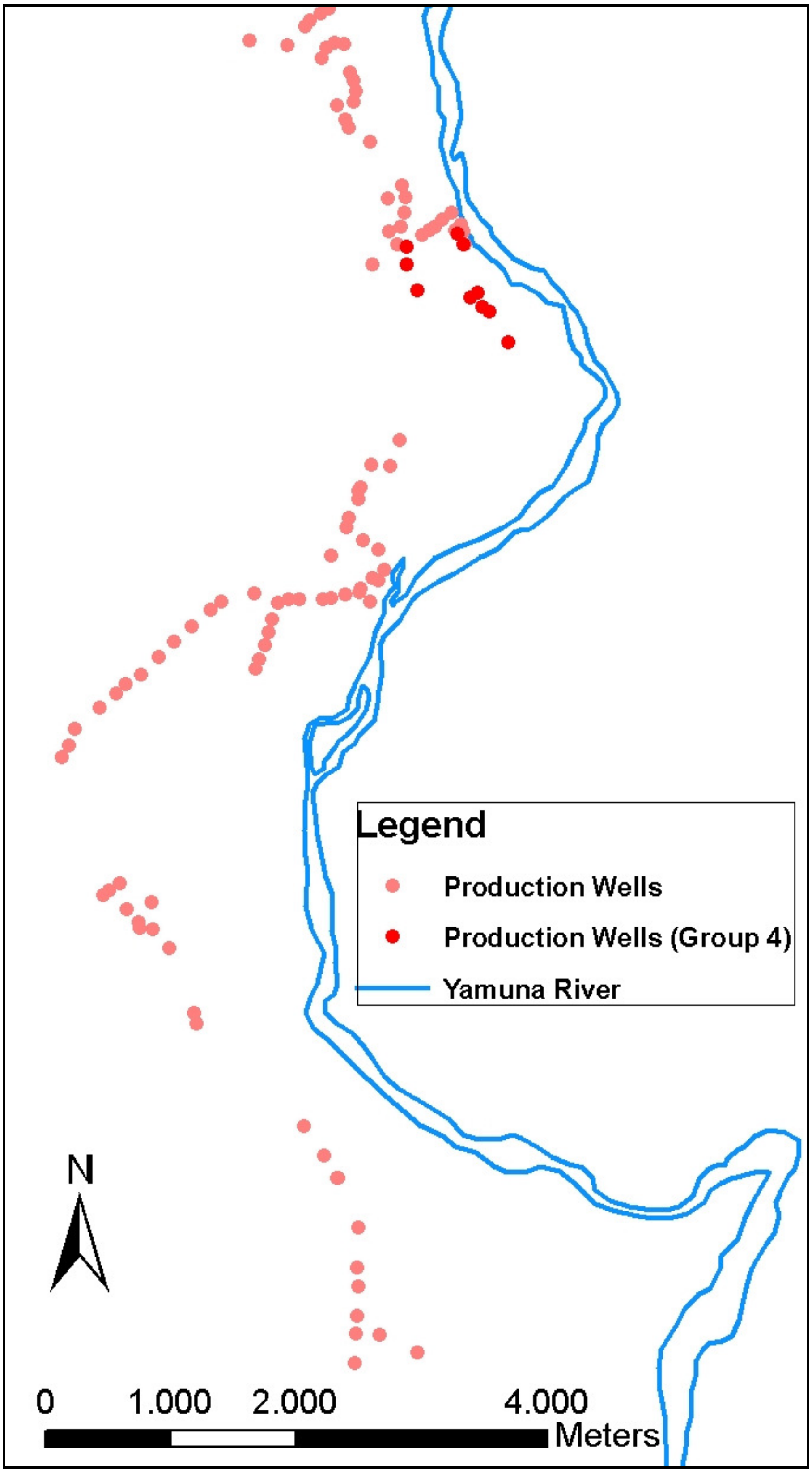


Figure 5 *Location of the production wells within the Palla well field (based on data by FUB, 2009)*

3.1.2 *Data Availability*

The topographical and hydrogeological data, which are listed in *Table 2*, are derived from literature (RAO et al. 2007, JARVIS et al. 2008, LORENZEN et al. 2010).

Table 2 Available data for the Palla well field site

Domain	ID	Parameter	Value	Reference
Topography	1	Surface Elevation [m]: Western Yamuna Canal (WYC)	225	(JARVIS et al. 2008)
	2	Surface Elevation [m]: Yamuna River (YR)	210	(JARVIS et al. 2008)
	3	Distance [m]: WYC - YR	16000	GIS FUB
Hydrogeology	4	Hydraulic conductivity K [m/s]	0.00012	(RAO et al. 2007)
	5	Effective porosity [-]	0.2	(RAO et al. 2007)
	6	Aquifer thickness [m]	85	(RAO et al. 2007)
	7	Saturated aquifer thickness [m]	80	(RAO et al. 2007), FUB

The following additional parameters and assumptions are necessary as input for the BFS and were derived as stated below:

- Hydraulic gradient (I): the groundwater flow is assumed to follow the surface elevation gradient, which is derived from Digital Elevation Data (JARVIS et al. 2008) according to the following equation:

  $$I = \frac{SurfaceElevation(WYC - YR)}{Distance(WYC - YR)} \approx 0.001$$

  with: WYC – Western Yamuna Canal
  YR – Yamuna River

- Subsurface catchment: western and eastern extents are limited by natural hydrologic boundaries, the Western Yamuna Canal and the Yamuna River, respectively. Both infiltrate water due to a low water table in the adjacent aquifer compared to the river stage (RAO et al. 2007, LORENZEN et al. 2010). Subsequently it is assumed that a sufficient groundwater ridge is created that acts as groundwater divide (see *Figure 7*).

- Baseflow: assumed to be perpendicular to the Yamuna River; thus a 'no-flow' boundary is set in the North and the South of the modelled area.

In addition water quality data is available for February and September 2007 (see Appendix A, Table 7 and Table 8). These are assumed to be representative samples for the two distinct hydro-meteorological regimes of non-monsoon and monsoon, respectively. The sampling points for assessing the water quality of both, surface water (Yamuna River) and ambient groundwater, are shown in Figure 6.

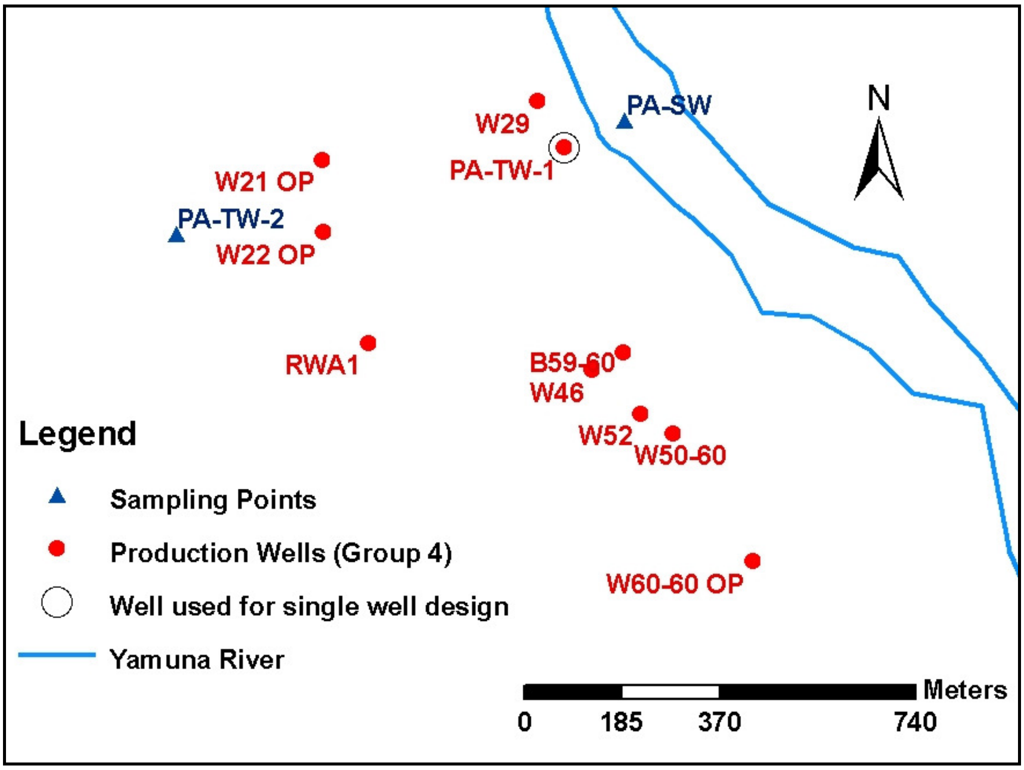


Figure 6 *Location of two selected FUB water quality points for surface water (Yamuna River) and ambient groundwater in the Palla well field (Group 4)*

3.1.3 *Conceptual Model*

With the available data and assumed parameter values (see Chapters 3.1.2), a conceptual model for a part of the Palla well field was developed (Figure 7). The area of interest is limited to 10 production wells (which are labelled as Group 4 in the work of RAO et al. (2007), because within this part of the well field most data is available (Figure 6).

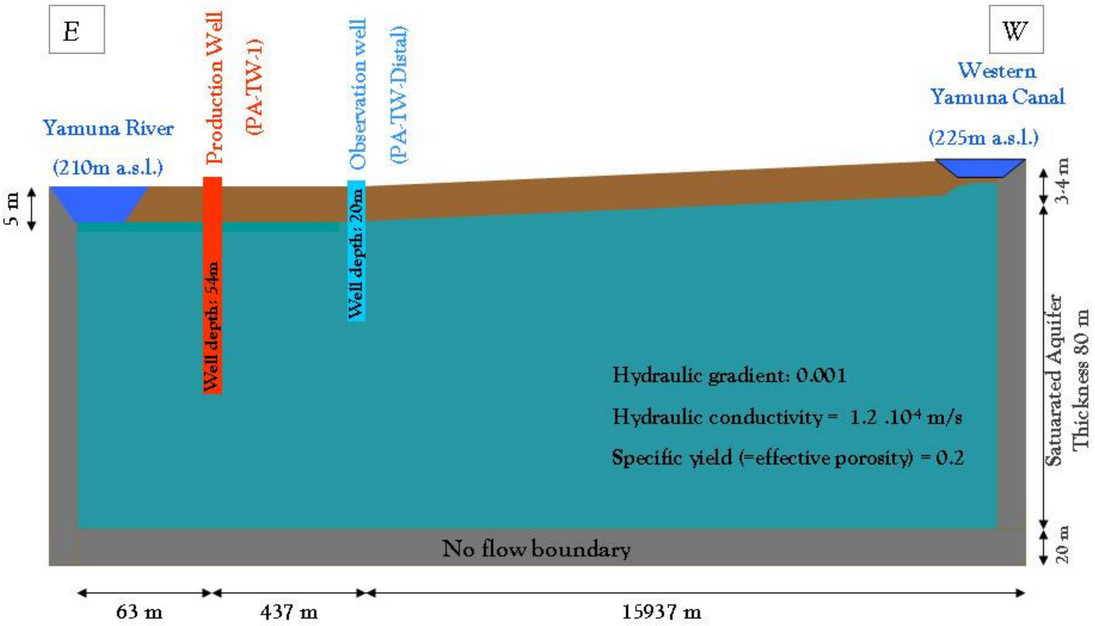


Figure 7 *Cross-section of the conceptual Palla well field model (Note: E and W are inverted!)*

Since the well field design and operational optimization with the BFS requires a specific horizontal spatial model discretisation (the bank has to be a straight line either on the left y-axis or the bottom x-axis) the coordinates had to be adapted to the model structure as relative coordinates according to Figure 8. Thus the Yamuna River is located on the left y-axis in the model. It is further assumed that the y-coordinate increases from South (origin: production well W 60-60-OP) to North (*Figure 8*). For the x-coordinate the shortest distance between the left bank of the Yamuna River for each production well is chosen (*Figure 8*). Subsequently they are transformed into the model space (Figure 9 and Appendix, Table 6).

Note that the horizontal extent of the cross-sectional model (Figure 7) and the plan view model (Figure 9) do not coincide. The former has a much larger horizontal extent (ending to the assumed groundwater divide of the Western Yamuna Canal) which is only important for estimating the hydraulic gradient (see Chapter 3.1.2). Thus the smaller extent does not affect the calculation of the (average) BF share based on an analytical method (which assumes that the hydraulic boundary is infinitely far away).

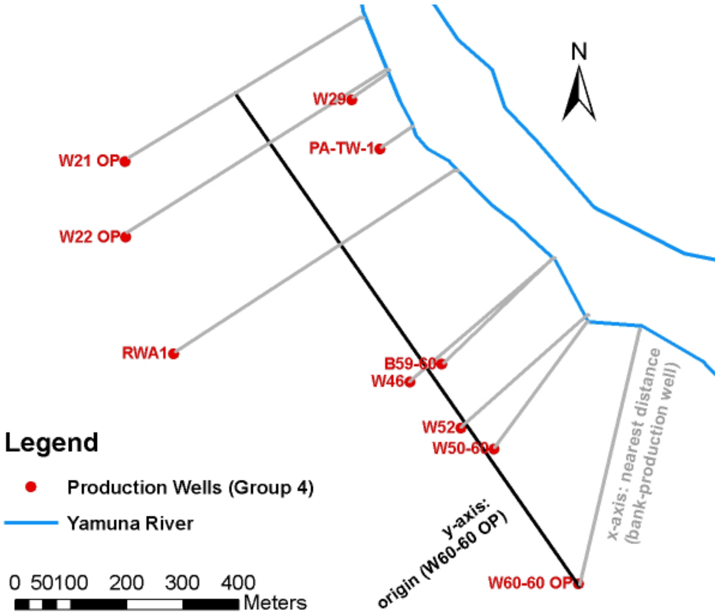


Figure 8 *Real-world coordinates of production wells (red dots) and transformation concept for BF simulator, see Figure 9 below (back line represents the hypothetic y-coordinate originating at PW W-60-60 OP, while the grey line illustrates the minimum distance for each well to the left bank of the Yamuna River which is used as x-coordinate for the well field parameterisation within the BF simulator, see also Appendix A, Table 6)*

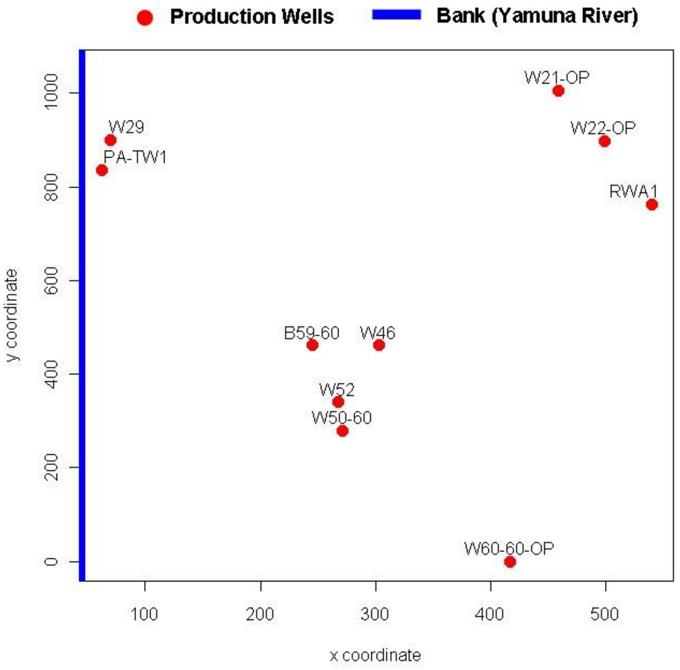


Figure 9 *Plan view of the Palla well field model; note that the location of the Yamuna River is inversed for technical reasons compared to* Figure 8*. The pumping well coordinates are adopted from the transformed coordinates (see Appendix A, Table 6). All wells are used for the multiple production well calculations, but only PA-TW1 for the single production well calculations*

3.1.4 Parameterisation and Scenarios

Two distinct model scenarios for water quality and water availability are simulated with the DSS due to different hydro-meteorological regimes (monsoon and non-monsoon). Natural variability of precipitation and evapotranspiration patterns between both seasons affects the computation of the well field optimization due to varying model parameters:

- Water table: the water level is 1 m to 2 m higher during monsoon ($T=9.84*10^{-5}$ m^2/s) in the unconfined aquifer compared to non-monsoon season ($T=9.86*10^{-5}$ m^2/s). Hence the saturated aquifer thickness (H) increases from 80m to 82m (RAO et al. 2007). This only implies a very small change in the aquifer transmissivity ($\delta T=2*10^{-7}$ m^2/s or 2.5%) according the following equation:

  $$T=H*K*I$$

  with: K= 0.00012 m/s (hydraulic conductivity),
  I= 0.001 (hydraulic gradient)

  Subsequently it is justified to assume a constant transmissivity for both seasons, since the resulting error made by this assumption is small compared to the high uncertainty associated with the hydraulic conductivity. In a real aquifer the hydraulic conductivity varies (dependent on the scale of interest) over several orders of magnitude due to the lognormal distribution of the hydraulic conductivity (KRESIC 2007).

- Clogging Parameter: during flood events (monsoon) disposed fine grained sediments are eroded (remobilized) due to increased flow velocities and shear forces so that the infiltration rate is increased; the opposite is the case of drought periods (non-monsoon) (WANG et al. 2003). We have to consider that the clogging parameter is higher during the non-monsoon season and lower during the monsoon season. In addition it has to be taken into account that near a BF well field the drag force usually leads to higher clogging (WANG et al. 2003). Since the clogging layer during monsoon is lower, more surface water can infiltrate leading to a higher water table in the aquifer, which increases groundwater availability.

- Pumping rates: different scenarios for daily pumping rates are calculated for single and multiple production well designs (Chapter 3.3.1). For the single well design different pumping rates are calculated from the specific pumping capacity of production well PA-TW-1 (3800 m^3/d, see Figure 10) by varying the operating hours per day between 3 and 24 (Table 4). For the multiple production well design the pumping rate for each well (Table 5) is derived from information given in (RAO et al. 2007). Consequently the total pumping rates of the single and multiple production wells scenario differ by factor ten. Note that the maximum pumping rate at the Palla well field needs to be limited by the fact that upconing of deeper saline groundwater is likely to occur (RAO et al. 2007).

Figure 10 Production well PA-TW-1 information table (picture: G. Lorenzen)

The optimization of the well field operation is simulated with the BFS for two distinct well field designs (see Figure 9), single production well (PA-TW1) and multiple production wells (Group 4), respectively. Apart from the distinct parameterisation of grid (Table 3

Table 3) and the well characteristics (Table 4-Table 5 and Appendix A, Table 6) the aquifer characteristics are kept constant (Appendix A, Table 12) for all model runs. However, in order to address the inherent uncertainty due to the large natural variability of the clogging layer the clogging parameter is varied (range: 0m – 5000m). In addition it is hypothesized that for each scenario (monsoon or non-monsoon), steady-state conditions prevail and transient (time dependent) processes can be neglected.

Seasonal fluctuations do not only have an effect on water availability, but also on water quality. Measured water quality parameters (see Appendix A, Table 7 and Table 8) for different water sources (surface water of Yamuna River and ambient groundwater, see Figure 6) are available for February and September 2007, which are used as input data for the water quality calculation within the DSS (see Chapter 2.4.1.1 - 2.4.1.3). It is further assumed that the water quality parameters are representative for non-monsoon and monsoon season, respectively.

Table 3 Grid parameterisation for single production well and multiple production well scenario

Grid Parameter	Scenario	
	Single production well	Multiple production wells
Grid spacing [m]	1	1
Grid extent [xmin:xmax]	[0:400]	[0:400]
Grid extent [ymin:ymax]	[-200:200]	[600:1000]

Table 4 Pumping rate scenarios for a single production well (PA-TW-1, see Figure 9); installed capacity: 3800m³/d (=0.044m³/s). No distinctions were made between monsoon and non-monsoon!

Well operation [h/d]	Pumping rate [m³/s]
24	0.044
18	0.033
12	0.022
6	0.011
3	0.005

Table 5 Pumping rate scenarios for the multiple production wells design (Group 4, see Figure 9) for monsoon and non-monsoon season (Rao et al. 2007)

Id	Parameter	Season		Reference/Calculation
		Monsoon	Non-monsoon	
1	Total pumping rate [m³/d]	18763	14151	(RAO et al. 2007)
2	Operation time/well [h/d]	18.4	13.9	(RAO et al. 2007)
3	Pumping rate/well [m³/s]	0.022	0.016	$\frac{TotalPumpingRate[m^3/d]}{10 \cdot 86400}$

3.2 Water Quality Assessment

3.2.1 Input data

In a first step the water quality input file with the concentrations in surface water and ambient groundwater for monsoon and non-monsoon season is specified (see Appendix A, Table 7 and Table 8). Although it is known that trace elements like Fe, Mn or As are mainly a function of redox conditions they were included in the considerations as examples. Subsequently nine substances (As, Cl, DOC, F, Fe, Mn, NO_2, NO_3, NH_3) are used as input substances for monsoon season and six substances (As, Cl, DOC, Fe, Mn, NO_3) for non-monsoon season, respectively.

3.2.2 Hazard Calculation

From the above specified input substances a list of potential hazard substances is calculated in the second step (see Chapter 2.4.1.2). As a result four (As, DOC, Fe, Mn potential hazards are identified for monsoon and two (Fe, Mn) for non-monsoon season. Since the iron concentration is above 90 percent of the threshold value of the German drinking water ordinance (= 0.18 mg/l) in both, surface water (0.25 mg/l) and ambient groundwater (1.32 mg/l), iron can not be attenuated by the mixing process. Thus, iron is excluded from the input file for the further analysis in order to find an optimum BF share for all considered substances (global optimum).

3.2.3 Mixing Calculation

Excluding iron from the input file, there is an 'optimum' BF share boundary for the remaining potential hazard substances of 65.66 - 65.91% during non-monsoon (Figure 11) and 32 - 100% during monsoon season (Figure 12). Note that the range for the latter is very high, since only one input substance (Manganese) is identified as potential hazard.

As a result, the DSS can identify 'optimal' BF shares in case of insufficient surface- or groundwater quality. Thus it can be an advantage to use BF systems instead of surface water to (i) lower treatment costs and (ii) add operational flexibility in case of hydrological droughts. However, with the implemented simple conservative mixing model (see Chapter 2.4.1.3), the potential remobilization of trace elements (such as Fe/Mn/As) under anoxic/anaerobic conditions during the subsurface passage is not taken into account. Therefore it is recommended to accomplish field measurements for the current redox potential to assess whether this process is important for the area of interest or not. Only in the latter case, mobilization can be neglected.

In order to 'optimise' the BF share (here: 65.66-65.91%for non-monsoon and 32-100% for monsoon season) another tool – the BFS (for further details, see RUSTLER et al. 2009) – is used, which is described in the following chapter.

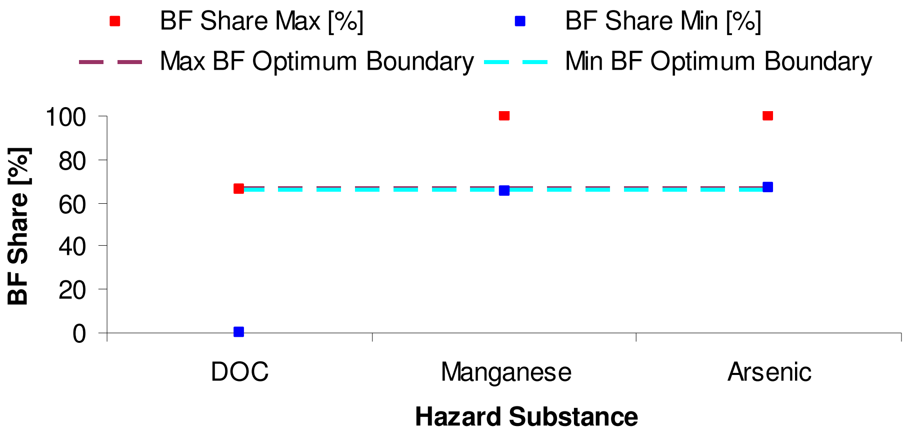


Figure 11 *Non-monsoon Season: optimum maximum (red squares) and minimum (blue squares) BF share for each input substance and resulting overall optimal maximum (purple dashed line) and minimum (blue dashed line) BF boundary. Calculated on the basis of water quality data of February 2007*

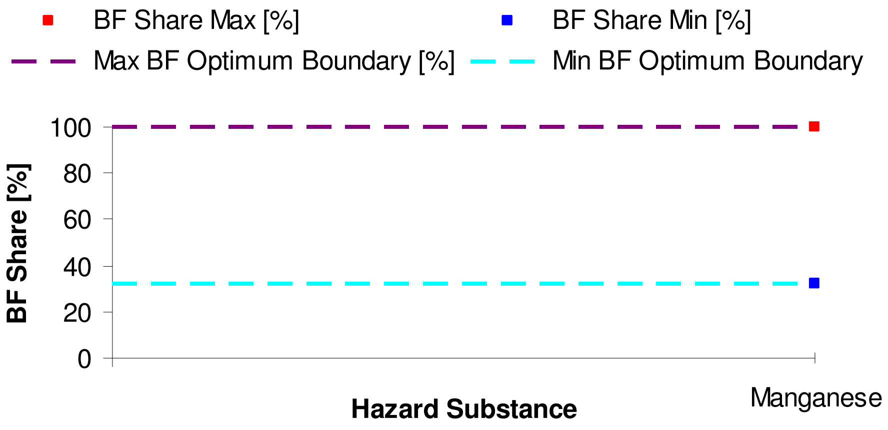


Figure 12 *Monsoon Season: optimum maximum (red squares) and minimum (blue squares) BF share for each input substance and resulting overall optimal maximum (purple dashed line) and minimum (blue dashed line) BF boundary. Calculated on the basis of water quality data of September 2007*

3.3 Optimization of Well Field Operation

The objective of the well field optimization is to obtain a predefined BF share which is determined by a minimum raw water quality (see Chapter 3.2). For the calculations carried out by the BF Simulator only the well operation (pumping rate) is considered to be a decision parameter, since the infrastructure is already installed at Palla. In addition the impact of the inherently uncertainty of the clogging layer (due to its high temporal and spatial variability) on the model outputs (BF share, minimum travel time) is assessed. This is implemented by varying the clogging parameter (boundary condition) over several orders of magnitude. The results of the search for the 'optimal' operational management solution under the constraint of inherently uncertain natural boundary conditions (here: only clogging parameter considered!) are presented in the following chapters. The parameterisation of the BFS is listed in Appendix A, Table 12 for all variables which are assumed to be constant for two designs: single production well and multiple production wells. A detailed sensitivity analysis for the impact of each of these input parameters on the model results is given in RUSTLER et al. (2009).

3.3.1 Single Production Well Scenario

For the single production well scenario the pumping rate is limited to only one well (PA-TW-1, see Figure 6). The impact of different pumping rates (decision parameter) and clogging parameters (boundary condition) on the BF share are shown in Figure 13.

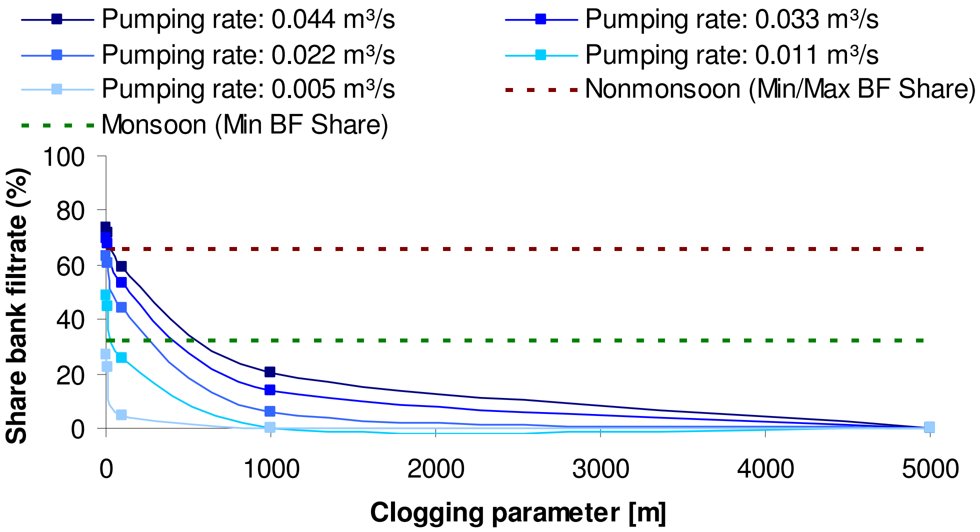


Figure 13 *Single Production Well: Influence of the clogging parameter on the BF share for five different pumping rates. Note that minimum (green dashed line) and the minimum/maximum (purple dashed line) 'optimal' BF share range differs significantly for monsoon and non-monsoon season, respectively*

On the one hand the BF share increases with increasing pumping rate, due to a larger depression cone. The latter induces a larger hydraulic gradient between bank and production well, which leads to a higher BF share according Darcy's law. On the other hand the BF share decreases with increasing clogging parameter, because the water flux between the bank and the aquifer is reduced. For the monsoon setting the 'optimum' minimum BF share boundary (32%, see Chapter 3.2) is achieved with pumping rates higher than $0.011m^3/s$ (only for clogging parameters smaller than 600m!). During non-monsoon season the 'optimal' BF share range (65.66-65.91% BF) is very small and not achievable for real-world operation. This would not only require very high pumping rates ($>0.033m^3/s$, here: danger of up-coning deeper saline groundwater) but also a non-clogged or at least very little clogged bank (which again is an unrealistic assumption, see Chapter 3.1.2).
Figure 14 shows the impact of both pumping rates and clogging parameters on the minimum travel time. The minimum travel time between bank and production well is largest for (i) low pumping rates and (ii) high clogging parameters. That may have a positive effect on the quality of the abstracted water due to multiple chemical reactions that take place (see Figure 3).

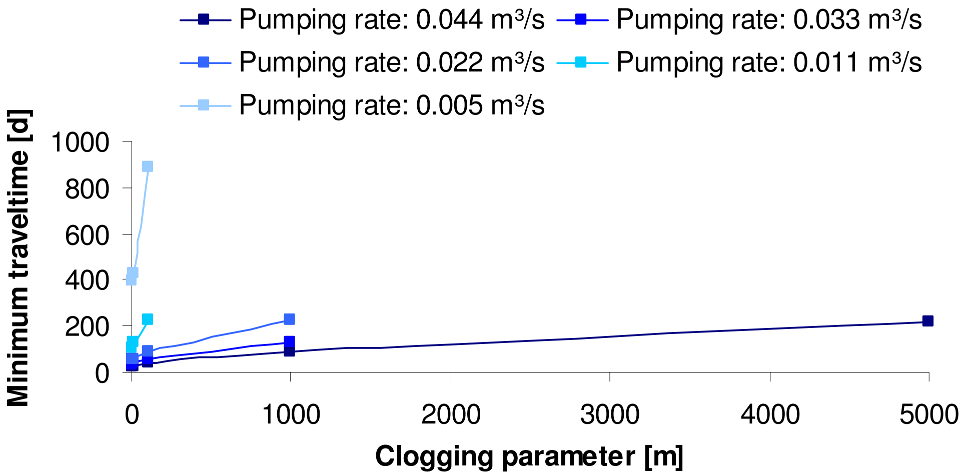


Figure 14 *Single Production Well: Influence of the clogging parameter on the minimum travel time for five different pumping rates.*

Note that the minimum travel time is not included as objective for the water quality assessment (see Chapter 2.4.1.3) and only presented here for completeness. Adding e.g. a minimum travel time of 50 d as second constraint (simplest form of a multiple objective optimization problem) would make the 'optimisation' of the BF system a more complex task, since the implementation of this additional constraint (i) requires that decision makers have to specify its value which in turn (ii) further limits the feasibility space for 'optimal' operational management solutions.

For illustration the impact of zero and very high bank clogging on the depression cone is shown in Figure 15 and Figure 16, respectively. For the latter the groundwater levels near the shore of the bank are significantly lowered due to a decreased flux of surface water (lower BF share, Figure 13) which in turn increases the minimum travel time between bank and production well (Figure 14).

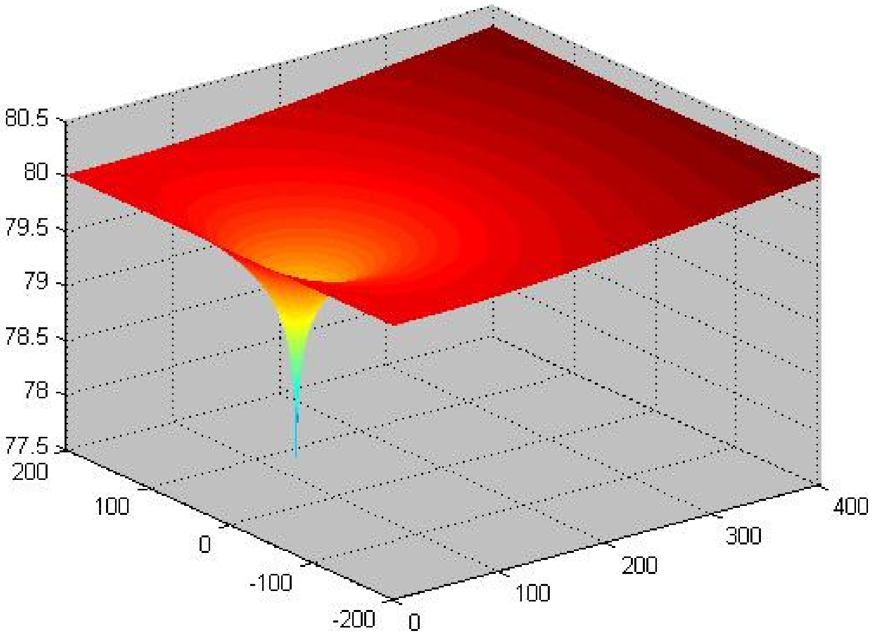


Figure 15 *3D hydraulic head distribution for a pumping rate of 0.022 m^3/s (without clogging).*

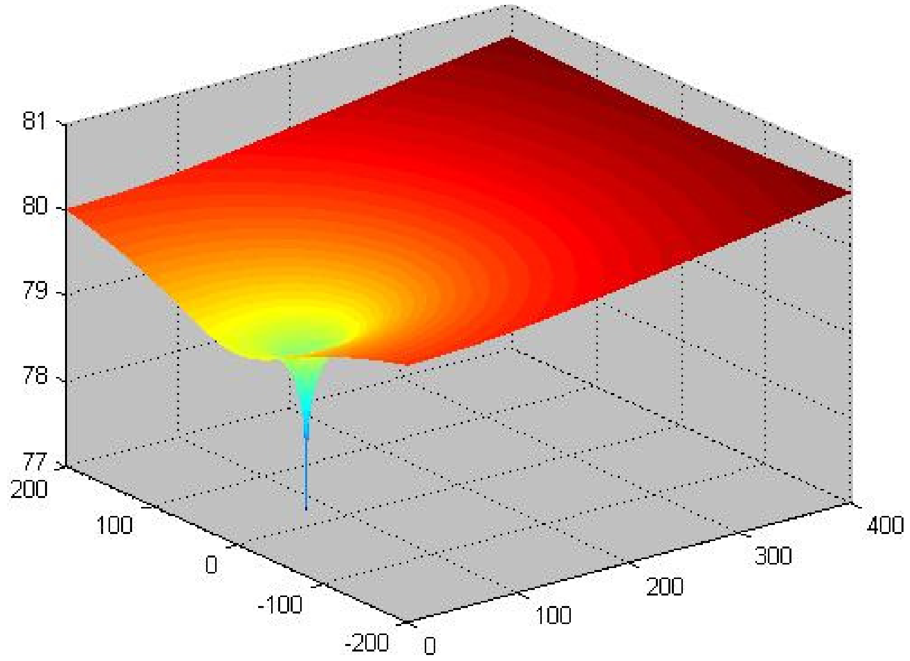


Figure 16 *3D hydraulic head distribution for a pumping rate of 0.022 m^3/s (clogging parameter = 5000 m)*

Furthermore the impact of both assumptions on the groundwater streamlines is shown in Figure 17 and Figure 18, respectively. On the one hand it can seen that the number of streamlines between the bank and the production well varies between 2 (very high clogging) and 12 (zero clogging). Thus, since the groundwater flow paths are parallel to the streamlines, the mass transport is highly dependent upon the choice of the clogging parameter. On the other hand the infiltration length along the bank remains approximately the same (~400m) for both clogging parameter scenarios. This is due to the fact, that the groundwater flow field for the single production well design is very simple and the reduced flux of surface water cannot be compensated through an increased infiltration length as in the case of a multiple production well design described in the following chapter.

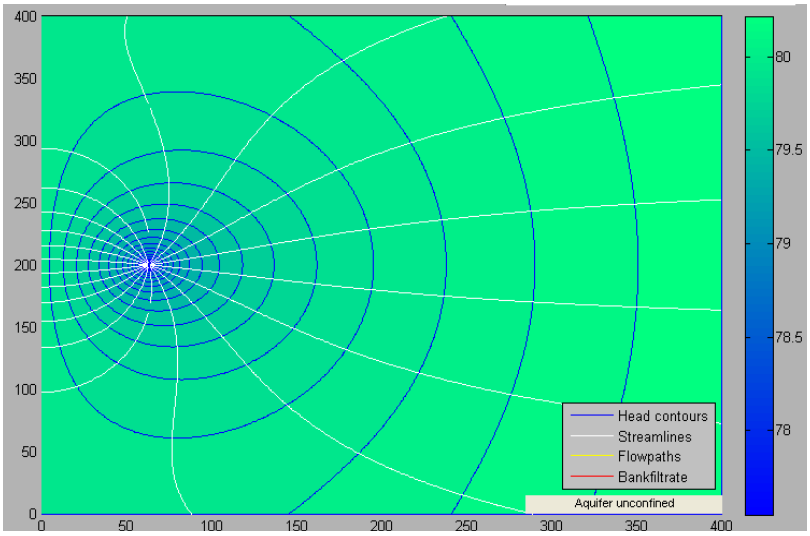


Figure 17 2D visualisation of the groundwater streamlines for the zero clogging scenario (clogging parameter = 0 m, pumping rate: 0.022 m³/s). Note that the total infiltration length is 407 m!

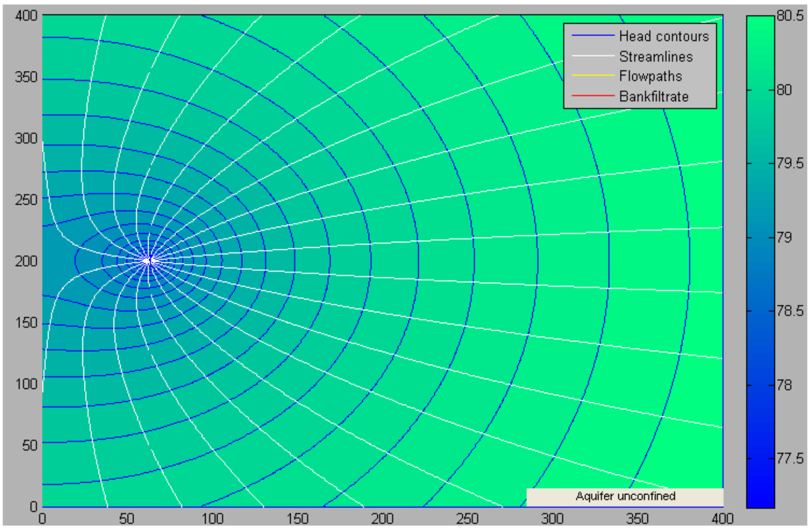


Figure 18 2D visualisation of the groundwater streamlines for the high clogging scenario (clogging parameter = 5000 m, pumping rate: 0.022 m³/s). Note that the total infiltration length is 378 m!

3.3.2 *Multiple Production Wells Scenario*

For the multiple production wells scenario (see Chapter 3.1.2, Figure 6) the results for both BF share (Figure 19) and minimum travel time (Figure 20) are qualitatively comparable to the single well design, which was analysed in the previous Chapter 3.3.1. Subsequently the BF share decreases with (i) increasing clogging parameter or (ii) decreasing pumping rate.

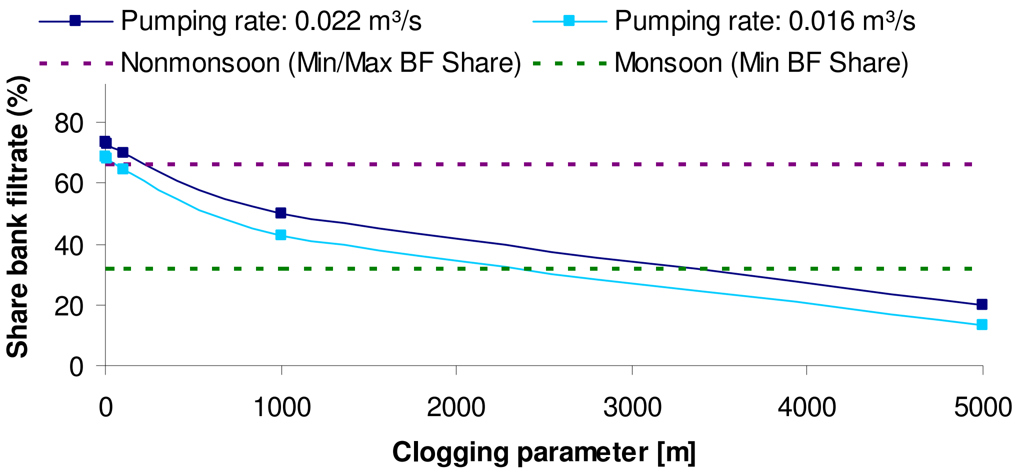


Figure 19 *Multiple Production Wells: Influence of the clogging parameter on the BF share for two different pumping rates per well (total pumping rate approximately ten times higher compared to single production well design). Note that minimum (green dashed line) and the minimum/maximum (purple dashed line) 'optimal' BF share range differs significantly for monsoon and non-monsoon season, respectively*

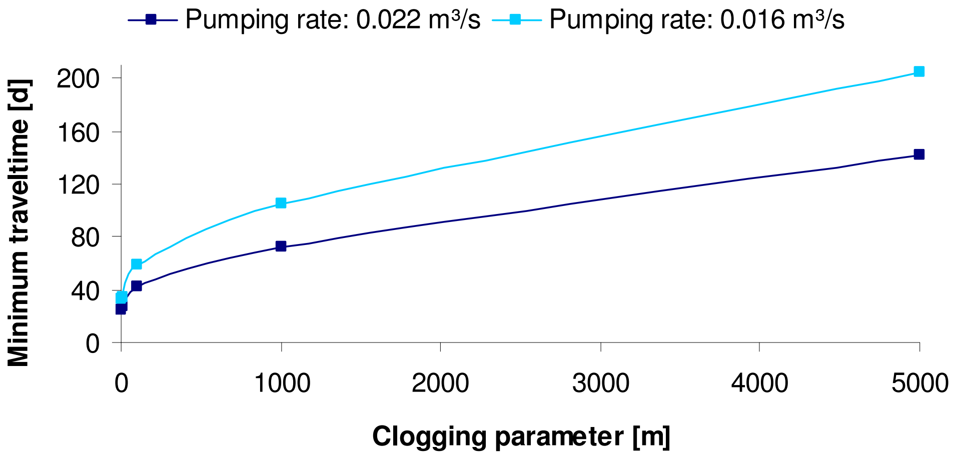


Figure 20 *Multiple Production Wells: Influence of the clogging parameter on the minimum travel time for two different pumping rates per well (total pumping rate approximately ten times higher compared to single production well design)*

However, the results for single and multiple production wells scenario differ quantitatively, since the total pumping rate for the multiple production well scenario (well field consisting of ten production wells) is approximately ten times larger compared to the single production well scenario. In addition the BF share output of the BFS is an average value for the whole production well field. Thus it is not possible to conduct a detailed analysis of the BF share distribution for each production well numerically. Nevertheless the approximate BF share for each production well can be estimated visually by dividing the number of streamlines originating from the bank through the number originating from the ambient groundwater (Figure 23 and Figure 24).

The complex hydraulic head distribution of the multiple production well field scenario are shown in Figure 21 and Figure 22 for two different clogging parameter scenarios. In case of zero clogging (clogging parameter = 0m) water levels in the aquifer adjacent to the bank are high (Figure 21), because the water flux between the bank-aquifer interface is not reduced. However, in the case of a high resistance of the clogging layer (clogging parameter = 5000m) the water flux between bank and adjacent aquifer is reduced, leading to a lowered water table in the aquifer (Figure 22). Differences in the hydraulic head distributions for the different clogging parameters have a high impact on the (i) groundwater streamlines and the (ii) infiltration length as shown in Figure 23 and Figure 24. The infiltration length varies between 3110m (no clogging, Figure 23) and 5001m (high clogging, Figure 24), which is approximately ten times larger than for the single production well design (see Chapter 3.3.1). Thus it is reasonable, that the BF share decreases much slower for increasing clogging parameters in case of the multiple production wells scenario, since the lowered flux of surface water is compensated by an increased infiltration length. In case of the single production well design this opportunity is lacking, because the simple groundwater flow field cannot compensate the flux reduction (infiltration length stays approximately the same, see Figure 17 and Figure 18).

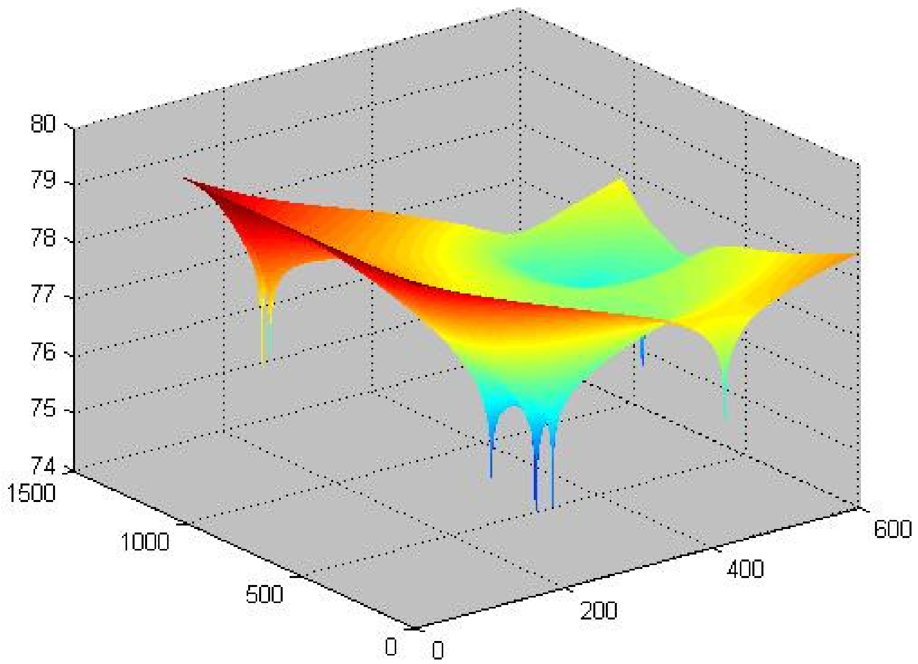


Figure 21 *3D hydraulic head distribution for the monsoon season scenario (pumping rate: 0.022m³/s for each production well, no clogging). Note that the grid parameters chosen here: x-axis: [0:1:550] y-axis: [0:1:1050] are not the optimal ones used for the BFS outputs calculation but they enable an overview of the well field.*

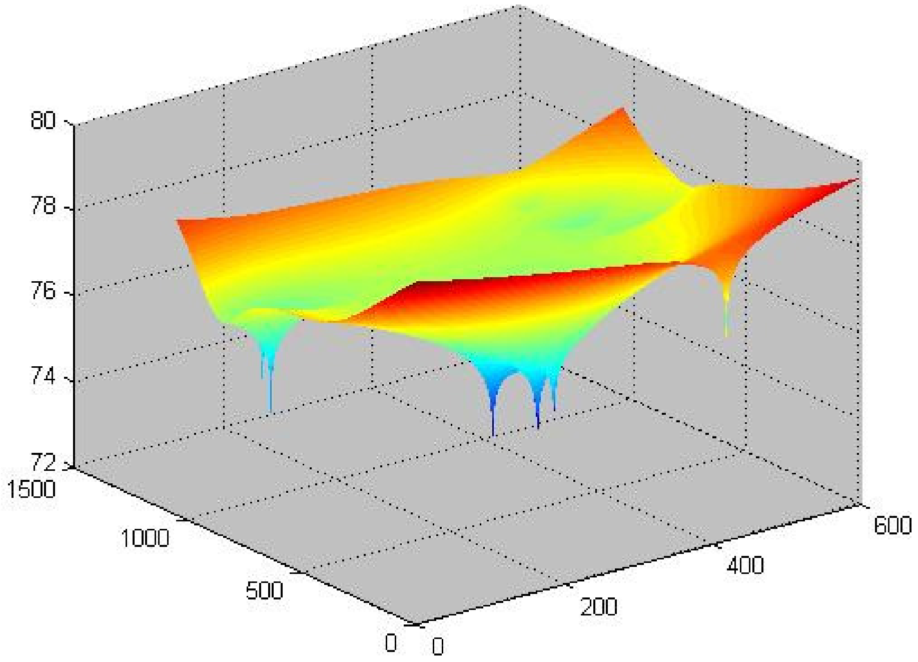


Figure 22 *3D hydraulic head distribution for the non-monsoon season scenario (pumping rate: 0.022 m³/s for each production well, clogging parameter: 5000 m). Beware that the grid parameters chosen here: x-axis: [0:1:550] y-axis: [0:1:1050] are not the optimal ones for the BFS outputs calculation but they enable an overview of the well field.*

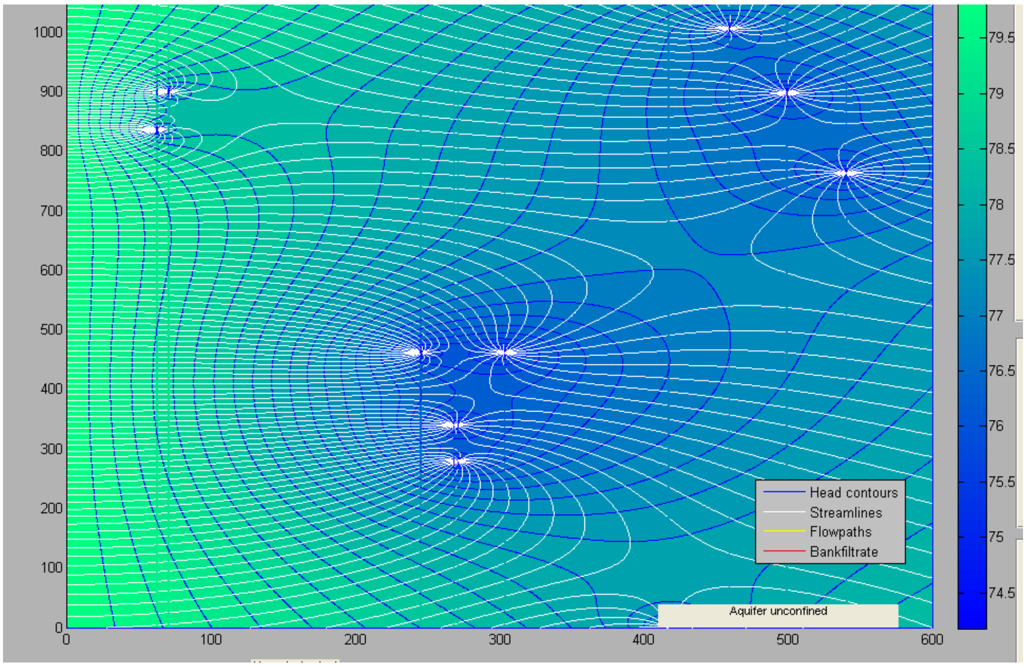


Figure 23 *2D visualisation of the groundwater streamlines for the no clogging scenario (clogging parameter = 0 m, pumping rate: 0.022 m³/s,). Note that the total infiltration length is 3110 m*

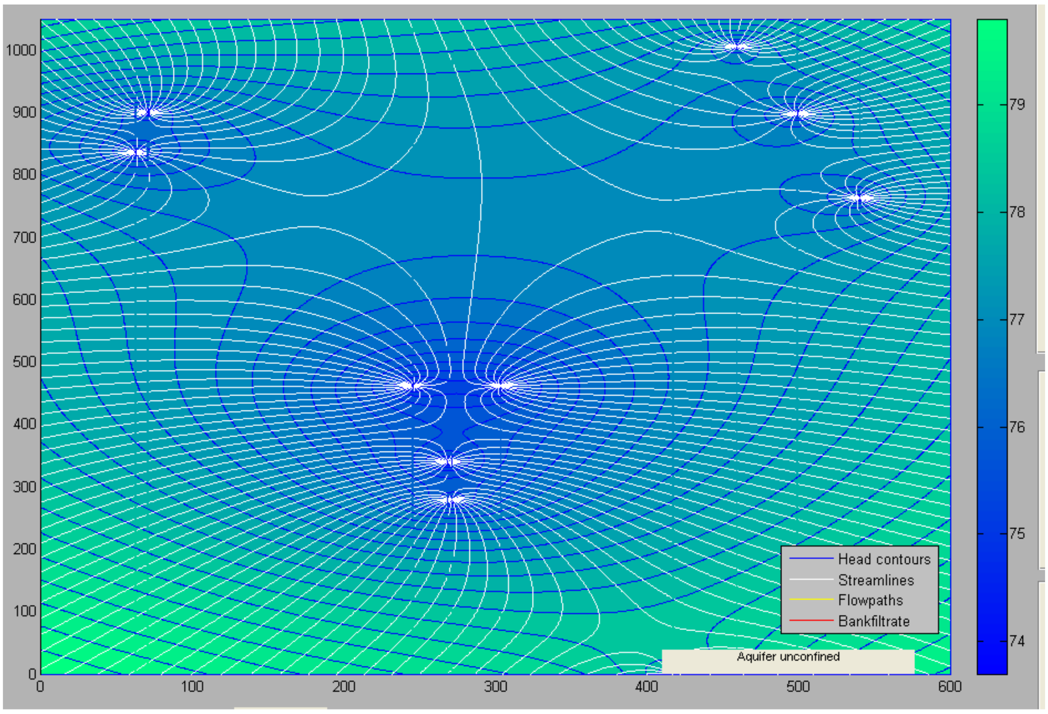


Figure 24 *2D visualisation of the groundwater streamlines for the high clogging scenario (clogging parameter = 5000 m, pumping rate: 0.022 m³/s). Note that the total infiltration length is 5001 m*

4 Discussion and Conclusions

4.1 General remarks

The following limitations of the DSS need to be taken into account before its application to a particular site and while interpreting the results obtained:

- The current version the DSS is only intended to 'optimize' well field design and operation to achieve a BF share, for which the raw water quality is in line with the WHO drinking water guidelines. This single objective optimization does not consider additional management objectives (e.g. cost-efficiency of well field design and operation), which might be important factors to consider in practice.
- Only dilution is taken into account by mixing calculation within the DSS. However, out of the 9 input substances that were used for water quality assessment at the Palla well field only the parameters DOC, Mn and As were identified as potential hazards. Although their concentrations mainly depend upon other processes than mixing/dilution (e.g. redox conditions) - which are not implemented in the DSS - they were included in the considerations, as examples for any conservative substance (e.g. chloride). Otherwise no hazardous substance would have been identified with the existing water quality data and thus it would not be possible to optimize the share of BF concerning raw water quality.

4.2 Water quality assessment for Palla well field

The water quality assessment for the Palla well field has shown that the seasonal variability (monsoon, non-monsoon) has a major impact on the (i) number of identified potential hazard substances and their (ii) concentrations in surface water and ambient groundwater. This in turn strongly influences the 'optimal' BF share range (=difference between maximum and minimum 'optimal' boundary value for all potential hazard substances), leading to very small ranges during non-monsoon (65.66-65.92%) and large ranges during monsoon (32-100%). For the former the 'optimal' BF share range is approximately zero! In real-world application only slight changes of (i) decision parameters (here: pumping rates), (ii) natural boundary conditions (here: clogging parameters) or both will result in sub-optimal operational management solutions, which in turn requires additional post-treatment. Consequently only during monsoon season the 'optimal' BF share range is large enough to derive operational management schemes which are resilient over a wide range of boundary conditions as, e.g. the clogging parameter.

In order to fulfil the precautionary principle (VAN DER SLUIJS et al. 2005), which requires high safety margins – in this case a large 'optimum' BF share range – the following general recommendations are given:

- Do not include substances in the water quality input file (see Chapter 2.4.1.1), which concentrations are either (i) above 90% of the threshold limit both in surface water and ambient groundwater (here: iron) or (ii) which would otherwise limit the 'optimal' BF share range too

sharply (< 0.5 % difference). For safety reasons it is recommended to have an 'optimal' share of BF range of at least 40%, so that a long term increase/decrease of pumping rates has no impact for assuring an adequate raw water quality.
- Add additional post-treatment infrastructure for each of the substances which is excluded from the water quality assessment.

4.3 Optimization of well field operation

The optimization of well field operation is done in a trial-and-error approach: The BF Simulator is used to calculate the BF share for different operation schemes (pumping rate per well) and boundary conditions (clogging parameters). Subsequently the simulated BF share of each model run is compared against the 'optimal' BF share range (obtained during water quality assessment described above) in order to find an 'optimal' value for the pumping rate.

Quantitatively, the resulting 'optimal' decision parameter 'pumping rate per well' for the two well field design scenarios of the case study Palla are summarized below:

- Single production well scenario (Chapter 3.3.1): during monsoon season a pumping rate between 0.011 and 0.044 m^3/s is required to achieve the 'optimal' BF share (> 32%) if the clogging parameter remains below 600m. However, during non-monsoon season the 'optimal' BF share range (65.66-65.92%) is achieved only in case of zero clogging and with a pumping rate of 0.033 m^3/s.
- Multiple production wells scenario (Chapter 3.3.2): during monsoon season an 'optimal' pumping rate per well of 0.022m^3/s is required to achieve the 'optimal' BF share (>32%) if the clogging parameter remains below 3300m. Thus, operating multiple production wells is more resilient to higher clogging compared to the single production well scenario, since the flow reduction at the bank-aquifer interface is compensated through an increased infiltration length along the bank. However, during non-monsoon season the 'optimal' BF share range (65.66-65.92%) is only achieved in case of medium clogging (clogging parameter: 100m) and a pumping rate per well of 0.016m^3/s.

Note that the quantitative results for single and multiple production wells scenario are not directly comparable, since the total pumping rate between both scenarios differs approximately by factor ten. In addition the BFS only calculates an average BF share for the multiple production wells scenario instead of one BF share for each production well. Thus no quantitative comparison of BF shares between both scenarios is possible.

Qualitatively the BF share increases for (i) larger pumping rates and (ii) lower clogging parameters, while the behaviour of the minimum travel time is exactly inversely. Thus optimizing both, BF share and minimum travel time (e.g. not less than 50 d) is a multi-objective optimization problem which only can only be solved by (i) identification of trade-offs and subsequent (ii) definition of target values/ranges for each objective in the discussion making process with e.g. environmental agencies or water supply managers.

4.4 Concluding remarks

The conventional approach for designing BF sites for drinking water production is primarily focussed on water availability in cases in which groundwater resources are not sufficient. BF is favoured against direct surface water use because an additional barrier is introduced. The approach followed with the decision support system for BF systems developed in the frame of TECHNEAU 5.2 emphasizes the role of water quality for the design and operation of BF systems and neglects availability or demand constraints. On the other hand it may broaden the view of decision makers to treat BF not only as a means for additional water resources but to include water treatment aspects into their considerations, saving costs, energy and resources for post-treatment.

So far, the DSS follows a conservative approach, taking into account only mixing / dilution for concentration reduction. This is due to the fact that substance removal, e.g. by degradation is highly site-specific and difficult to quantify. The user is referred to supporting information for possible removal rates of different substance groups. Further research in this field could extend the database and lead to an additional "removal calculation" module.

Similarly, mobilization (e.g. of iron during anoxic subsurface passage) is not integrated so far. This is a clear draw back but is also due to the fact that predicting redox conditions in the subsurface is a difficult task. Ongoing research in this field might help to further develop this aspect of water quality in BF systems.

The test application of the DSS for the Palla well field (India) yielded 'optimal' BF shares for monsoon and non-monsoon conditions on the basis of DOC, Mn and As concentration reduction. Unfortunately, all three parameters are likely to be influenced by other reactions than mixing /dilution. They would certainly not be used in practice for well field optimization. However, in case that conservative substances like chloride or sulphate would be of relevance for water quality, optimal BF shares with practical value can be obtained and operational parameters (i.e. pumping rates) derived, thus showing that the DSS is capable of giving decision makers support.

Again, we emphasize that this DSS for BF shall by no means replace a thorough hydrogeological investigation and hydrodynamic modelling. However, it may raise the awareness of designers or decision makers to the water treatment potential that lies within BF for drinking water production.

5 References

BUYTAERT, W.; REUSSER, D.; KRAUSE, S. & RENAUD, J. P. (2008): Why can't we do better than topmodel? Hydrological Processes 22(20): 4175-4179, http://www.scopus.com/inward/record.url?eid=2-s2.0-61849096640&partnerID=40

CALVER, A. (2001): Riverbed permeabilities: Information from pooled data Ground Water 39(4): 546-553, http://www.scopus.com/inward/record.url?eid=2-s2.0-0034946714&partnerID=40

GNU PROJECT (1999): GNU Lesser General Public License, version 2.1. Retrieved 15.9.2009, http://www.gnu.org/licenses/lgpl-2.1.html

GRISCHEK, T.; SCHUBERT, J.; JASPERSE, J. L.; STOWE, S. M. & COLLINS, M. R. (2007): What is the appropriate site for RBF? ISMAR, Phoenix, Arizona, USA, ACACIA, Phoenix, Arizona.

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. (2009): Bank Filtration Simulator

HÜLSHOFF, I.; GRESOWIAK, J.; WIESE, B. & GRÜTZMACHER, G. (2009): Relevance and opportunities of RBF to provide safe water for developing and newly industrialised countries. Techneau Integrated Project. D5.2.9

JARVIS, A.; REUTER, H. I.; NELSON, A. & GUEVARA, E. (2008): Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), http://srtm.csi.cgiar.org

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

LORENZEN, G.; SPRENGER, C.; TAUTE, T.; PEKDEGER, A.; MITTAL, A. & MASSMANN, G. (2010): Assessment of the potential for bank filtration in a water stressed megacity (Delhi, India) Environmental Geology

MASSMANN, G.; HEBERER, T.; GRÜTZMACHER, G.; DÜNNBIER, U.; KNAPPE, A.; MEYER, H.; MECHLINSKI, A. & PEKDEGER, A. (2007a): Trinkwassergewinnung in urbanen Räumen – Erkenntnisse zur Uferfiltration in Berlin Grundwasser 12(3): 232-245

MASSMANN, G.; NOGEITZIG, A.; TAUTE, T. & PEKDEGER, A. (2007b): Seasonal and spatial distribution of redox zones during lake bank filtration in Berlin, Germany Environmental Geology 54(1): 53-65

MASSMANN, G.; SÜLTENFUß, J.; DÜNNBIER, U.; KNAPPE, A.; TAUTE, T. & PEKDEGER, A. (2008): Investigation of groundwater residence times during bank filtration in Berlin: a multi-tracer approach Hydrological Processes 22(6): 788-801

PEKDEGER, A.; LORENZEN, G.; SPRENGER, C. & TAUTE, T. (2006): IDB India: International Development of Bank Filtration - Case study India: 35 p.

RAO, S. V. N.; KUMAR, S.; SHEKAR, S.; SINA, S. K. & MANJU, S. (2007): Optimal pumping locations of skimming wells Hydrol. Sci. J. 52(2): 352-361

RUSTLER, M.; BOISSERIE-LACROIX, C. & HOLZBECHER, E. (2009): Bank Filtration Simulator - Manual. TECHNEAU Integrated Project. D5.2.5, www.techneau.org

TELLAM, J. H. & LERNER, D. N. (2009): Management tools for the river-aquifer interface Hydrol. Processes 23(15): 2267-2274

THE MATHWORKS (2009a): MATLAB 7.9 (R2009b). Natick, Massachusetts, The MathWorks

THE MATHWORKS (2009b): MATLAB Compiler 4.11 (R2009b). Natick, Massachusetts, The MathWorks

TRINKWV (2001): Trinkwasserverordnung vom 21. Mai 2001 ('Drinking Water Ordinance'). http://bundesrecht.juris.de/bundesrecht/trinkwv_2001/

VAN DER SLUIJS, J. P.; KAISER, M.; BEDER, S.; HOSLE, V.; KEMELMAJER, A. & KINZIG, A. (2005): The Precautionary Principle. COMEST Report. Paris, UNESCO, http://unesdoc.unesco.org/images/0013/001395/139578e.pdf

WANG, J. Z.; HUBBS, S. & SONG, R. (2003): Evaluation of Riverbank Filtration as a Drinking Water Treatment Process. AWWA Res. Fdn.: 145

WHO (2008): Guidlines for drinking water quality. Geneva, World Health Organization, http://www.who.int/water_sanitation_health/dwq/fulltext.pdf

WIESE, B. & NÜTZMANN, G. (2009): Transient leakance and infiltration characteristics during lake bank filtration Ground Water 47(1): 57-68, http://www.scopus.com/inward/record.url?eid=2-s2.0-58149250615&partnerID=40

Appendix A

Table 6 *Relative coordinates for production wells of Group 4 (derived according to Figure 9). Note that the x-coordinate represents the nearest distance between each pumping well and the Yamuna River bank; the y-coordinate increases from south (origin: W 60-60-OP) to north*

Well name	y coordinate [m]	x coordinate [m]
W21-OP	1006	459
W29	900	70
W22-OP	898	499
PA-TW-1	836	62
RWA 1	763	540
B 59-60	462	245
W 46	462	303
W 52	340	268
W 50-60	279	271
W 60-60-OP	0	417

Water quality assessment

Table 7 *Water quality input for the non-monsoon season (February 2007); (LORENZEN et al. 2010)*

Value ID	Substance Name	ConcSW	UnitSW	ConcGW	UnitGW	Additional Information	Substance ID
57	Cl	90	mg/L	20	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	3
121	NO3	6	mg/L	0.05	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	28
80	DOC	3	mg/L	0.8	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	32
97	Iron	0.25	mg/L	1.32	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	167
104	Manganese	0.02	mg/L	1.01	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	154
32	Arsenic	0.008	mg/L	0.011	mg/L	SW (Yamuna River) - GW (distal) 01.02.2007	146

Table 8 Water quality input for the monsoon season (September 2007); (LORENZEN et al. 2010)

Value ID	Substance Name	ConcSF	UnitSF	ConcGW	UnitGW	Additional Information	Substance ID
25	Ammonia	0.0025	mg/L	0.5	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	166
32	Arsenic	0.005	mg/L	0.01	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	146
57	Cl	132	mg/L	21	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	3
80	DOC	2.3	mg/L	0.1	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	32
91	Fluoride	1.2	mg/L	1.2	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	152
97	Iron	0.23	mg/L	0.67	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	167
104	Manganese	0.02	mg/L	0.52	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	154
120	NO2	0.45	mg/L	0.0025	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	29
121	NO3	0.9	mg/L	1	mg/L	SW (Yamuna River) - GW (distal) 01.09.2007	28

Table 9 Water quality threshold concentrations

Substance ID	**Substance Name**	**Threshold Concentration**	**Unit**	**LimitSource**
166	Ammonia	0.5	mg/L	(TRINKWV 2001)
146	Arsenic	0.01	mg/L	(WHO 2008)
3	Cl	250	mg/L	(TRINKWV 2001)
32	DOC	2.5	mg/L	maximum value for Chlorination (TRINKWV 2001)
152	Fluoride	1.5	mg/L	(WHO 2008)
167	Iron	0.2	mg/L	(TRINKWV 2001)
154	Manganese	0.4	mg/L	(WHO 2008)
29	NO2-	3	mg/L	(WHO 2008)
28	NO3-	50	mg/L	(WHO 2008)

Table 10 Mixing calculation output of the DSS for the non-monsoon season (February 2007); Note that the analytical computed optimum bank filtration share boundary without Iron ranges from 65.91-66.66%

Hazard Substance	**SW Conc.**	**GW Conc**	**Threshold Conc.**	**0.9*Threshold Conc.**	**BF Share Max [%]**	**BF Share Min [%]**
DOC	3	0.8	2.5	2.25	65.91	0
Iron	0.25	1.32	0.2	0.18	0	0
Manganese	0.02	1.01	0.4	0.36	100	65.66
Arsenic	0.008	0.011	0.01	0.009	100	66.66

Table 11 Mixing calculation output of the DSS for the monsoon season (September 2007); Note that the analytical computed optimum bank filtration share boundary without Iron is equal to the optimum bank filtration share boundary of Manganese

Hazard Substance	**SW Conc.**	**GW Conc**	**Threshold Conc.**	**0.9*Threshold Conc.**	**BF Share Max [%]**	**BF Share Min [%]**
Iron	0.23	0.67	0.2	0.18	0	0
Manganese	0.02	0.52	0.4	0.36	100	32

Optimization of Well Field Design and Operation

Table 12 Parameterisation of the BFS

Parameter ***Aquifer characteristics***	**Value** ***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]	***varied***
Well(s) characteristics	
Pumping rate [m^3/s]	***varied***
Position in grid [x,y]	***varied***

Scenario: Single Production Well

Table 13 Share of bank filtrate calculation output of the BFS for different pumping rates and clogging parameters

		Pumping rate [m³/s]				
	Share of bank filtrate (%)	**0.044**	**0.033**	**0.022**	**0.011**	**0.005**
Clogging parameter [m]	**1**	73.71	69.72	63.10	48.61	26.76
	10	71.75	67.48	60.42	45.06	22.41
	100	59.16	53.41	44.24	25.95	4.58
	1000	20.10	13.80	6.11	-	-
	5000	0.25	-	-	-	-

Table 14 Minimum travel time calculation output of the BFS for different pumping rates and clogging parameters

		Pumping rate [m³/s]				
	Minimum travel time [d]	**0.044**	**0.033**	**0.022**	**0.011**	**0.005**
Clogging parameter [m]	**1**	23.23	33.07	53.13	103.38	397.61
	10	27.33	37.04	55.91	125.37	425.55
	100	42.36	59.05	91.48	228.04	890.95
	1000	89.05	130.41	228.97	Inf	Inf
	5000	221.11	Inf	Inf	Inf	Inf

Scenario: Multiple Production Wells

Table 15 Share of bank filtrate calculation output of the BFS for different seasons and clogging parameters

		Season	
	Share of bank filtrate (%)	**Monsoon**	**Non monsoon**
Clogging parameter [m]	**1**	73.33	68.63
	10	72.93	68.17
	100	69.64	64.40
	1000	49.98	42.67
	5000	20.02	12.99

Table 16 Minimum travel time calculation output of the BFS for different seasons and clogging parameters

		Season	
	Minimum travel time [d]	**Monsoon**	**Non monsoon**
Clogging parameter [m]	**1**	24.32	33.38
	10	27.19	33.90
	100	41.87	58.61
	1000	72.14	105.18
	5000	141.43	204.00