Freie Universität Berlin

Surface- / groundwater interactions associated with river bank filtration in Delhi (India) – Investigation and modelling of hydraulic and hydrochemical processes

Oberflächen–/ Grundwasser Wechselwirkungen verbunden mit Uferfiltration in Delhi, Indien – Untersuchungen und Modellierung von hydraulischen und hydrochemischen Prozessen

Dissertation
zur Erlangung des Doktorgrades des Fachbereichs
Geowissenschaften der
Freien Universität Berlin

vorgelegt von
Christoph Sprenger

Berlin 2011

Erstgutachter: Prof. Dr. Michael Schneider
Freie Universität Berlin

Zweitgutachterin: Prof. Dr. Gudrun Massmann
Carl von Ossietzky Universität Oldenburg

Tag der Disputation: 18.08.2011

Preface

The present thesis was conducted as part of the integrated project "TECHNEAU – Technology enabled universal access to safe water" funded by the European Commission. The project was performed in cooperation with the Centre of Competence for Water Berlin (KWB) and the Indian Institute of Technology Delhi (IITD). The sometimes difficult organisation of fieldwork, the drilling and sampling campaigns, the shipping of water and sediment samples and interpretation of the data were made hand in hand with Gunnar Lorenzen and the author of this thesis.

The thesis contains the following contributions by other scientists, technicians and students:

- In part, geochemical properties of sediment samples were analysed by the technical staff of the Freie Universität Berlin (FUB)
- Standard water, stable isotope and organic trace pollutant analysis were carried out at the hydrochemistry laboratory of the FUB
- Only few sampling campaigns in Delhi were performed by students or technical staff from the IITD
- Microbiological analysis of bacteriophages was carried out by scientists from the Federal Environmental Agency (Umweltbundesamt), Universitat de Barcelona and the IITD

Table of contents

Table of contents I

List of figures IV

List of tables VIII

Declaration of originality IX

Acknowledgements X

Summary… XI

Zusammenfassung XIV

1 Introduction 1
- 1.1 Objectives 1
- 1.2 Synopsis of the remaining chapters 1

2 Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India)5
- 2.1 Introduction 5
- 2.2 Review on water stress in the mega city of Delhi 9
  - 2.2.1 Population and water demand 9
  - 2.2.2 Geological and geographical characteristics 10
  - 2.2.3 Surface water strain and pollution 11
  - 2.2.4 Groundwater strain and pollution 12
- 2.3 Field sites and methods 13
- 2.4 Results and discussion 16
  - 2.4.1 Hydraulic situation and flow field 16
  - 2.4.2 Temperature profiles 17
  - 2.4.3 Water quality 19
- 2.5 Summary and conclusion 26

3 Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and Haryana, India 30
- 3.1 Introduction 30
- 3.2 Review on common sources of inland salinity in shallow 31
- 3.3 The study area 33
- 3.4 Methods 36
- 3.5 Results 37
- 3.6 Discussion of results and salinity sources in the regional context 47
- 3.7 Conclusions 51

4 Environmental tracer application and purification capacity at a riverbank filtration well in Delhi (India) 53
4.1 Introduction 53
4.2 Hydrogeology of the well field 54
4.3 Methods 58
4.4 Results and discussion 58
4.4.1 Estimation of bank filtrate travel times with hydrogeological tracers 58
4.4.2 Attenuation and purification capacity of RBF in Delhi 61
4.5 Conclusions 64

5 Numerical quantification of surface-/groundwater interactions at the flood plain aquifer in central Delhi (India) using a multi tracer approach 66
5.1 Introduction 66
5.2 Materials and Methods 67
5.2.1 Field site and hydrogeology 67
5.2.2 Drilling, levelling and sampling of observation wells 69
5.2.3 Construction of water table map 69
5.2.4 Model construction 70
5.2.5 Transport parameters 75
5.2.6 Sensitivity analysis 77
5.3 Results and discussion 78
5.3.1 Transport simulation 81
5.3.2 Sensitivity analysis 85
5.3.3 Surface-/groundwater budget 86
5.4 Conclusions 87

6 Removal of bacteriophages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India) 89
6.1 Introduction 89
6.2 Materials and methods 91
6.2.1 Study area description 91
6.2.2 Construction of observation wells, sampling and analysis 93
6.2.3 Pathogenic viruses 94
6.2.4 Bacteriophages, coliform bacteria 95
6.2.5 Organic compounds 95
6.2.6 Description of the numerical model approach 96
6.3 Results and discussion 100
6.3.1 Hydrogeology 100
6.3.2 Attenuation of organic compounds 101
6.3.3 Attenuation of bacteriophages and enteric viruses 104
6.4 Conclusions 109

7 Vulnerability of bank filtration systems to climate change 110
  7.1 Introduction 110
  7.2 Discussion on climate sensitive factors influencing BF performance 111
    7.2.1 Impacts on BF water quantity 112
    7.2.2 Impacts on BF water quality 114
      7.2.2.1 Physicochemical parameters 115
      7.2.2.2 Suspended solids 116
      7.2.2.3 Dissolved Organic Carbon 116
      7.2.2.4 Nutrients 117
      7.2.2.5 Inorganic Trace Contaminants 119
      7.2.2.6 Pathogens 120
      7.2.2.7 Cyanotoxins 121
      7.2.2.8 Organic Micropollutants 121
      7.2.2.9 Pesticides 122
      7.2.2.10 Pharmaceuticals 123
      7.2.2.11 Hydrocarbons 123
      7.2.2.12 Endocrine disruptors 124
    7.2.3 Synthesis of projected climate change effects on BF performance 125
  7.3 Conclusions 128

8 References 129

Appendix 1 List of publications arising from this thesis 149
Appendix 2 List of related publications 150
Appendix 3 Tables 151

List of figures

Figure 2.1 Water stress in Delhi: The Yamuna River receives high loads of untreated wastewater in the urban stretch of the mega city between Wazirabad barrage (WB) and Oklah barrage (OB). Groundwater resources are contaminated with NO_3^- and F^- in large parts of the territory and threatened by salinity ingress. Overexploitation of the aquifer is leading to an alarming decline of the groundwater table. 7

Figure 2.2 Hydraulic heads at the field sites indicate horizontal and vertical hydraulic gradients in different seasons. The Yamuna is a loosing river at all times at the Palla and Central Delhi sites. By contrast, the Najafgarh Drain is draining the terrain in post-monsoon and cold season but changes to a loosing stream in the hot and dry season (pre-monsoon), when groundwater levels have declined. 17

Figure 2.3 Temperature profiles from the deep piezometers of each field site from cold season (February), pre-monsoon (May) and post-monsoon (September). The surficial zone is influenced by the annual changes in surface water temperature. It is elongated at the Central Delhi site and especially the Palla site, indicating the infiltration of river water. Retardation of seasonal temperature peaks from surface water can be used to estimate travel times of the bank filtrate........ 18

Figure 2.4 TDS concentrations (log scale) at the field sites and seasonal variations: Mineralisation of the river Yamuna and the ambient groundwater is low at Palla (upstream Delhi) and increases significantly in Central Delhi. At the Najafgarh Drain, TDS in the groundwater clearly exceeds the WHO recommended threshold of 1200 mg/L. Adjacent to the drain, multi-level sampling indicates salinity ingress with depth........ 19

Figure 2.5 Fe^{2+} concentrations (log scale) at the field sites and seasonal variations: At Palla and the Najafgarh Drain sites, Fe^{2+} concentrations in most samples remain in the range of the WHO limit or below it. At the Central Delhi site, in contrast, the infiltration of the degraded river water under anoxic conditions triggers the dissolution of Fe-(hydr)oxides and leads to increased concentrations in the bank filtrate (at shallow and medium depth)........ 21

Figure 2.6 As concentrations (log scale) at the field sites and seasonal variations: At Palla, As from the river water is attenuated during BF but further away from the river, the As concentrations reach the WHO limit in the distal well. At the Central Delhi site, where Fe-(hydr)oxides get dissolved, associated As is detected in high concentrations........ 22

Figure 2.7 F^- concentrations (linear scale) at the field sites and seasonal variations: F^- concentrations remain below the WHO limit in most samples and even decrease from the Yamuna to the shallow bank filtrate in Central Delhi. Only in the deep piezometers at Palla and Central Delhi and the distal dug well in the rural Najafgarh Drain site F^- concentrations are considerably elevated........ 24

Figure 2.8 Medium concentrations of N^- species NO_3^- and NH_4^+ (cumulative bars) at the field sites. Whereas concentrations of both N-species are low at Palla (upstream Delhi), their cumulative concentration is elevated in the Yamuna at the Central Delhi site and further increases during BF. At the Najafgarh Drain, only the surface water is affected by high concentrations of the nutrients, because the adjacent groundwater does not contain a significant share of bank filtrate. 26

Figure 2.9 The schematic cross-section illustrates potential sources of inorganic contaminants (red, bold letters) and attenuation processes identified at the field sites in Delhi. The big arrows represent schematic fow-paths. The relevance for existing wells and for the development of new BF facilities depends on site-specific conditions. Significant parameters identified are: (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, deep groundwater). 27

Figure 3.1 Schematic sketches of common sources of geogenetic inland salinity in shallow aquifers and processes leading to salinity ingress. The origin and dynamic of saline and brackish groundwater is often controlled by a combination of these processes. They are in many cases accelerated or triggered by man-made modifications that affect the natural equilibrium in the water cycle. 33

Figure 3.2 Location of the study areas (sampling areas A-C) and topographic features of the study region. The low-lying terrain is embedded between the Himalayan range in the north and the denudated Aravalli range in the south. The elongated depression forms part of the Indo-Gangetic alluvial plains and is situated in the broad intersection zone of the catchments of both streams. A network of irrigation canals distributes Himalayan waters across the semiarid terrain. 35

Figure 3.3 Location of groundwater sampling points in the study area and salinity ranges (for regional context compare figure 3.2). 38

Figure 3.4 Temperature profiles and depth dependant salinity in groundwater at the Delhi field site. 39

Figure 3.5 Salinity (as TDS) and mass concentrations of the anions of major salts. 40

Figure 3.6 Ca^{2+} concentrations in relation to the anions of its major salts. Ca^{2+} concentrations in general increase with salinity and many samples plot close to the $CaSO_4$ dissolution line (molar ratio = 1). In the HCO_3^- vs. Ca^{2+} diagram, most samples plot on or below the $CaCO_3$ saturation line (calculated for an exemplary solution at $pCO_2 = 10^{-1.5}$ and ionic strength i = 0.18). The equilibrium with the $CaCO_3$ solid phase is suggested to impose a constraint on the ion product of $[Ca^{2+}] * [HCO_3^-]^2$. 42

Figure 3.7 Correlations of Cl^- salinity and other ions: In the rural area, NO_3^- is suggested to mainly originate from fertilizers and seep to groundwater with irrigation return flow. Cl^-/Br^-- ratios are increased in the brackish and saline groundwater, suggesting that the dissolution of salts is a significant contributing factor to groundwater salinity. 44

Figure 3.8. Stable isotope composition and groundwater salinity: In the $\delta^{18}O$ vs. $\delta^{2}H$ diagram, most samples plot along the evaporation line that intersects with the local meteoric water line in the range of late monsoon precipitation. Where enrichment in heavy isotopes correlates with Cl^-, evaporations may be a driving factor of salinity ingress. The most saline waters do not have very negative $\delta^{18}O$ values, so their salinity is rather a result of the dissolution of salts. 46

Figure 4.1 Location map of the well field in north Delhi. 56

Figure 4.2 Well assembly of the studied RBF well with the local lithology (mbgl = meter below ground level, m.s. = mild steel). 57

Figure 4.3Temperature (°C), chloride (mg/L) and $\delta^{18}O$ (‰-VSMOW) of the Yamuna River (squares) and bank filtration well (open circles) against time............................. 59

Figure 4.4 Box plots of physicochemical parameters (temperature, dissolved oxygen, pH) measured in the Yamuna River (dark grey) and the RBF well (light grey). 62

Figure 4.5 Box plots of electrical conductivity, DOC and nitrate measured in the Yamuna River (dark grey) and RBF well (light grey). 63

Figure 5.1 A) Location map of India and Delhi; B) City limits of Delhi and the main river with barrages and main geology; C) The study area with the urbanized parts of Delhi, X-Y indicates the geological cross section shown in figure 5.2; D) Location map of the observation wells at the field site; Hydrogeological cross sectional view with the filter screen depths of the observation wells (vertical bars). 68

Figure 5.2 Grid discretization and boundary conditions. 72

Figure 5.3 Groundwater table map for the dry season (May 2006) and the field site (May 2007); the black triangles show the interpolation points (depth-to-water measurements from CGWB, interpolation by the author) 79

Figure 5.4 Modelled Hydrographs (line) and manual depth-to-water measurements (squares) in OW1, OW2 and OW3. The stage of the Yamuna River was measured in a 3-month interval by theodolite survey and the dotted line represents the interpolated river stage used as model input. 80

Figure 5.5 Measured temperature (square) with the calculated curves (line) in the shallow (OW1), medium (OW2) and deep observation wells (OW3) and the Yamuna River. The grey line at the upper part of the diagram indicates the mean air temperature. 82

Figure 5.6 Measured chloride (square) with the calculated curves (line) in the shallow (OW1), medium (OW2) and deep observation wells (OW3) in combination with the Yamuna River... 84

Figure 5.7 Sensitivity analysis of riverbed conductance, groundwater abstraction, porosity and hydraulic anisotropy on the average river water infiltration rate (left) and on the average travel time to the OW2 (right). 85

Figure 5.8 Temporal changes of river stage, infiltration rates, storage................................. 87

Figure 6.1 Location map of the study area (A, B, D) and differences in fecal coliforms between the Palla well field and the central Delhi field site (C). Section D, which is not drawn to scale, depicts the top view of the monitoring wells sampled, Line A-B refers to the cross section shown in figure 6.2. 93

Figure 6.2 Cross sectional view with the model domain and boundary conditions, zoomed area close to the river with grid refinement. 97

Figure 6.3 Calibration results with measured chloride concentration (square) in the OW4 and OW5 and the Yamuna River with the simulated curves (solid line) against time. 98

Figure 6.4 Organic compounds at the central Delhi field site: the non-polar (F1), medium polar (F2) and polar (F3) fractions prepared for the GC-MS-screening are plotted separately. The sample from the OW5 is shown in the foreground (black line) and the surface water in the back (grey line). 103

Figure 6.5 Time series of attenuation of bacteriophages between the Yamuna River and OW5 after 50 m distance or approx. 120 days of travel time. 105

Figure 6.6 Attenuation of somatic bacteriophages against travel time measured in OW1, OW2 and OW3 108

Figure 7.1 Climate sensitive factors influencing BF performance 112

List of tables

Table 2.1 Possible benefits of using BF for water supply compared to the direct use of surface water or groundwater 8

Table 2.2 Specifications of sampling points at the three field sites 15

Table 3.1 Sampling areas and methods. 37

Table 3.2 Potential sources of groundwater salinity and influences on the salt/water balance through man made perturbation of the natural equilibrium 52

Table 5.1 Parameters (d_{10}, d_{60}) determined from grain size distribution of the aquifer at different depths and calculated coefficients of hydraulic conductivity (k) according to Hazen 1893 and Beyer 1964 71

Table 5.2 Boundary conditions during monsoon and non-monsoonal time 75

Table 5.3 Parameters for heat transport simulation 77

Table 6.1 Parameters used for calculation of single-collector efficiency (η_0) 100

Table 6.2 Hydrogeological and hydrochemical properties of groundwater and aquifer at the study area 101

Table 6.3 Enteric virus genomes in the river water and in the bank filtrate of the OW5 observation well. 104

Table 6.4 Bacteriophage concentration, removal parameters and physical parameters of the infiltration site. 106

Table 7.1 Projected climate change effect on contaminant removal efficiency under two major climate change scenarios 126

Table A.1 Physicochemical properties and ion concentrations of the water samples (selected parameters). 151

Table A.2 Groundwater samples and the results of hydrogeochemical and stable isotope analysis. 152

Declaration of originality

I hereby certify, as the author of this thesis, and as one of the main authors of the publications arising, that I was the person involved in fieldwork, organisation, implementation, evaluation, analysis and manuscript preparation. I declare that the work presented in this thesis is to the best of my knowledge and belief original, except as acknowledged in the text, and that the work was not submitted previously to any other institution.

Christoph Sprenger

Acknowledgements

Preparation of any thesis can be a lonely and isolating experience, but without the support of numerous persons it would not be possible. Individuals and organisations that spend their support are acknowledged at the end of each chapter in this thesis. But I wish to thank my supervisor, Prof. A. Pekdeger for his guidance and patience and without his confidence this work would not have been possible. I also want thank Birgit Fritz and Thomas Taute who initiated the project and had the idea to promote the concept of River bank filtration as a low-tech and low-cost water treatment technology in India.

And I wish to thank Teresa; she had the love and understanding to support my sometimes long lasting trips to India.

Summary

In the densely populated semiarid territory in and around Delhi (India), the water demand is rising continuously, while the surface- and groundwater resources are threatened by contamination and overexploitation. This is a typical scenario in many newly industrialising and developing countries, where new approaches for a responsible water management have to be found. River bank filtration (RBF) holds great potential, thus being a reliable and low tech method, benefiting from the storage and contaminant attenuation capacity of the aquifer. For this study, three field sites have been constructed to investigate hydraulic, hydrochemical and microbiological processes during river bank filtration in different environments in the mega city of Delhi. The frequent (monthly) and long term (1.5 years) monitoring of the hydraulic behaviour of RBF and the wide range of investigated water quality parameters (e.g. major ions, pH, electrical conductivity, temperature), pathogens and its indicators (e.g. adeno-, norovirus, bacteriophages) and organic compounds (e.g. pesticides, pharmaceuticals) provided new insights to the function of RBF under the given environmental conditions.

In order to characterize the environmental conditions of the study area the origin and dynamics of groundwater salinity was investigated on both regional and local scale in detail. Density stratification and local up coning of saline waters was identified by multi level monitoring and temperature logging. Stable isotope ratios ($\delta^{18}O$, $\delta^{2}H$) were used to identify evaporation rates and for a better understanding of recharge processes and mixing dynamics in the study area. The results lead to the conclusion, that surface and groundwater influx into the poorly drained semiarid, geomorphological basin naturally results in the accumulation of salts in soil, sediments and groundwater. Man made changes of hydrological conditions, especially the implementation of traditional canal and modern groundwater irrigation have augmented evapotranspiration and led to water logging in large areas. In addition, water level fluctuations and perturbation of the natural hydraulic equilibrium favour the mobilization of salts from salt stores in the unsaturated zone and deeper aquifer sections.

Another part of this thesis was focusing on a RBF system in northern Delhi which was sampled monthly for hydrochemical/-physical parameters over one and a half years. Environmental tracers (chloride, $\delta P^{18P}O$ and temperature) were used to estimate travel time of the bank filtrate from the river to the abstraction well. Selected physico-chemical parameters were used to investigate purification and attenuation capacity of the RBF system. The study revealed that the combination of environmental tracers, with different transport behaviour, allow to characterise travel times during RBF reliably. The winter peak in the Yamuna River was found in the RBF well around 2.5 months later, while the summer or monsoon peak is observed in the bankfiltrate after 2 months of travel time. In terms of purification and attenuation capacity a good equilibration of temperature, electrical conductivity (EC) and 58 % attenuation of dissolved organic carbon (DOC) was observed after RBF passage.

At the central Delhi field site the impact of highly contaminated surface water infiltration on the urban aquifer systems was investigated. At this field site, RBF takes place because of dominant loosing river conditions due to large groundwater abstraction. Fluctuations of the hydraulic head in combination with a conservative tracer (chloride) and a retarded tracer (heat) were measured, evaluated and modelled to determine (i) infiltration rates and (ii) groundwater travel times, (iii) to perform a sensitivity analysis and (iv) to calculate a water budget for the flood plain aquifer. This study leads to the conclusion, that groundwater recharge by bank filtration is the most important recharge mechanisms. This calibrated numerical model was then used to describe the transport and deposition of indigenous bacteriophages during RBF. Removal of bacteriophages was calculated by non-equilibrium (rate-limited) sorption approach. The measurement of bacteriophages at this high contaminated field site offered the opportunity to test removal models based on the Colloid Filtration Theory (CFT). Somatic, indigenous bacteriophages underwent attenuation of almost 5 log after only 8 days of travel time during RBF. Additional, a series of organic trace compounds were considerably attenuated and human pathogenic viruses, two of them present in the Yamuna at 10P^{5P} genomes/100 ml, were undetectable after RBF passage.

Considering all three field sites and depending on site-specific conditions, distinct hydrogeological conditions were observed and both positive and negative effects on RBF performance were identified during this study. Most concerning issues are the impact of anthropogenic ammonium, the mixing with ambient brackish groundwater and the mobilisation of arsenic during the reductive dissolution of manganese- and iron-(hydr)oxides. Positive aspects are the dilution of contaminants during the mixing of waters from different sources, the sorption of arsenic, denitrification, the high attenuation capacity of pathogens and the precipitation of fluoride under favourable conditions.

On a generic level, this thesis also aims at identifying climate sensitive factors affecting bank filtration performance and assesses their relevance based on hypothetical ‘drought’ and ‘flood’ climate scenarios. The climate sensitive factors influencing water quantity and quality also have influence on substance removal parameters such as redox conditions and travel time. Droughts are found to promote anaerobic conditions during bank filtration passage, while flood events can drastically shorten travel time and cause breakthrough of pathogens, suspended solids, DOC and organic micropollutants. The study revealed that only RBF systems comprising an oxic to anoxic redox sequence ensure maximum removal efficiency. The storage capacity of the banks and availability of two source waters renders BF for drinking water supply less vulnerable than surface water or groundwater abstraction alone.

Considering all parts, this thesis provides new insights on the function and relevance of RBF both on the site-specific and generic level. It also contains knowledge and solutions for science and practioners of RBF.

Zusammenfassung

In dem dicht besiedelten, semiariden Territorium in und um Delhi (Indien) steigt der Wasserbedarf kontinuierlich, während das Oberflächen- und Grundwasser von Verschmutzung und Überbeanspruchung belastet ist. Dies ist ein typisches Szenario für viele Schwellen- und Entwicklungsländer, für die neue Ansätze für ein verantwortungsvolles Wasser Management gefunden werden müssen. Die Uferfiltration (UF) besitzt ein großes Potenzial, da es eine nur mit geringem technischem Aufwand verbundene und bewährte Methode ist, die von der Speicher- und Reinigungskapazität des Grundwasserleiters profitiert. In dieser Studie wurden drei Feldstandorte entwickelt um hydraulische, hydrochemische und mikrobielle Transport- und Abbauprozesse bei der Uferfiltration unter unterschiedlichen Umweltbedingungen in der Megastadt Delhi zu untersuchen. Durch das häufige (monatlich) und langzeitliche (eineinhalb Jahre) Monitoring des hydraulischen Verhaltens der Uferfiltrations-Standorte und die große Bandbreite der beobachteten Wasserqualitätsparameter (z.B. Hauptinhaltsstoffe, pH, elektrische Leitfähigkeit, Temperatur), Pathogene und Pathogenindikatoren (z.B. Adeno- und Noroviren, Bakteriophagen) und organische Spurenstoffe (z.B. Pestizide, Medikamentenrückstände) wurden neue Einsichten in die Funktionsweise der UF unter den gegebenen Umweltbedingungen erlangt.

Um die Umweltbedingungen im Untersuchungsgebiet besser charakterisieren zu können, wurde die Herkunft und Dynamik der Grundwasserversalzung auf regionaler sowie lokaler Ebene näher untersucht. Dichteschichtungen und lokales Upconing von Salzwasser wurden mithilfe tiefenorientierter Beprobung und durch Temperatur Messungen festgestellt. Stabile Isotope ($\delta^{18}O$, $\delta^{2}H$) wurden benutzt um Verdunstungsverluste zu berechnen und um ein besseres Verständnis über die Grundwasserneubildungs- und Mischungsdynamik im Untersuchungsgebiet zu erlangen. Die Ergebnisse führen zu den Schlussfolgerungen, dass der Zufluss von Oberflächen- und Grundwasser in ein semiarides, geomorphologisches Becken mit geringem Abfluss, zur Akkumulation von Salz im Boden und Grundwasser führt. Anthropogene Änderungen der hydraulischen Bedingungen, insbesondere der Bau von Bewässerungskanälen führen zu vermehrter Evapotranspiration und Staunässe in Teilen des Untersuchungsgebietes. Hinzu kommt, dass Fluktuationen der Grundwasserstände und Eingriffe in das natürliche hydraulische Regime die Mobilisierung von Salz in der ungesättigten Zone und im tiefen Grundwasser begünstigen.

Ein weiterer Teil dieser Arbeit widmet sich einem einzelnen UF System im nördlichen Teil von Delhi. Hier wurden monatliche Beprobungen von hydrochemischen und –physikalischen Parametern über einen Zeitraum von mehr als einem jährlichen Zyklus durchgeführt. Umweltmarker (Chlorid, $\delta^{18}O$ und Temperatur) wurden benutzt um Fließzeiten des Uferfiltrats vom Fluss zu dem UF Brunnen abzuschätzen. Einige ausgewählte physico/chemische Parameter wurden benutzt um die Reinigungsleistung des UF Systems zu untersuchen. Die Studie zeigt, dass eine Kombination von Markern mit unterschiedlichem Transport Verhalten eine zuverlässige Charakterisierung von Fließzeiten erlaubt. Dabei wurde festgestellt, dass die Aufenthaltszeiten des Uferfiltrats im Jahresverlauf sehr variabel sind und zwischen ca. 2,5 Monaten im Winter und ca. 2 Monaten im Sommer schwanken. Hinsichtlich der Reinigungsleistung wurde eine Abschwächung des Temperatursignals und der elektrischen Leitfähigkeit und eine Verminderung des gelösten organischen Kohlenstoffs (DOC) um 58% nach der UF Passage beobachtet.

An einem weiteren Feldstandort, im zentralen Bereich Delhis, wurde der Einfluss der Infiltration von stark kontaminiertem Oberflächenwasser auf den städtischen Grundwasserleiter untersucht. An diesem Standort findet UF statt, weil der natürliche hydraulische Gradient durch hohe Grundwasserentnahmen umgedreht ist und influente Verhältnisse permanent vorherrschen. Ein Numerisches 2D Modell wurde entwickelt um (i) Infiltrationsraten des Flusses und (ii) Fließzeiten des Uferfiltrats zu bestimmen und um (iii) eine Sensitivitätsanalyse durchzuführen und (iv) ein Wasserbudget für den Grundwasserleiter der Überflutungsebene zu berechnen. Das Modell wurde anhand der gemessenen Wasserstände im Fluss und Grundwasser in Verbindung mit Zeitreihen eines hydrochemisch konservativen (Chlorid) und eines retardierten Markers (Temperatur) kalibriert. Dabei wurde festgestellt, dass die Infiltration von kontaminiertem Oberflächenwasser in den städtischen Grundwasserleiter die dominierende Art der Grundwasserneubildung ist. Das kalibrierte numerische Modell wurde dann benutzt, um das Transport- und Sorptionsverhalten von Bakteriophagen bei der Uferfiltration zu beschreiben. Die Entfernung von Bakteriophagen wurde mithilfe eines Nicht-Gleichgewichts Sorptions Ansatzes berechnet. Die Messungen der Bakteriophagen an diesem stark kontaminierten Standort ermöglichten eine Überprüfung der Kolloid Filtration Theorie. Die somatischen, indigenen Phagen wurden um 5 log Stufen nach nur acht Tagen Aufenthaltszeit im Grundwasserleiter verringert. Dabei wurde auf den ersten Infiltrationsmeter die höchste Entfernungsrate festgestellt. Zusätzlich waren eine ganze Reihe von organischen Spurenstoffen, die im Fluss gemessen wurden, nach der UF Passage erheblich verringert oder nicht mehr nachweisbar. Humanpathogene Viren, welche im Fluss in Konzentrationen von bis zu 10^5 Genome/100 mL vorhanden waren, waren nach der UF Passage nicht mehr nachweisbar.

Bei der Betrachtung aller drei Feldstandorte konnten sehr unterschiedliche, standortspezifische hydrogeologische Bedingungen beobachtet werden. Hinsichtlich der Reinigungsleistung der UF wurden sowohl positive als auch negative Faktoren festgestellt.

Der Einfluss von anthropogenem Ammonium, die Mischung mit brackischem Grundwasser und die Mobilisierung von Arsen während der Lösung von Mangan- und Eisen(hydro-)oxiden sind negative Aspekte der UF in Delhi. Positive Aspekte sind die Verdünnung von Schadstoffen, die Sorption von Arsen, die Denitrifikation, die hohe Rückhaltekapazität von Pathogene und die Ausfällung von Fluorid unter geeigneten Bedingungen.

Auf einer übergeordneten, allgemeinen Ebene wird in dieser Arbeit der Einfluss der Folgen des Klimawandels auf die Leistung der UF untersucht. Anhand von hypothetischen „Trocken-“ und „Überflutungs-“ Szenarien wurden die Einflüsse von klimasensitiven Faktoren, wie Temperatur und Niederschlag, auf die Leistung der UF untersucht. Die klimasensitiven Faktoren beeinflussen die Wasserverfügbarkeit und die Wassergüte, haben aber auch Einfluss auf die Reinigungsleistung durch eine Veränderung der Redoxbedingungen und Fließzeiten. Bei Zeiten anhaltender Trockenheit werden verstärkt anoxische Redoxbedingungen bei der UF Passage entwickelt, während Überflutungen die Aufenthaltszeiten des Uferfiltrats drastisch verkürzen können und damit zu einem Durchbruch von Pathogenen, Schwebstoffen, DOC und organischen Spurenstoffen führen können. Die Studie zeigt, dass nur UF Systeme die eine oxische zu anoxische Redoxsequenz besitzen eine maximale Reinigungsleistung gewährleisten. Die Speicherkapazität des Grundwasserleiters und die Verfügbarkeit von zwei Quellen bei der UF macht diese viel weniger anfällig gegenüber den Folgen des Klimawandels als eine Wasserversorgung, die nur auf Oberflächenwasser oder Grundwasser allein beruht.

Insgesamt betrachtet bietet diese Arbeit neue Einsichten in die Funktionsweise und Relevanz der Uferfiltration auf standortspezifischer und übergeordneter Ebene. Diese Arbeit beinhaltet Wissen und Lösungen für Wissenschaftler und Praktiker von Uferfiltration.

1 Introduction

1.1 Objectives

The broad objectives of this thesis are:

- Investigation of the hydraulic function of RBF under the given monsoonal climate conditions
- Identification and understanding of the fate and transport processes of relevant pollutants during RBF
- Description of the advantages and constraints of RBF in a regional and generic context

1.2 Synopsis of the remaining chapters

The following provides a synopsis of the remaining chapters with their main scientific contributions, the connecting link to the general objectives of this thesis and the approximate share of the author contribution. More detail is, of course, given in each of the respective chapters that follow.

Chapter 2: Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India)[1]

This chapter gives a broad overview of the study area. The main problems related to surface-/groundwater pollution and availability were presented here and all three investigated field sites in Delhi have been introduced. Prior to this study, RBF was not practised intentionally in Delhi and the capabilities of RBF were unknown to a large extent. This study revealed advantages and disadvantages of RBF within the Delhi context and received the attention of

---

[1] Lorenzen G, **Sprenger C**, Taute T, Pekdeger A, Mittal A, Massmann G (2010) Environmental Earth Sciences, Volume 61, Number 7, 1419-1434, DOI 10.1007/s12665-010-0458-x

local and national authorities, stakeholders and the interested public through various dissemination activities. In this paper the function and relevance of RBF in Delhi was described for the first time within a scientific context.

As the second author, I was mainly involved in field campaigns and correction of manuscript templates. My contribution was focusing on discussion with the first author and the common development of the manuscript structure. Only the data interpretation concerning iron and arsenic at the field sites was my personal contribution.

Chapter 3 Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and Haryana, India[2]

This chapter gives more details on the environmental conditions focusing on salinity ingress in the study area. The combination of depth-dependant and regional sampling and the analysis of classical hydrochemical parameters along with stable isotopes of water provided new insights to the origin and dynamics of salinity ingress. An innovative aspect of this chapter is the description of salinity ingress over historical and geological time scales. The connecting link to the other chapters is the improved understanding of the hydrogeological context of the study area.

As the second author, I was mainly involved in the field campaigns in Haryana and Delhi. My contribution to this manuscript was focusing on discussion with first author, improving the manuscript and the interpretation of the stable isotope data.

Chapter 4: Environmental tracer application and purification capacity at a river bank filtration well in Delhi (India)[3]

This chapter focuses on the hydraulic behaviour and the attenuation capacity of selected physico-chemical parameters of a RBF well in the northern part of Delhi. The frequent and long term monitoring of the RBF well revealed, for the first time in India, the influence of the monsoon climate on travel times of bank filtrate. This characterisation was achieved by frequent and long term monitoring and the combination of multiple environmental tracers

---

[2] Lorenzen G, **Sprenger C**, Baudron P, Gupta D, Pekdeger A (accepted) Hydrological Processes, DOI: 10.1002/hyp.8311

[3] **Sprenger C**, Lorenzen G, Pekdeger A (2011) in Journal of Indian Water Works Association (accepted)

(chloride, $\delta^{18}O$ and temperature). This is a standard procedure in Europe but new approach in the Indian context.

In combination with the studie in chapter 2 it could be shown that RBF provides water that meets Indian and international (WHO) drinking water standards.

As the first author, I was responsible for manuscript preparation, data interpretation and data display. Field work was equally distributed between the first and second author.

Chapter 5: Numerical quantification of surface-/groundwater interactions at the flood plain aquifer in central Delhi (India) using a multi tracer approach

This chapter focuses on the hydraulic surface-/groundwater interactions at the central Delhi field site. The hydraulic connection of the Yamuna River to the local aquifer was unknown prior to this study. It was assumed that the river is receiving groundwater (gaining river conditions), but this study had shown that the opposite is true. By the means of numerical modelling it was achieved to establish a water budget for the surface-/groundwater interaction at the central Delhi field site. This chapter provides also more details on the flow and transport model that is used in the following chapter to simulate transport and deposition of bacteriophages.

This chapter is the only chapter of this thesis that is not published in a peer-reviewed journal. I was responsible for the whole content of this chapter.

Chapter 6: Removal of bacteriophages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India)[4]

This study was conducted at the central Delhi field site to ascertain if RBF can significantly improve the quality of the highly polluted surface water in terms of virus removal (bacteriophages, enteric viruses) and organic pollutant attenuation during anoxic underground passage. The experimental setting of this study was unique since it provided the possibility to investigate the transport of indigenous viruses under field conditions. The detailed description of the hydrogeological properties and the transport parameters yielded by the numerical modelling allowed the comparison with other field studies.

---

[4] **Sprenger C**, Lorenzen G, Grunert A, Ronghang M, Dizer H, Selinka HC, Girones R, Lopez-Pila JM, Mittal A, Szewzyk R (2011) Journal of Water, Sanitation and Hygiene for Development (revised April 2011)

As the first author, I was the main contributing author but with a focus on the virological part. I was responsible for organisation and realisation of the sampling campaigns, the manuscript preparation, data interpretation and data display in cooperation with the co-authors.

Chapter 7: Vulnerability of bank filtration systems to climate change [5]

This chapter can be considered as a summary and concluding chapter as it reviews not only climate sensitive factors influencing the performance of RBF, but also gives a comprehensive overview of relevant removal processes during RBF for a wide range of pollutants. The assessment of the vulnerability of RBF systems to climate change was achieved by extensive literature review in combination with the author's experiences and considerations. Prior to this publication the literature focusing on the likely effects of climate change on RBF performance was very limited.

As the first author, I was the main contributing author for this paper. Most of the relevant pollutants were reviewed by me. I was responsible for the manuscript preparation, data interpretation and data display in cooperation with the co-authors.

---

[5] **Sprenger C**, Lorenzen G, Hülshoff I, Grützmacher G, Ronghang M, Pekdeger A (2010) Science of the Total Environment, Volume 409, Issue 4, 655-663, doi:10.1016/j.scitotenv.2010.11.002

2 Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India) [6]

Abstract

In the densely populated semiarid territory around Delhi, the water demand is rising continuously, while the surface- and groundwater resources are threatened by contamination and overexploitation. This is a typical scenario in many newly industrialising and developing countries, where new approaches for a responsible water management have to be found. Bank filtration holds a great potential, thus being a low tech method and benefiting from the storage and contaminant attenuation capacity of the natural soil/rock. For this study, three field sites have been constructed to investigate bank filtration in different environments in and around the mega city with a main focus on inorganic contaminants. Hydraulic heads, temperature gradients and hydrochemistry of surface water and groundwater were analysed in three different seasons. Depending on site specific conditions, distinct hydrogeological conditions were observed and both positive and negative effects on water quality were identified. Most concerning issues are the impact of anthropogenic ammonia, the mixing with ambient saline groundwater and the mobilisation of arsenic during the reductive dissolution of manganese- and iron-(hydr)oxides. Positive aspects are the dilution of contaminants during the mixing of waters from different sources, the sorption of arsenic, denitrification, and the precipitation of fluoride under favourable conditions.

---

[6] Lorenzen, G., **Sprenger, C.**, Taute, T., Pekdeger, A., Mittal, A., Massmann, G., (2010) Environmental Earth Sciences, Volume 61, Number 7, 1419-1434, DOI: 10.1007/s12665-010-0458-x

3 Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and Haryana, India[7]

Abstract

Groundwater salinity is widespread problem and increasing concern in the alluvial plains of Delhi and neighbouring Haryana state. This study aims to identify potential sources of dissolved salts and the driving mechanisms of salinity ingress in the shallow aquifer. It combines a review of environmental conditions and the analysis of groundwater samples from 25 sampling points. Major ions are analysed to describe the composition and distribution of saline groundwater and dissolution/precipitation dynamics. Density stratification and local up coning of saline waters was identified by multi level monitoring and temperature logging. Bromide-chloride ratios hold information on the formation of saline waters and nitrate is used as an indicator for anthropogenic influences. In addition, stable isotope analysis helps to identify evaporation and to better understand recharge processes and mixing dynamics in the study area. The results lead to the conclusion, that surface and groundwater influx into the poorly drained semiarid basin naturally results in the accumulation of salts in soil, sediments and groundwater. Man made changes of environmental conditions, especially the implementation of traditional canal and modern groundwater irrigation have augmented evapotranspiration and led to water logging in large areas. In addition, water level fluctuations and perturbation of the natural hydraulic equilibrium favour the mobilization of salts from salt stores in the unsaturated zone and deeper aquifer section.

---

[7] Lorenzen, G., **Sprenger, C.**, Baudron, P., Gupta, D., Pekdeger, A. (accepted) Hydrological Processes, DOI: 10.1002/hyp.8311

4 Environmental tracer application and purification capacity at a riverbank filtration well in Delhi (India)[8]

Abstract

A riverbank filtration (RBF) system in northern Delhi was sampled monthly for hydrochemical/-physical parameters through more than one annual cycle. Environmental tracers (chloride, $\delta^{18}O$ and temperature) were used to estimate travel time of the bank filtrate from the river to the abstraction well. Selected physical/chemical parameters were used to show purification and attenuation capacity of the RBF system. The study revealed that a combination of tracers allow to characterise travel times reliably. The winter peak in the Yamuna River was found in the RBF well around 2.5 months later, while the summer or monsoon peak is observed in the bankfiltrate after 2 months of travel time. In terms of purification performance the studied RBF well showed a good equilibration of temperature, electrical conductivity and 58 % attenuation of dissolved organic carbon.

4.1 Introduction

Riverbank filtration (RBF) is a natural water treatment method in which surface water is infiltrated into an aquifer and subsequently abstracted for agricultural or drinking water purposes (Dillon, 2002). The abstracted water is a mixture between the infiltrated surface water (bank filtrate) and the ambient groundwater. The quality of water derived from RBF strongly depends on site specific conditions (Lorenzen, et al. 2010). Important factors are the quality of surface water, the hydrological and (hydro-) geochemical conditions of the subsurface and the travel time of the bankfiltrate. For groundwater resource protection, especially at RBF sites travel time of bankfiltrate plays an important role because pathogens (bacteria, viruses) do not survive beyond certain time periods in the aquifer. Typical groundwater protection regulations in Europe are 50 days travel time in Germany (DVGW, 1995) or 60 days in Denmark (Stockmarr, 1998). Another important aspect is the degradation of organic compounds during bank filtration.

---

[8] **Sprenger C**, Lorenzen G, Pekdeger A (in press) in Journal of Indian Water Works Association

In this paper, a case study from a bank filtration well field in Delhi is presented with field data from surface and groundwater. Travel times are estimated by the analysis of multiple tracers and degradation of organic compounds and nutrients is identified by the analysis of physicochemical and chemical data from surface water and the RBF well.

Information about flow velocities, travel times and fluxes between surface- and groundwater can be obtained by different hydrogeological tracer parameters (Massmann, et al. 2008a, Schubert, 2002). In this study, temperature, chloride and $\delta^{18}O$ were used as in-situ tracers for surface-/groundwater interactions. The ideal tracer is of either natural or anthropogenic origin, widely distributed in the study system, easy to detect, and its geochemical behaviour is conservative (or at least predictable). Seasonal variations of the tracer in the river are reflected by attenuated and time shifted curves in the groundwater, but if travel times are too long seasonal variations will diminish and cannot be detected in the groundwater anymore. Therefore, a combination of geochemically different tracers were used: (i) two conservative tracers (chloride, $\delta^{18}O$) and (ii) retarded tracer (temperature or heat).

Since many decades hydrogeologists investigated temperature (heat) transport in the subsurface to estimate groundwater velocities or exchange rates with surface waters (Anderson, 2005, Stallmann, 1963). Heat is transported not only by the flowing water (advective heat flow) but also by heat conduction through non-moving solids and fluids (conductive heat flow). The mutual heat exchange of the groundwater with the surrounding aquifer material retains the heat signal compared to pure advective transport, resulting in attenuation and retardation of the temperature signal. The use of heat as a tracer has several advantages over hydrochemical tracers. Temperature is inexpensive, easy and a robust parameter to measure. In contrast to chemical tracers, no laboratory analysis is required and the data is immediately available.

4.2 Hydrogeology of the well field

The well field is situated in north Delhi (Palla) on the western flood plain of the Yamuna River, upstream of the confluence with the Najafgarh Drain (Figure 4.1). The Central

Groundwater Board (CGWB) drilled around 90 wells since 2001 to cope with the growing water demand of the capital. The well field was reported to abstract around 100,000 L/day (24 MGD) (Rao, et al. 2007) to the municipal water supply of Delhi.

Initially the well field was designed to abstract groundwater mostly during flood events, recharged from the inundated plains. Pump houses of all wells and the transformators for the power supply were contructed on pillars, which allows operation also during flood events. However, over the last decades, it was observed that the once periodic flooding is nowadays occurring only as an extreme event. According to the statements of Central Ground Water Board officials a major flood event, setting the entire floodplain area under water has not occurred for at least 15 years.

The geology of the floodplain is dominated by sandy fluviatile deposits which build up the younger alluvium, covering the entire area with a thickness of tens of meters. The upper aquifer is unconfined and groundwater level is found at about 4 – 6 metres below ground level. These sediments have been deposited upon a series of several hundreds of meters of older alluvium, which is less permeable and predominately composed of silt, clay and sand. The bedrock is represented by the Delhi Ridge, a precambian metamorphic rock composed of quartzite with intercalations of schist phyllite (Thussu, 2006). The land of the well field and its surrounding is used intensively for cultivation of different kind of crops like turnip, rice and wheat.

Within one year, the course of the river seems to be relatively stable, meandering only within the slopes of the riverbed. Anyhow, oxbow lake structures within the floodplain and comparison of satellite images and maps from different years show that locally the riverbed has shifted several hundred meters throughout the last decades (Figure 4.1).

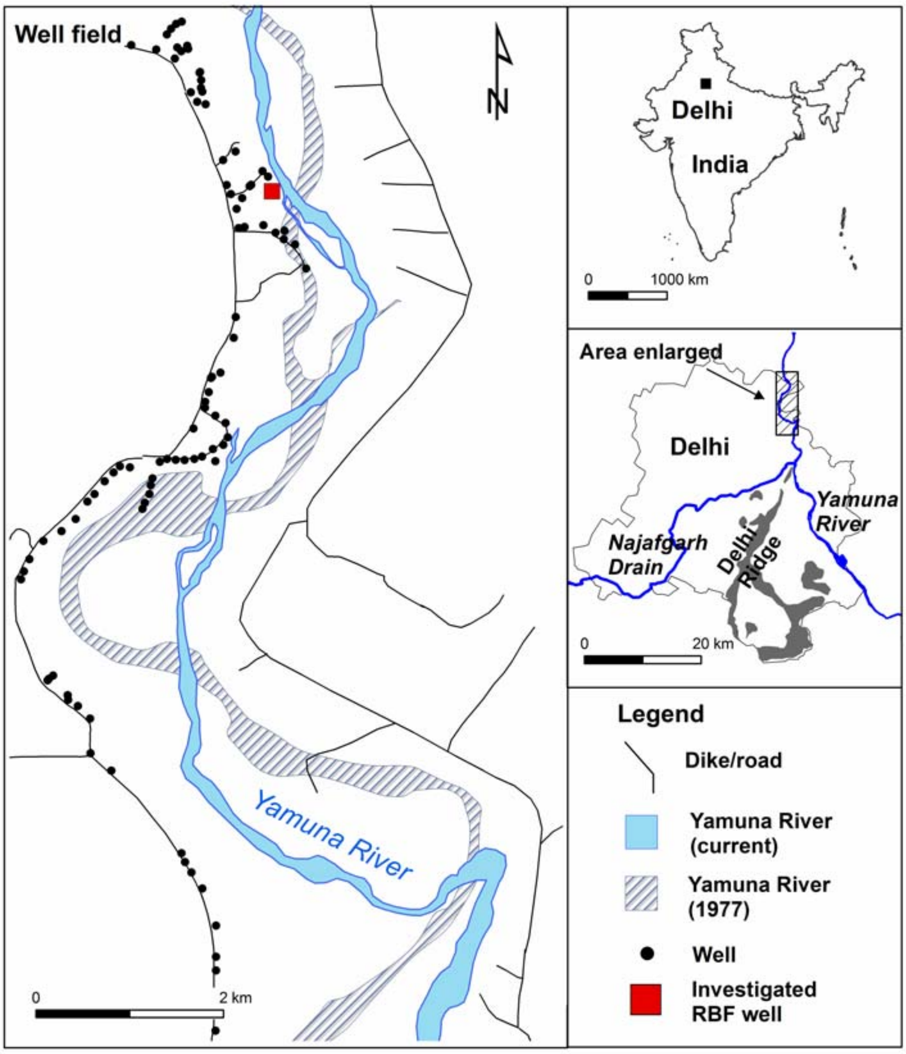

Figure 4.1 Location map of the well field in north Delhi.

Saline and brackish groundwater that occurs in deeper wells are covered by a horizon of some tens of meters of sweet water in the floodplain area (Shekhar and Prasad, 2009). Salinisation is a severe problem in the southern part of the well field (Rao et al. 2007).

The lithology of the aquifer and the well assembly of the studied RBF well is shown in figure 4.2. The well is partially penetrating with a total depth of 54 m below ground level. Depending on the river stage and the course of the Yamuna River the RBF well is between 40 - 60 m distance from the river. Diameter of the casing is given with 12” and the well diameter is around 15“ (CGWB, 2005). A gravel pack filled the entire depth of the well and no clay grout was build. The filter screen were constructed with a total length of 29 m (CGWB, 2005). The drawdown of the pumping well could not be measured directly but is estimated to be 5-6 m. The well is operating between 6 – 12 hours per day with an estimated maximum discharge of 1200 L/min.

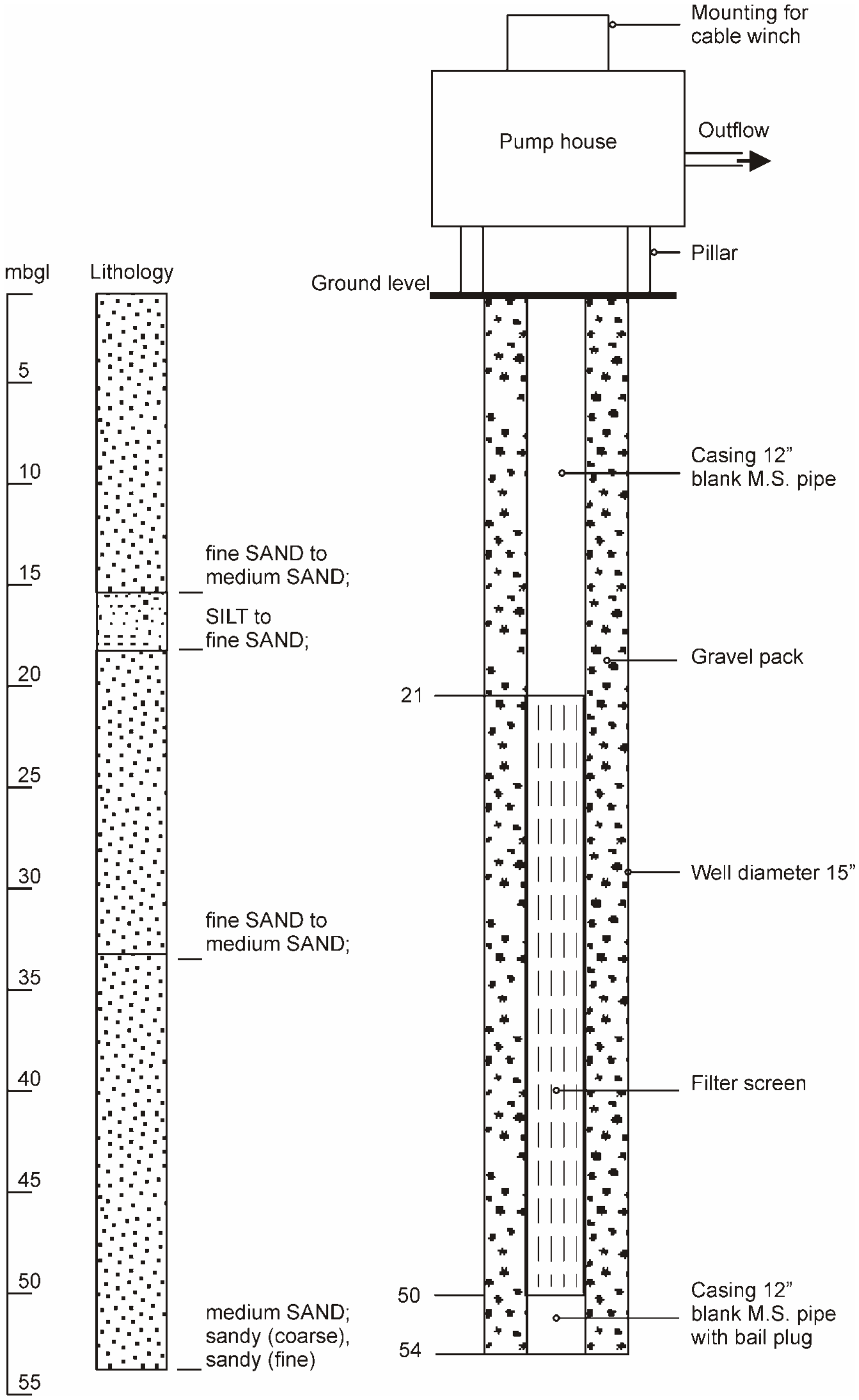

Figure 4.2 Well assembly of the studied RBF well with the local lithology (mbgl = meter below ground level, m.s. = mild steel).

4.3 Methods

The Yamuna River and the studied RBF well were sampled monthly from September 2006 to March 2008 in order to detect seasonal changes of hydraulic and hydrochemical parameters. The removal of at least three static water volumes of the observation wells was applied in this study according to German guidelines. In-situ parameters like pH, temperature, ORP (Oxygen reduction potential), EC (electrical conductivity) and DO (dissolved oxygen) were measured with Eutech Cyberscan devices in a flow-through cell. After the in-situ parameters were stable samples were taken and stored in 20 mL polypropylene bottles with watertight caps. All samples for ion determination were filtered on site with 0.2 µm acetate cellulose filters. Isotope analysis was performed at the Freie Universitaet Berlin on a Thermo Finnegan Mat 253 isotope ratio spectrometer using a Gas Bench II peripheral unit with autosampler-assisted loop injection. Analytical values were standardised to the international reference Vienna Standard Mean Ocean Water (VSMOW) and internal standards. For $\delta^{18}O$ measurements, a sample volume of 1000 µL were flushed with 0.5% CO_2 in He environment and then equipped with platinum catalyst to accelerate equilibrium. Measurement was performed after an equilibration time of 40 minutes. Precision was ±0.02 for $\delta^{18}O$ ‰ - VSMOW.

4.4 Results and discussion

4.4.1 Estimation of bank filtrate travel times with hydrogeological tracers

The temporal distribution of temperature (°C), chloride (mg/L) and $\delta^{18}O$ (‰-VSMOW) of the Yamuna River and the RBF well is shown in figure 4.3. The seasonal signal in the Yamuna River for all three tracers is attenuated and shifted in the corresponding curve of the RBF well. However, seasonal peaks (positive and negative) in the surface water and the corresponding curve in the bank filtrate were different for each tracer.

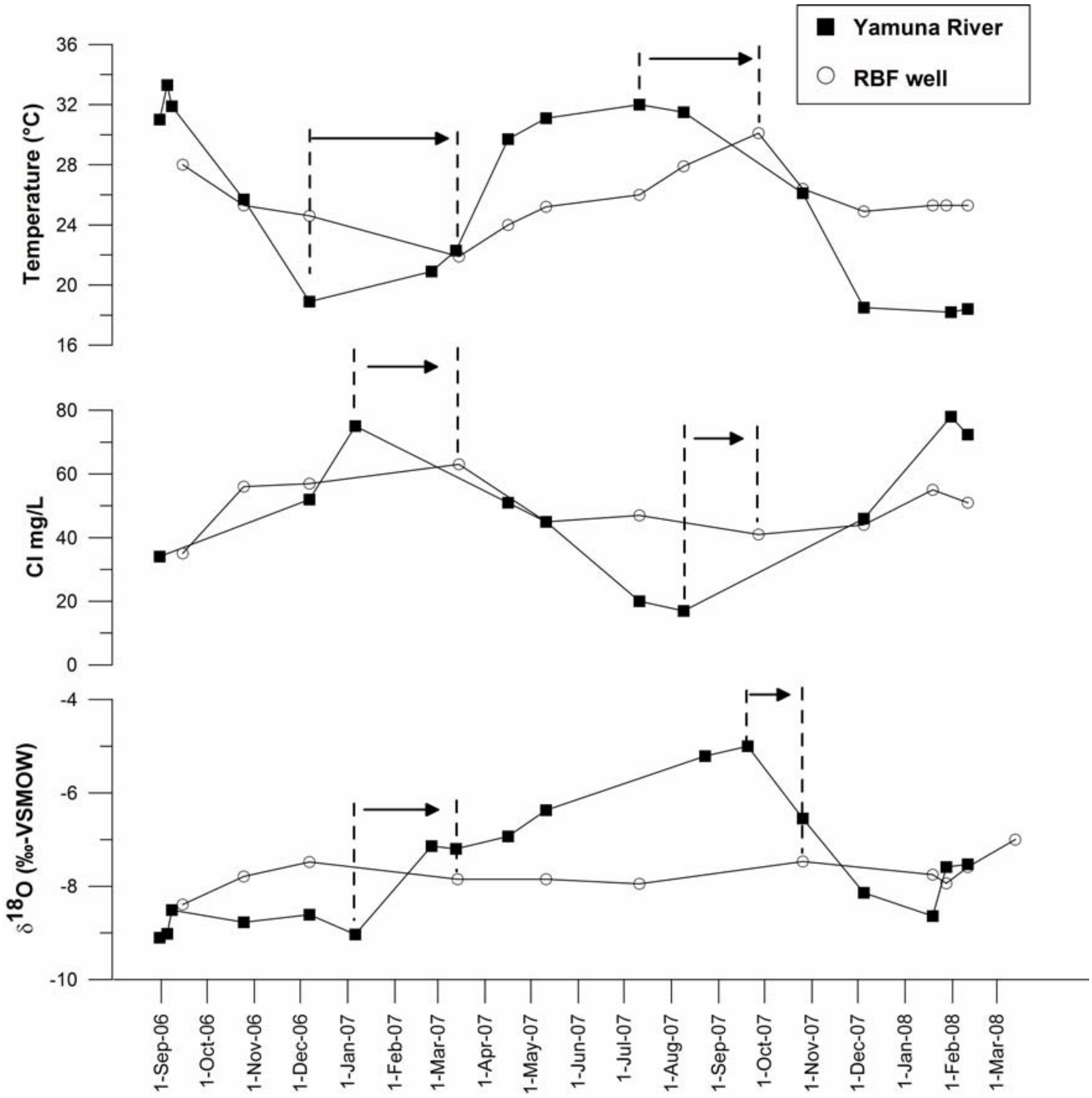

Figure 4.3 Temperature (°C), chloride (mg/L) and $\delta^{18}O$ (‰-VSMOW) of the Yamuna River (squares) and bank filtration well (open circles) against time.

Chloride and $\delta^{18}O$ are highly mobile in groundwater and not involved in most geochemical reactions that commonly occur in aquifers (Clark and Fritz, 1997, Freeze and Cherry, 1979). Both are conservative tracer, which are only transported by the flow of water (advective transport) and hydrodynamic dispersion.

The pronounced seasonal variation in the surface water makes chloride an ideal tracer, with a high concentration in winter (maximum 75 mg/L) and low concentration due to dilution during monsoon in September (minimum 17 mg/L). The winter peak in the Yamuna River (early January) can be found in the RBF well around 2.5 months later (middle of March), while the summer or monsoon peak (August) is observed in the bankfiltrate after 2 months (end of September) travel time.

Stable isotope of water (δ^{18}O ‰ VSMOW) show clear fluctuations in the Yamuna River, but the signal was not following a regular pattern. E.g. the monsoon isotope ratio in 2006 was around -9 ‰ while the ratio during the monsoon 2007 was enriched by heavy isotopes (from -6.5 to -5 ‰ VSMOW). Rozanski et al. (1993) showed that the isotopic seasonal precipitation pattern in Delhi is characterised by enriched δ^{18}O signatures during the dry, non-monsoon months (from -2 to -1 ‰ VSMOW) and by depleted δ^{18}O signatures during monsoon (-10 to -9 ‰ VSMOW). During the non-monsoonal period, the amount effect enriches δ^{18}O and imparts a negative Temperature - δ^{18}O correlation (Clark and Fritz, 1997, Datta et al. 1991, Rozanski et al. 1993). The strong enriched isotopic signature in monsoon 2007 cannot be explained by natural conditions, it is rather likely that the natural signal is interfered by anthropogenic impacts such as inter basin water transfer. However, also an irregular seasonal isotopic signal may be used as a tracer. The amplitude of the isotopic signal in the river was lower compared to the chloride or temperature amplitude, and the isotopic amplitude in the bankfiltrate well is almost completely attenuated but still above the analytical error of 0.1 ‰ VSMOW. Therefore, the winter peak (January) can be observed in the bankfiltrate well ~2.5 months later (middle of March), while the summer peak (September) is observed after ~1.5 months (end of October). It must be taken into account that due to the low seasonal amplitude/analytical error ratio, the error is higher compared to the two other tracers.

Because of its tracer-like behaviour, heat carried by groundwater can be used as a tracer for estimating travel times (Anderson, 2005, Becker et al. 2004, Cox et al. 2007). Temperature in the Yamuna River is following the annual air temperature with a winter minimum in December (~18°C) and summer maximum in July (~32°C), before the onset of the monsoon season. The annual peaks can be observed attenuated, but still clearly visible (accuracy 0.5°C) in the RBF well after around 3.5 months (winter peak) and after approx. 3 months (summer peak). Compared to pure advective flow, heat transfer is retarded by a factor (R), which is the ratio between the transport velocity of the temperature (v_T) and the pore water velocity (v_a) according to:

$$R = \frac{v_a}{v_T} \qquad \text{eq. 4.1}$$

The retardation factor R calculated with travel times taken from the chloride and the temperature signal is for the winter and summer season 1.4 and 1.5, respectively. That means that temperature is transported around 1.5 times slower than chloride.

All three tracer parameters show that travel times of the bank filtrate are shorter in monsoon period compared to the dry season. This is probably a consequence of increased hydraulic gradient between the river and the adjacent groundwater level in the aquifer. During monsoon, river stage was observed to be elevated by about 2 m compared to dry season.

4.4.2 Attenuation and purification capacity of RBF in Delhi

Physicochemical parameters, namely temperature, dissolved oxygen and pH from the Yamuna River and the RBF well are presented as box plots in figure 4.4. The box plots show minimum (bottom line), maximum (top line), median (line in the box), lower (bottom of box) and upper (top of box) quartile for the respective parameter.

The median temperature in the Yamuna River and the RBF well is around 25.5°C, but the seasonal fluctuations in the river were equilibrated during the underground passage (see also Figure 4.3). The equilibration is generally more effective in longer underground passages and will be confined to the mean annual temperature of the region. Riverbank filtration provides the possibility for a cost-effective equilibration of strongly fluctuating surface water temperatures. This is especially important when RBF is used as a pre-treatment and the subsequent treatment steps can be managed better if the input temperature is rather constant.

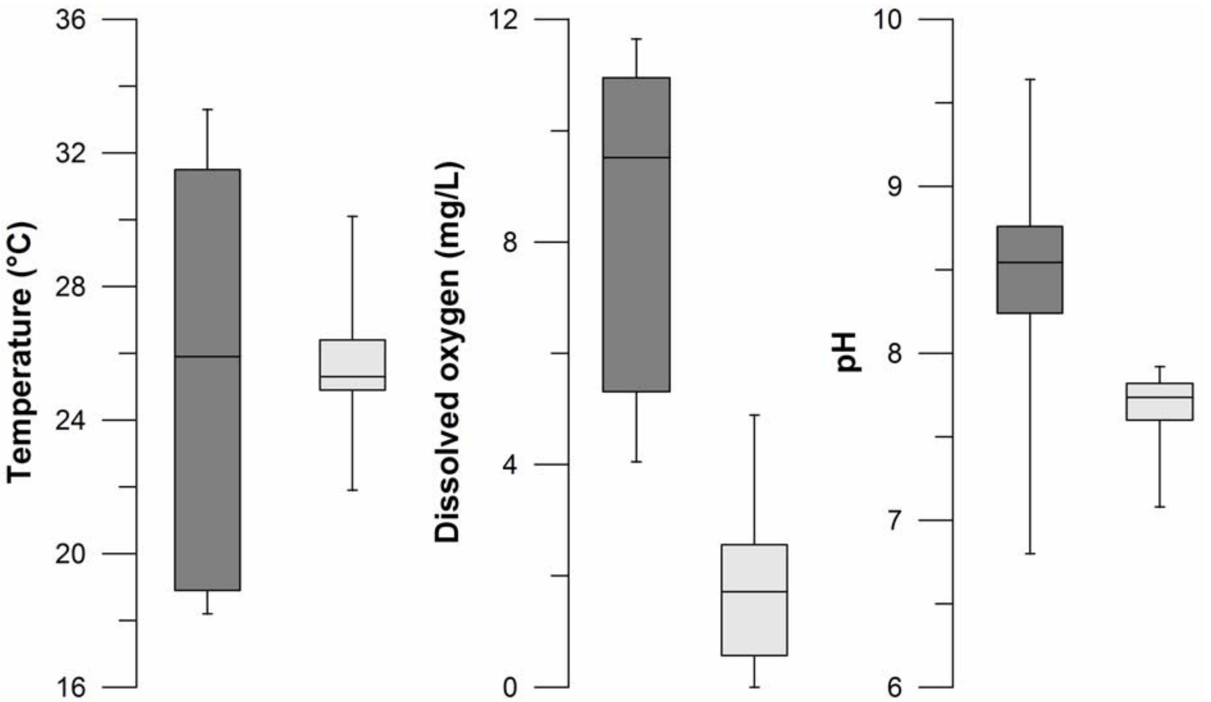

Figure 4.4 Box plots of physicochemical parameters (temperature, dissolved oxygen, pH) measured in the Yamuna River (dark grey) and the RBF well (light grey).

Surface water is in direct contact with the atmosphere and the dissolution of oxygen is a function of the partial pressure of oxygen in the air and the temperature. The capacity to dissolve oxygen is lowered in warm water: e.g. water of 18°C (measured minimum river temperature) can dissolve 9.7 mg/L of O_2 until saturation while water with 32°C (measured maximum river temperature) can dissolve only 7.7 mg/L of oxygen in equilibrium with the atmosphere. The median value of dissolved oxygen in the Yamuna River is 9.5 mg/L indicating a slight super saturation of oxygen. With respect to most organic compounds, the most favourable degradation processes in the subsurface occur under oxygen consumption and the production of CO_2 (eq. 4.2). As a consequence of the oxidation of dissolved organic matter, oxygen levels in groundwater systems are usually lower than in surface water. Figure 4.4 shows that oxygen is decreased during underground passage but not completely consumed in the bank filtrate (median 1.7 mg/L). The remaining oxygen must not necessarily come from the surface water. The cone of depression produced by the abstraction well is dewatering a certain volume of the aquifer that was water saturated before. The dewatering introduces atmospheric air to the aquifer pores and the oxygen will dissolve when the well is turned off and the groundwater level recovers. This effect is more pronounced at wells without protective soil cover and at wells with frequent interruptions in pumping.

The pH from the Yamuna River to the abstraction well is attenuated and decreased. The most likely process to decrease the pH during underground passage is the degradation of organic matter according to:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \text{ (aerobic respiration)} \qquad \text{eq. 4.2}$$

A proportion of the CO_2 reacts with water to form carbonic acid and hydrogen carbonate, thereby lowering the pH.

Box plots of electrical conductivity, dissolved organic carbon (DOC) and nitrate from the Yamuna River and the RBF well are shown in figure 4.5.

Electrical conductivity (EC) of the surface water is fluctuating largely between 1254 µS/cm and 260 µS/cm. In the RBF well EC is attenuated but the median is slightly increased compared to the surface water. The increase of EC from 511 µS/cm to 561 µS/cm (median values) must be attributed to dissolution processes during underground passage.

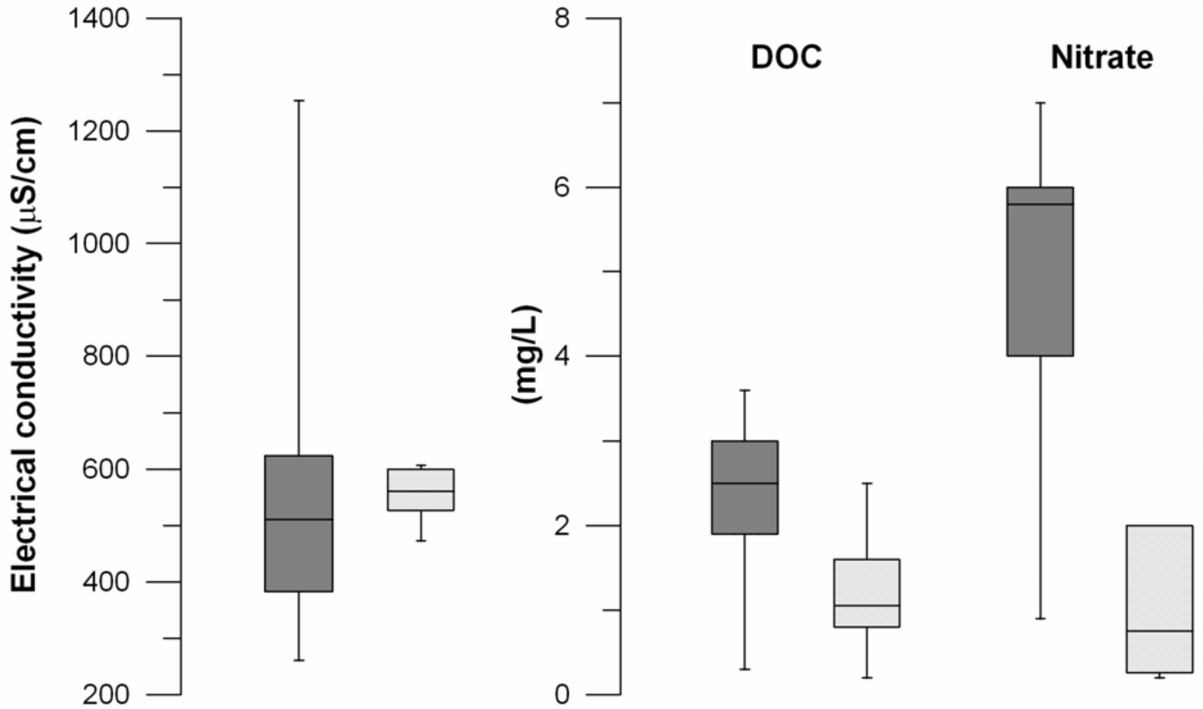

Figure 4.5 Box plots of electrical conductivity, DOC and nitrate measured in the Yamuna River (dark grey) and RBF well (light grey).

DOC is a complex sum parameter, composed of humic and fulvic acids and non-humic substances such as amino acids and carbohydrates (Frimmel, 1998). Many authors reported on the removal potential of bank filtration for DOC (Ray et al. 2003) and most of the DOC removal occurs at the very first cm of the underground passage at the river-aquifer interface. In this study, the median DOC concentration in the river and the RBF well were given with 2.5 mg/L and 1.05 mg/L, respectively. Based on the median values the total removal of DOC can be calculated with 58 %.

Nitrate (NO_3^-) in surface- and groundwater can be of natural and anthropogenic origin. Apart from its common application as fertilisers, nitrate may originate from diffuse and point sources such as seepage from unlined drains, domestic sewage, cattle sheds or landfill sites. At the RBF well the NO_3^- concentrations from the surface water (median 5.8 mg/L) are lowered to 2.5 mg/L. The reduction of nitrate to N_2 by organic matter (denitrification) is the dominant process and can be described as (Appelo and Postma, 1993):

$$5CH_2O + 4NO_3^- \rightarrow 2N_2 + 4HCO_3^- + H_2CO_3 + 2H_2O \text{ (denitrification)} \qquad \text{eq. 4.1}$$

The reaction product N_2 will degas to the atmosphere. Intermediate metastable products such as nitrite (NO_2^-) occurred at low concentration (median 5 µg/L, not shown).

4.5 Conclusions

Reliable characterisation of travel times during riverbank filtration can be achieved by a combination of conservative and retarded environmental tracers. The seasonal signal of stable isotopes ($\delta^{18}O$) can be very different from year to year during the same season and the low amplitude/analytical error ratio allows only reliable estimation for short travel times. Chloride and temperature showed large seasonal variations in the Yamuna River and a retardation factor of 1.5 was found for temperature. It was found that travel times during monsoon (2 months) are substantially shorter compared to pre-/post monsoon period (2.5 months). Anyhow, travel times in this range should be sufficient for a reliable and robust removal of pathogens. This was also confirmed by microbiological studies, carried out at the field site where fecal and total coliform counts in the RBF well were always below detection limit (Sprenger et al. 2008).

The study has also shown that nitrate decreases during bank filtration and organic compounds are degraded under the consumption of oxygen. Hence, riverbank filtration can significantly lower the concentrations of many surface water pollutants (DOC, nitrate) and can attenuate large fluctuations of physico-chemical parameters (temperature, electrical conductivity, pH). DOC concentrations in the surface water were lowered by 58%.

The improvement in water quality makes RBF an attractive technique with the potential to replace or support other treatment steps. The natural treatment during underground passage is cost effective and can lead to decreased overall water treatment costs.

AKNOWLEDGEMENTS

The study was realized within the frame of the European Union integrated project TECHNEAU. We are grateful for suggestions, comments and fruitful discussions with water experts and scientists from India, especially Dr. S.B. Singh, Dr. P.S. Datta, Dr S. Shekhar and Dr. D.V. Reddy.

5 Numerical quantification of surface-/groundwater interactions at the flood plain aquifer in central Delhi (India) using a multi tracer approach

Abstract

So far, little was known about the impact of contaminated surface water infiltration on the urban aquifer systems, which are of the highest importance as a water resource for the present and future water management of the mega city. Fluctuations of the hydraulic head in combination with a conservative tracer (chloride) and a retarded tracer (heat) were measured, evaluated and modelled to determine (i) infiltration rates and (ii) groundwater travel times, (iii) to perform a sensitivity analysis and (iv) to develop a water budget for the flood plain aquifer at the study site in central Delhi. The advection/dispersion model was used and provided approximations for travel times and infiltration rates, which are more comparable to field-based observations than standard particle-tracking simulations. Heat transfer was simulated using the linear sorption isotherm. The Yamuna River and the adjacent aquifer are in hydraulic contact and the river is characterized by losing river conditions on the eastern banks. The infiltration rate during monsoon was 5.5×10^{-2} m^3/m^2/day and during non-monsoonal time 3.6×10^{-2} m^3/m^2/day with an average pore water velocity of 0.9 m/day, which makes groundwater recharge by bank filtration one of the most important recharge mechanisms.

5.1 Introduction

In Delhi the gap between water supply and demand has led to an uncontrolled groundwater abstraction and hence to a declining water table all over the city (CGWB 2006, Maria 2004). As a consequence the polluted surface water infiltrates into the central Delhi flood plain aquifer. The floodplain in central Delhi have an important hydrogeological role as the interface zone between river- and groundwater where exchange of water and solutes occur. It can be assumed that the rapid growth of many cities in developing and newly industrialized countries is leading to severe pollution of groundwater by losing river conditions (Foppen 2005, Lawrence et al. 2000). Therefore, it is important to determine the transport and fate of contaminants from the surface water to the groundwater under the influence of natural factors and anthropogenic practices. Understanding the transport of chemicals (and organics) requires estimates of infiltration rates, travel times and reaction rates. As part of this effort, the hydraulic behavior of the surface-/groundwater interface of the Yamuna River and the adjacent urban flood-plain aquifer in the central part of Delhi in India was investigated.

During SW/GW exchange, the hydraulic properties of the riverbed (Grischek et al. 2003), stream partial penetration and aquifer heterogeneities (Sophocleous 2002) control the interaction between the two hydro(geo)logical compartments. All parameters can vary over time and/or space, but most analytical approaches ignore these facts (Sophocleous 2002). Therefore, a numerical simulation was carried out to evaluate mixing, advective and dispersive processes calibrated with field site observation of environmental tracers (chloride and temperature). This section aims at quantifying the fluxes between surface water and groundwater compartment, namely river water infiltration rates, travel times of bank filtrate and abstraction rates.

Information about flow velocities, travel times and fluxes between surface- and groundwater can be obtained by different tracer parameters (Massmann et al. 2008a, Schubert 2002, Sheets et al. 2002, Wett et al. 2002). The ideal tracer is of either natural or anthropogenic origin, commonly occuring in the study system, easy to detect, and its geochemical behaviour is conservative (or at least predictable). Seasonal variations of the tracer in the river are reflected by attenuated and prolonged curves in the groundwater. In this section chloride and temperature were used as tracers. Chloride is used as a tracer substance to evaluate travel times in the SW/GW interface because it is highly mobile and conservative in its chemical behaviour. Because of its tracer-like behaviour, heat carried by groundwater can be used as a tracer for estimating travel times and infiltration rates (Becker et al. 2004, Cox et al. 2007).

5.2 Materials and Methods

5.2.1 Field site and hydrogeology

The study area is situated within the Indo-Gangetic alluvial plains in the central part of Delhi along the Yamuna River (Figure 5.1). Between two major dams upstream (Wazirabad barrage) and downstream (Okhla barrage), the Yamuna River is joined by a number of tributaries. These so-called drains are channelled water bodies used for urban wastewater disposal (predominantly untreated sewage) and flood control during monsoon season. The most important one is the Najafgarh Drain, which flows into the Yamuna River at the Wazirabad barrage. Within this segment, the Yamuna River is highly contaminated by discharge of sewage and industrial waste. For a more detailed description of the contaminants in the surface water see (CPCB 2006, CSE 2007, Lorenzen et al. 2010).

According to Daga (2003), almost every domestic complex in Delhi has a tube well to complement or replace the public water supply. Different sources estimate the actual number of private tube wells between 200 000 and 360 000 (Daga 2003, Maria 2004, Maria and Jaouen 2004). Groundwater levels monitored over the past decades indicate a dramatic decline of groundwater level in vast parts of the city territory (CGWB 2006). Groundwater recharge rates through rainwater infiltration are reported to be low, and most parts of Delhi receive less than 5% recharge. Lateral flow, canal/river seepage and localized infiltration of highly degraded agricultural and urban surface run-off through stagnant water pools are the main contributors to recharge (Datta and Tyagi 2004).

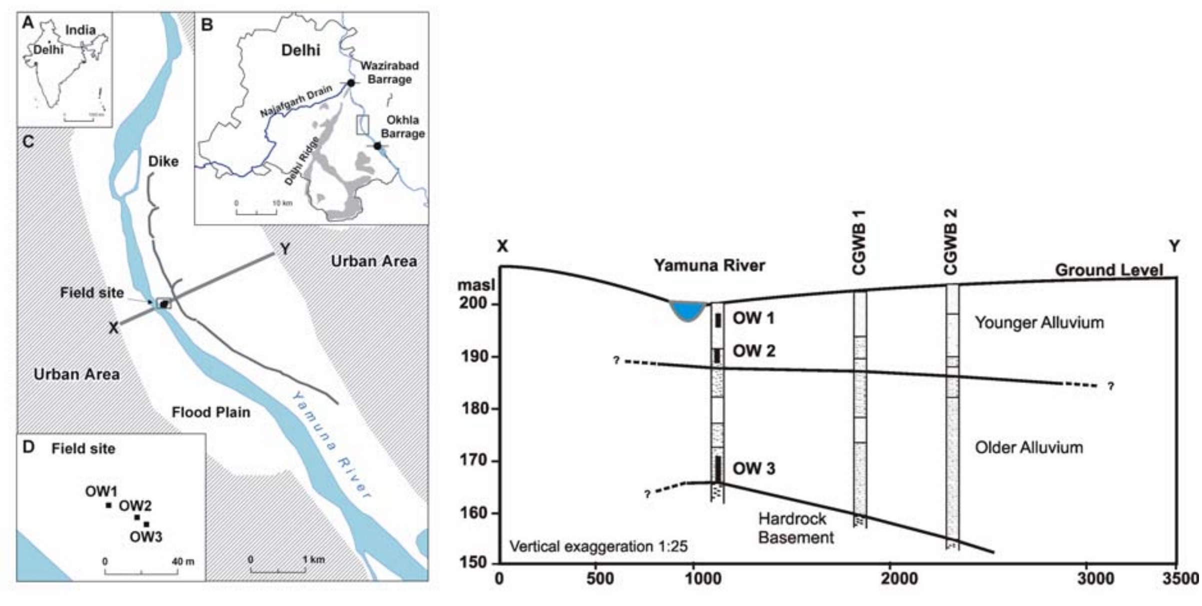

Figure 5.1 A) Location map of India and Delhi; B) City limits of Delhi and the main river with barrages and main geology; C) The study area with the urbanized parts of Delhi, X-Y indicates the geological cross section shown in figure 5.2; D) Location map of the observation wells at the field site; Hydrogeological cross sectional view with the filter screen depths of the observation wells (vertical bars).

5.2.2 Drilling, levelling and sampling of observation wells

A field site was established on the eastern banks of the Yamuna River in the central part of Delhi (Figure 5.1). Observation wells (OW1, OW2, OW3) consist of multiple, independent wells drilled by a rotary method to depths of 8, 10 and 32 m below ground level, respectively. All observation wells are 4" in diameter and were assembled with PVC pipes with 3-6 m filter screens at the end.

Levelling of each piezometer and the Yamuna River, relative to an arbitrary level, was measured by theodolite survey. Levelling was carried out 4 times within the study period using a Sokkia C410 device. The hydraulic changes were monitored by pressure- and temperature logger units and by manual depth-to-water measurements. Hydrographs were compensated by the barometric pressure measured a few kilometres away from the field site.

The observation wells were sampled monthly from November 2006 to March 2008 to detect seasonal changes of hydraulic and hydrochemical parameters through the annual cycle. During the sampling campaigns, at least three static water volumes within the observation wells were removed according to German groundwater sampling guidelines (DVWK 1992).

5.2.3 Construction of water table map

A new groundwater table trend map along the Yamuna River at the study area was developed. Three types of data were used to construct the regional-scale water table contour map, including depth-to-water measurements from observation wells (i.e. dug- , tube wells measured by the CGWB 2006, land surface topography from Shuttle Radar Topography Mission (SRTM) data in combination with land surface benchmarks from topographical maps and stage elevation data of the perennial river Yamuna. Considering all uncertainties (e.g. elevation accuracy of the SRTM data), this map should be regarded as a trend map and not as an exact groundwater table map. Nevertheless, this groundwater table map is an update to the regional groundwater table map presented by CGWB (2006b) and can be used (i) to provide a support frame for regional-scale water table maps, (ii) to analyse contaminant migration and (iii) to set boundary conditions for groundwater flow and transport model. The calculation of the groundwater table trend map was based on a May 2006 dataset.

5.2.4 Model construction

A vertical two-dimensional (2D) transient groundwater flow model was constructed using Modflow (Harbough and McDonald 2000), and transport was modelled with MT3DMS (Zheng and Wang 1999) under the graphical user interface of Visual Modflow (Waterloo Hydrogeologic, Inc.). The model accounts for infiltration into and processes in the saturated zone, but does not simulate surface runoff and percolation through the unsaturated zone. The model was calibrated with hydraulic heads and tracer curves of chloride and temperature. Prior to the transport modelling with MT3DMS, ModPath (Pollock 1994) was used to visualize groundwater flow directions and pure advective travel times. The simulation time from November 2006 to March 2008 was divided into 45 stress periods, each of ten-day duration. Each stress period was attributed to the corresponding hydraulic head and input for solute transport (chloride and temperature) at the river boundary. A steady-state model provided the initial hydraulic heads for the following transient simulations.

Hydraulic conductivity and storativity

During drilling of the observation wells, three lithological units were encountered: i) the younger alluvial, ii) the older alluvial, and iii) the quartzitic hardrock (Figure 5.1, Figure 5.2). The younger alluvium is composed of Holocene sediments of the Yamuna floodplain, deposited close to the present course of the river. This unit consists mainly of grey, medium-sand fluviatile deposits interbedded with calciferous gravel size concretion, locally known as kankar. This upper aquifer unit extends down to 12 m below ground level at the river and shows an increasing thickness to the east (up to 30 to 40 m below ground level). The coefficient of hydraulic conductivity (k-value) is estimated by grain size analysis with 29 - 33 m/d (Table 5.1). The younger alluvium was deposited upon a series of variable thickness of older alluvium. The older alluvium is composed of Tertiary sediments which are outcropping to the west of the present course of the Yamuna (CGWB 2006). This unit consists mostly of yellow to brown silt and is more consolidated than the upper floodplain sediments. Mica is accessory or absent, and in places the fine sand is interbedded with layers of fine to medium sand.

At a depth of 38 m below ground level, the Precambrian metamorphic hardrock (Aravalli formation forming the Delhi Ridge) was encountered. In the upper part of this formation these metamorphites are weathered, but owing to the low permeability of this quartzitic unit, it is considered to be an aquitard.

Table 5.1 Parameters (d_{10}, d_{60}) determined from grain size distribution of the aquifer at different depths and calculated coefficients of hydraulic conductivity (k) according to Hazen 1893 and Beyer 1964

Depth (mbgl)	d_{10} (mm)	d_{60} (mm)	Hazen 1893 k (m/d)	Beyer 1964 k (m/d)
3	0.15	0.39	33.3	29
6	0.15	0.4	33.3	28.9
13	0.06	0.38	5.3	3.9
20	0.02	0.1	0.6	0.5
30	0.01	0.08	0.1	0.1
40	0.002	0.08	0.01	0.002

Hazen (1893)

$k = C * d_{10}^2$ (only valid for d_{10}>0.06 mm)

$C = 0.7 + 0.03 * T / 86.4$ (T=26 °C)

Beyer (1964)

$k = g/v*C_b*d_{10}^2$ (only valid for d_{10}>0.06 mm)

g=gravity constant; v=kinematic viscosity of water

$C_b=0.0006*\log(500/U)$

$U=d_{60}/d_{10}$

Coefficients of hydraulic conductivities were calculated according to Hazen (1893) and Beyer (1964) under consideration of the temperature-dependent kinematic viscosity of water. Owing to the limited validity of the Hazen and Beyer method, the k-value was also estimated by small-scale pumping tests and slug/baile tests (not shown here). According to the k values obtained by the grain size distribution (Table 5.1) the model was subdivided into three zones of hydraulic conductivity. The k values were iteratively calibrated by trial-and-error to the measured tracer curves. Therefore, values were slightly higher than those derived from grain size distribution. The upper alluvium was attributed to k = 36 m/d. As a first approximation, it was assumed that the hydraulic conductivity was isotropic for the younger alluvium aquifer, but it was determined iteratively that an anisotropy factor of $K_h/K_v = 10$ gives the best fit. The older alluvium was attributed uniformly with a horizontal k = 5 m/d and the vertical conductivity was set to 0.05 m/d owing to the occurrence of small silt/clay layer. The bottom of the model corresponds to the quartzitic hardrock and was set inactive. The upper alluvium is unconfined, which means that the effective porosity is equal to the storage coefficient. The effective porosity was estimated to be 25% ($n_e = 0.25$). The storage coefficients were considered to decrease with depth.

Grid discretization, coverage and dispersion

The model area extends over a length of 2400 m on the eastern side of the Yamuna River in the central part of Delhi. The grid was oriented so that the flow is parallel to the x-axis. The model domain was divided into 100 m wide columns and 1 m layer thickness. Near the observation wells, the grid was refined to columns of 1 m width, resulting in 55 columns and 20 layers in total (Table 5.1**,** Figure 5.2). In total, the model represents 50 m depth of constant layer thickness. The bottom of the model domain corresponds to the hardrock unit and was attributed to a no-flow boundary.

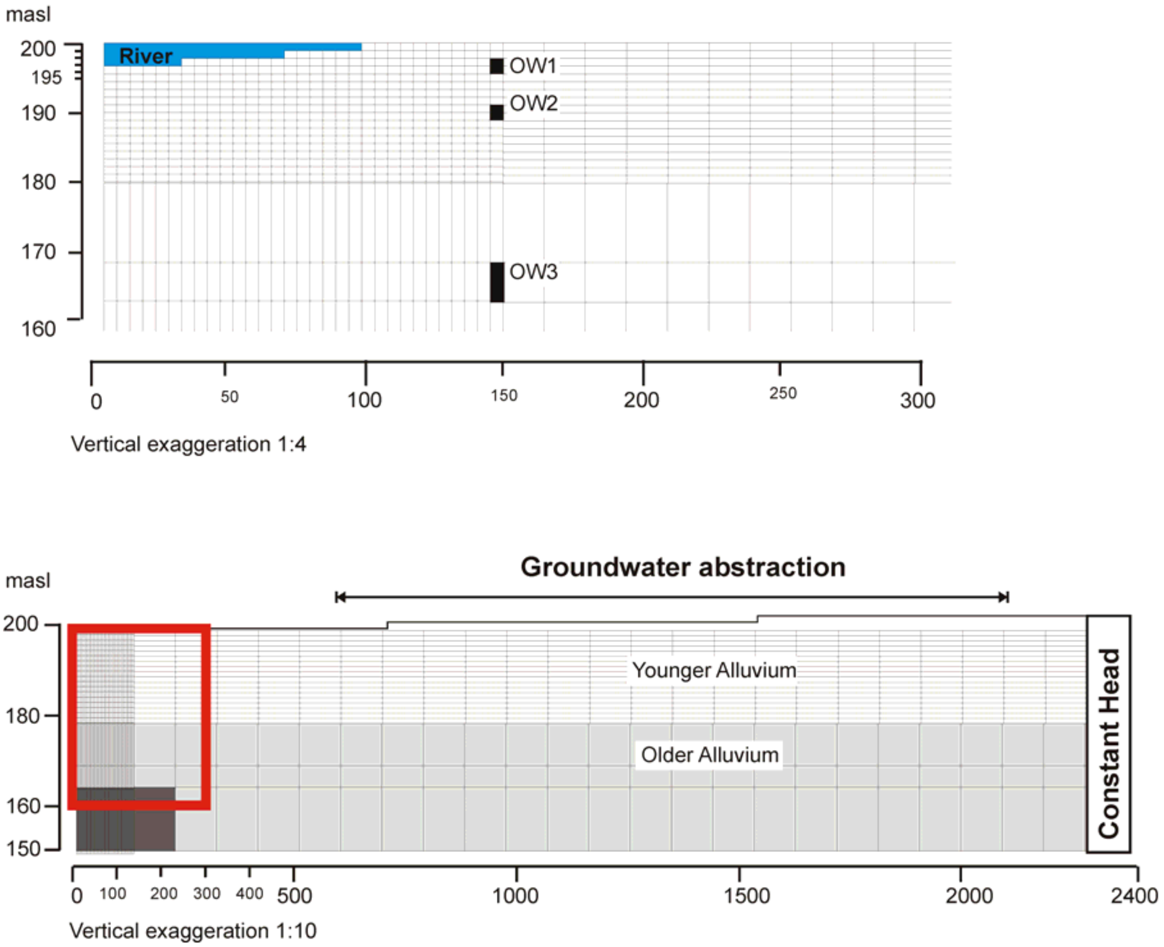

Figure 5.2 Grid discretization and boundary conditions.

To minimize numerical dispersion effect, grid discretization on the local scale was adapted so that the Peclet (and Courant 5/1) criteria are fulfilled. The grid peclet number should be ≤ 2

(Zheng and Bennett 2002). For the 2D case, the grid peclet number can be calculated according to:

$$Pe_x = \frac{u_x \Delta x}{D_x} = \frac{\Delta x}{\alpha_L}; Pe_z = \frac{u_z \Delta z}{D_z} \qquad \text{eq. 5.1}$$

where x is the grid length (m); D is the dispersion coefficient (m^2s^{-1}); α_L is the longitudinal dispersivity (m); u is the pore water velocity (m/s). The dispersion coefficient depends on the pore water velocity and can be calculated using the dispersivity α and pore water velocity u according to:

$$D = \alpha \times u \qquad \text{eq. 5.2}$$

The longitudinal dispersivity was set to α_L = 5 m which was approximated with one tenth of the total flow distance to the observation wells (Adams and Gelhar 1992, Käss 2004). Vertical transversal dispersivity was set to 0.5. By using equation 1 a Peclet number of 2 was obtained for both directions.

Boundary conditions

Groundwater abstraction data is critical for model calibration, especially when SW/GW interactions are involved. This data includes the spatial distribution and magnitude of pumping. Data about groundwater abstraction in urban Delhi is very general and cannot be used for site-specific problems. Therefore, a groundwater withdrawal survey was conducted in May 2008 to detect all types of wells that contribute to the total groundwater abstraction. Most of the groundwater is abstracted by suction pumps and it is assumed that hand pumps can be neglected. The abstraction amount was estimated by the engine power driving the suction pumps given in horsepower (HP). According to typical power curves, a 1 HP diesel engine will abstract 3 m^3/h. Assuming an average operational time of 4 h/day and 340 days per year (except for the rainy days) for an area of 1.54 km^2 will result in a total areal groundwater abstraction of approx. 0.004 m^3/m^2d. Groundwater abstraction was applied to a length of 1600 m, yielding a total abstraction of 6.4 m^3/d for the whole model domain. During the rainy days in the monsoon period (approx. 20 days), no irrigation takes place, and groundwater recharge was estimated at 3.84×10^{-5} m^3/m^2d (14 mm/a), which corresponds to 2 % of the annual rain (Datta and Tyagi 2004).

During the non-monsoonal period, fixed head of 196 masl was attributed to the eastern boundaries of the model domain. Hydraulic heads were used from the groundwater table map (Figure 5.3). During monsoon time, the groundwater table increase was only minor and no change to the eastern and western boundary was made.

The location and the width of the river were estimated from aerial photographs, and the depth of the river is based on bathymetric cross section measured by the authors with pressure transducers. The river is approximately 200 m wide and has a maximum depth of 3 m in the centre. For the sake of simplicity, the river was simulated with 100 m width and a constant increasing depth to 3m in the centre (Figure 5.2). The river was simulated using the MODFLOW river package (head dependent flux boundary) with a temporal variable fixed head boundary in the uppermost layer of the model. The river bed was attributed to a constant elevation of 198.50 masl, while the river head changes with time. Maximum head is 200.7 masl during monsoon, with an average river stage of 199.9 masl. The river bed elevation is taken from flood scenarios evaluated by Vijay et al. 2007. The riverbed conductance (C_{riv}) or river coefficient is calculated according to:

$$C_{riv} = \frac{K \times L \times W}{M} \qquad \text{eq. 5.3}$$

where C_{riv} = leakage factor L^2T^{-1}; K = hydraulic conductivity of riverbed LT^{-1}; L = river length (L); W = river width (L); M = thickness of clogging layer (L). The basic assumption of the MODFLOW approach is that losses from the river are governed by the low permeability of the clogging layer.

$$q_{riv} = C_{riv} \times \Delta h \qquad \text{eq. 5.4}$$

The flow from the river to the aquifer q_{riv} is now calculated with river coefficient (C_{riv}) and the head difference between the river stage and the adjacent groundwater head (Δh). The rate of streambed infiltration is a function of streambed conductance and the difference in the hydraulic head of the river and the aquifer. Both equations are solved individually for each model time step at each model grid cell, which is identified as a river cell. This approach enables consideration of the temporally and spatially variable extent of the interactions between the groundwater and the surface water. During the monsoonal high flow period, the river inundates the agricultural area between the river bank and the dike, but the short period of this flood event had no substantial effect on the infiltration rate of the river.

The 100 m wide river was divided into a 75 m part with a river coefficient (C_{riv}) of 360 m^2/d (k=3.6 m/d), whereas the bank of the river was attributed to 3.6 m^2/d (k=0.036 m/d). The thickness of the clogging layer was assumed to be 0.5 m (eq. 5.3), and the river coefficient was the object of calibration. Different scenarios were tested with i) no clogging layer ii) 0.5 m thickness and hydraulic conductivity of 1/10 of the aquifer hydraulic conductivity (3.6 m/d) and iii) 0.5 m thickness and 1/100 of the aquifer hydraulic conductivity (0.36 m/d).

Table 5.2 Boundary conditions during monsoon and non-monsoonal time

	Fixed head or Dirichlet (masl)	River or Cauchy (masl)	Abstraction (m/d)	Recharge (m/d)
Non-monsoon (340 days per year)	196	River stage highly transient 199.4 – 200.4	0.004	-
Monsoon (20 days per year)	196	High river stage 200.8	-	$9x10^{-5}$

5.2.5 Transport parameters

To simulate SW/GW interaction, MT3DMS was used, a solute transport package included in Visual MODFLOW Pro (Waterloo Hydrogeologic, Inc.). MT3DMS uses the flow velocity calculated by MODFLOW as an input value to solve the transport equation. Dispersion due to macroscopic heterogeneities is the main reason for the not purely advective transport of solutes in field observations. TVD (total variation diminishing) is used for solving the transport equation because it minimizes mass losses (Goedeke et al. 2004) compared to other solutions techniques such as MOC or HMOC.

Simulating heat transport

SW/GW fluxes were estimated by several authors by using heat transfer models (Anderson 2005, Cox et al. 2007, Keery et al. 2007). All parameters used for heat transport modelling is shown in table 5.3. In principle, MODFLOW is not capable to simulate heat transport, but by using the diffusion equation it is possible to simulate heat transport by linear sorption isotherm (Holzbecher 1998). Temperature is expressed as concentration and heat capacities by the distribution coefficient (k_d). Heat is transported not only by convection but also by heat conduction described by Fourier's law of conduction:

$$q_h = -K\frac{dT}{dx} \qquad \text{eq. 5.5}$$

where q_h= is the heat flux (J m^{-2} s^{-1}); K thermal conductivity (W m^{-1} K^{-1}); T is the temperature (K). By comparing eq. 5.5 to the diffusion equation (eq. 5.6), the same mathematical structure is obvious:

$$J_d = -D\frac{dc}{dx} \qquad \text{eq. 5.6}$$

where J_d is the diffusive flux (mol m^{-2} s^{-1}); D diffusivity (m^2/s); c concentration (mol/m^3). The thermal diffusivity D was calculated by dividing the thermal conductivity (K_{wet}) of 1.7 J/msK by the bulk heat capacity for water-saturated sand (C_{wet}) with $5.4x10^9$ J/m^3K according to:

$$D = \frac{K_{wet}}{C_{wet}} \qquad \text{eq. 5.7}$$

resulting in a thermal diffusivity of 3.1×10^{-10} m^2/s, which is then used in MODFLOW as the diffusion coefficient . The delayed transport of heat can be described by a retardation factor R (-) which is related to the ratio of heat capacities $\kappa = (\rho C)_{water} / (\rho C)_{bulk}$ and the effective porosity (n_e) by the formula:

$$R = \frac{\kappa}{n_e} \qquad \text{eq. 5.8}$$

where ρ_b is the bulk density of the sediment (kg/m^3); C_{bulk} is the heat capacity of bulk sediment (J/m^3K). The heat transport can be simulated using a linear sorption isotherm, and K_d can be calculated using the equation:

$$R = 1 + \frac{\rho_b}{n_e} k_d \qquad \text{eq. 5.9}$$

where k_d is the distribution coefficient. Now it is possible to equalize eq. 5.8 with eq. 5.9 according to:

$$\frac{1}{n_e \kappa} = 1 + \frac{\rho_b}{n_e} k_d \qquad \text{eq. 5.10}$$

Thus an equivalent k_d for heat transport can be obtained according to:

$$k_d = \frac{1}{\rho_b} (\kappa - n_e) \qquad \text{eq. 5.11}$$

bulk density of the sediment is given with 1900 kg/m^3, n_e is 0.25 and κ is 0.77 resulting in a distribution coefficient (k_d) of 1.4×10^{-7} mg/L.

Table 5.3 Parameters for heat transport simulation.

parameter	unit	value
porosity	-	0.25
heat conductivity s	J/msK	2.09
heat conductivity w	J/msK	0.54
heat capacity s	J/m^{3}K	2400000
heat capacity w	J/m^{3}K	4150000
density s	kg/m^3	2200
density w	kg/m^3	999
initial temperature	°C	25
aquifer heat capacity	J/m^{3}K	5.4E+09
bulk density	kg/m^3	1899.75
bulk heat capacity	J/m^{3}K	2837500
bulk thermal conductivity	J/msK	1.7

s = solid, w = water

5.2.6 Sensitivity analysis

To quantify the uncertainty of the calibrated model, a sensitivity analysis was performed. Hydraulic anisotropy (K_h/K_v), effective porosity (n_e), river coefficient and groundwater abstraction was object of the sensitivity analysis. For the sensitivity analysis, the values of the object parameters were increased/decreased sequentially within plausible ranges, and the effect on travel times and infiltration rates was examined.

5.3 Results and discussion

According to the groundwater table trend map the Yamuna River was dominated by losing river conditions on the eastern banks (Figure 5.3). It is important to note that this groundwater table map is based only on few measurements and the monitoring points were not levelled exactly to a common level. Hence, this map indicates only roughly the groundwater regime in the study area. Anyhow, no other groundwater table was available and the measured groundwater at the field site scale confirms the regional-scale flow regime.

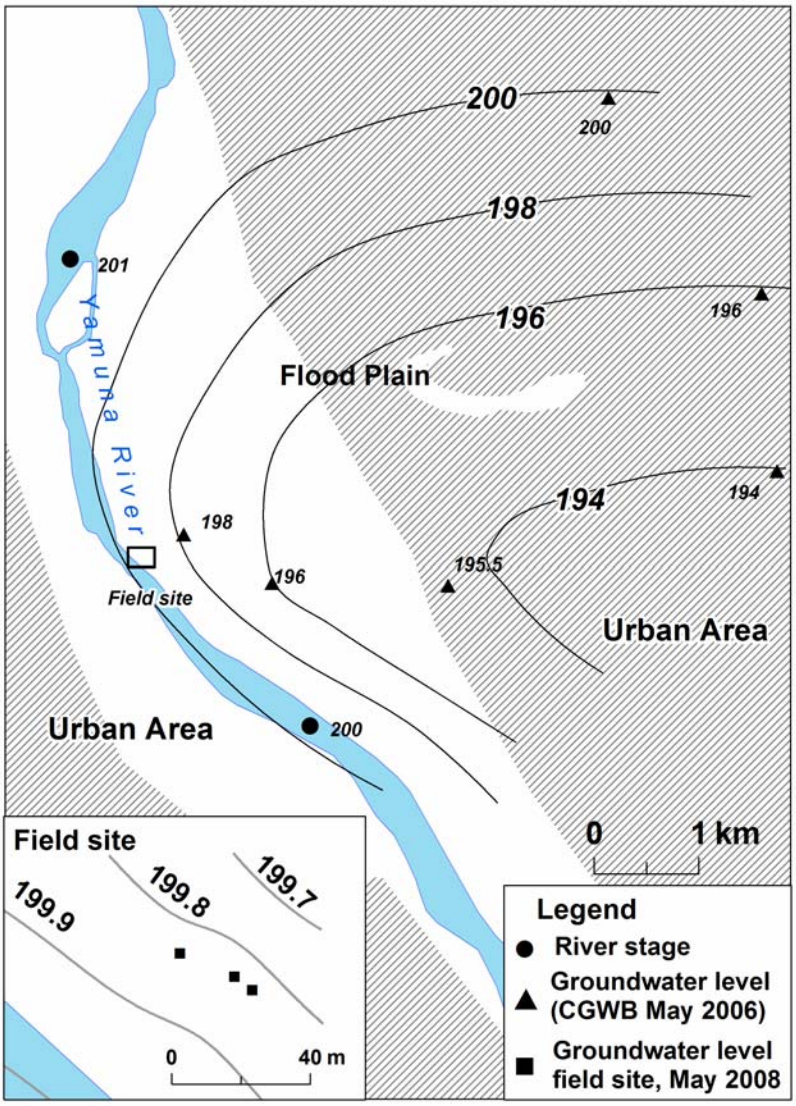

Figure 5.3 Groundwater table map for the dry season (May 2006) and the field site (May 2007); the black triangles show the interpolation points (depth-to-water measurements from CGWB, interpolation by the author)

Calibration results

The model accurately simulated the spatial and temporal distribution of the hydraulic heads in the model domain (Figure 5.4). The mean of absolute residual errors is 0.18 m, while the overall changes of the hydraulic heads during the study period in all observation wells were 1.41 m. A hydraulic anisotropy (K_h/K_v) of 10 was determined iteratively and reflects the field observations of a high mica content in the upper aquifer and sequences of clay and silt layers mixed with medium to fine sand in the lower aquifer. Changes in anisotropy (1 or 100) produced a poorer fit to the observed hydraulic heads.

During the 2007 monsoon (August – September) the flood plain was flooded twice, but the total flood period was short and lasted only for a few days. Therefore, no flood event was intended to be simulated by the model. Anyhow, river stage fluctuated by around 2 m, with a maximum stage of 202 m masl during monsoon. The average river stage was around 200 masl.

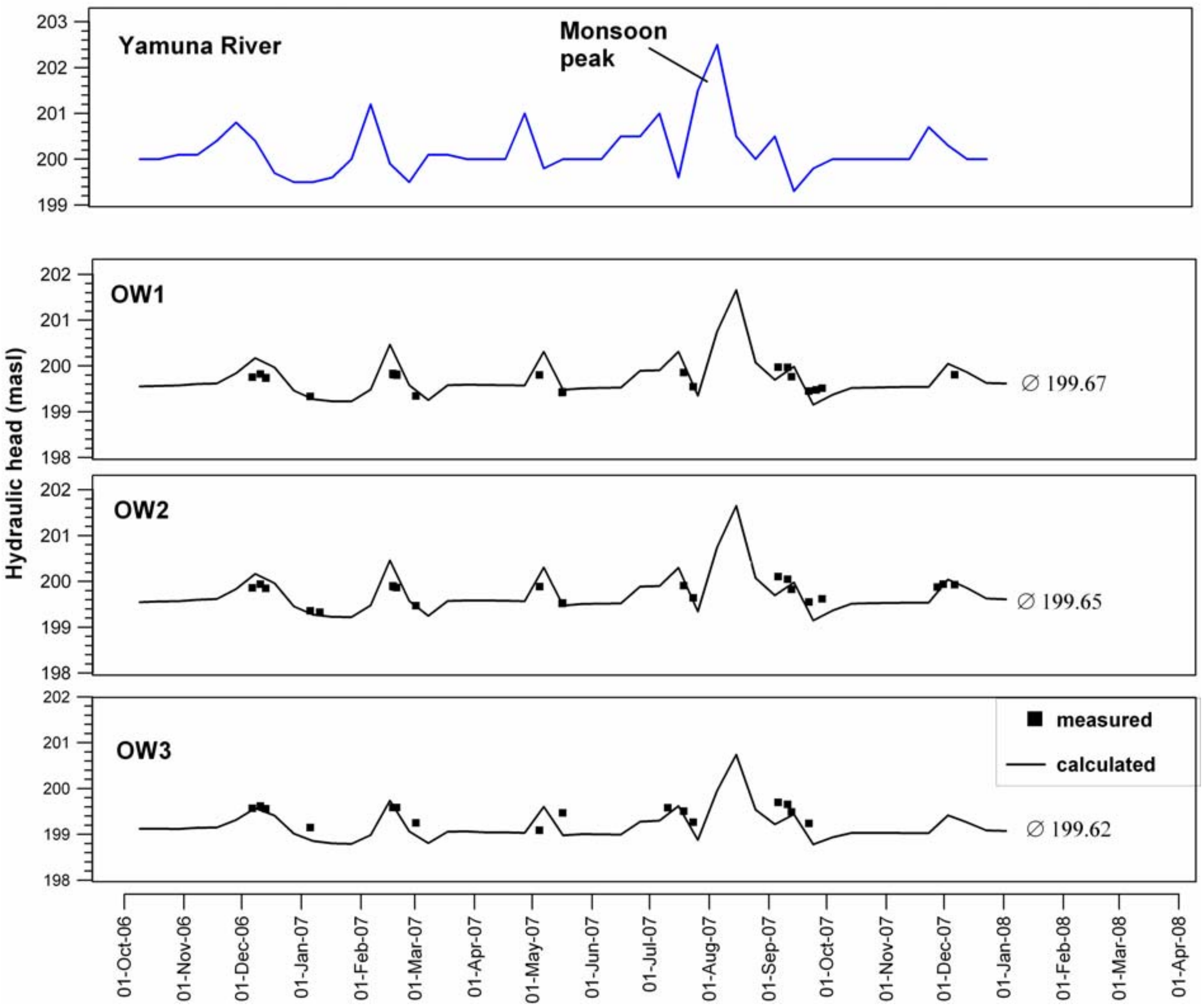

Figure 5.4 Modelled Hydrographs (line) and manual depth-to-water measurements (squares) in OW1, OW2 and OW3. The stage of the Yamuna River was measured in a 3-month interval by theodolite survey and the dotted line represents the interpolated river stage used as model input.

Measured water levels in the observation wells reveal the existence of a downward directed vertical head gradient. The downward directed hydraulic gradient between the river and the piezometer is present over the whole study period and is caused by high groundwater abstraction for agriculture, institutional and domestic purposes in the flood plains and the adjacent urban areas. The downward directed hydraulic gradient is typical for overexploited aquifers and groundwater table responded immediately with river stage fluctuations, reflecting the hydraulic connection between surface- and groundwater.

5.3.1 Transport simulation

Temperature

Temperature was used to evaluate travel times at the SW/GW interface because it has proved to be a robust and predictable tracer (Anderson 2005). Heat as a tracer uses natural variations in river water temperature and the resulting exchange of heat with the subsurface to assess SW/GW interactions. Heat is transported in the flowing water by advective heat flow and thermal conduction through the non-moving solids and fluids (conductive heat flow).

Monthly measured river water temperature showed strong seasonal pattern at the study area (Figure 5.5). The highest river water temperature (31.8 °C) was measured before the beginning of the monsoon in May 2007 and the lowest temperature (21.5 °C) was measured in January. From field sites under natural conditions it is known that the water temperature of the river will follow the temperature of the air. At the field site the temperature course of the river water differs substantially from the mean air temperature. Only during the hot season from April to September a similar temperature between air and river water be observed. During the rest of the year, river water temperatures were higher. It is assumed that the inflow of warm domestic and industrial wastewater and the urban microclimate increases the river water temperature.

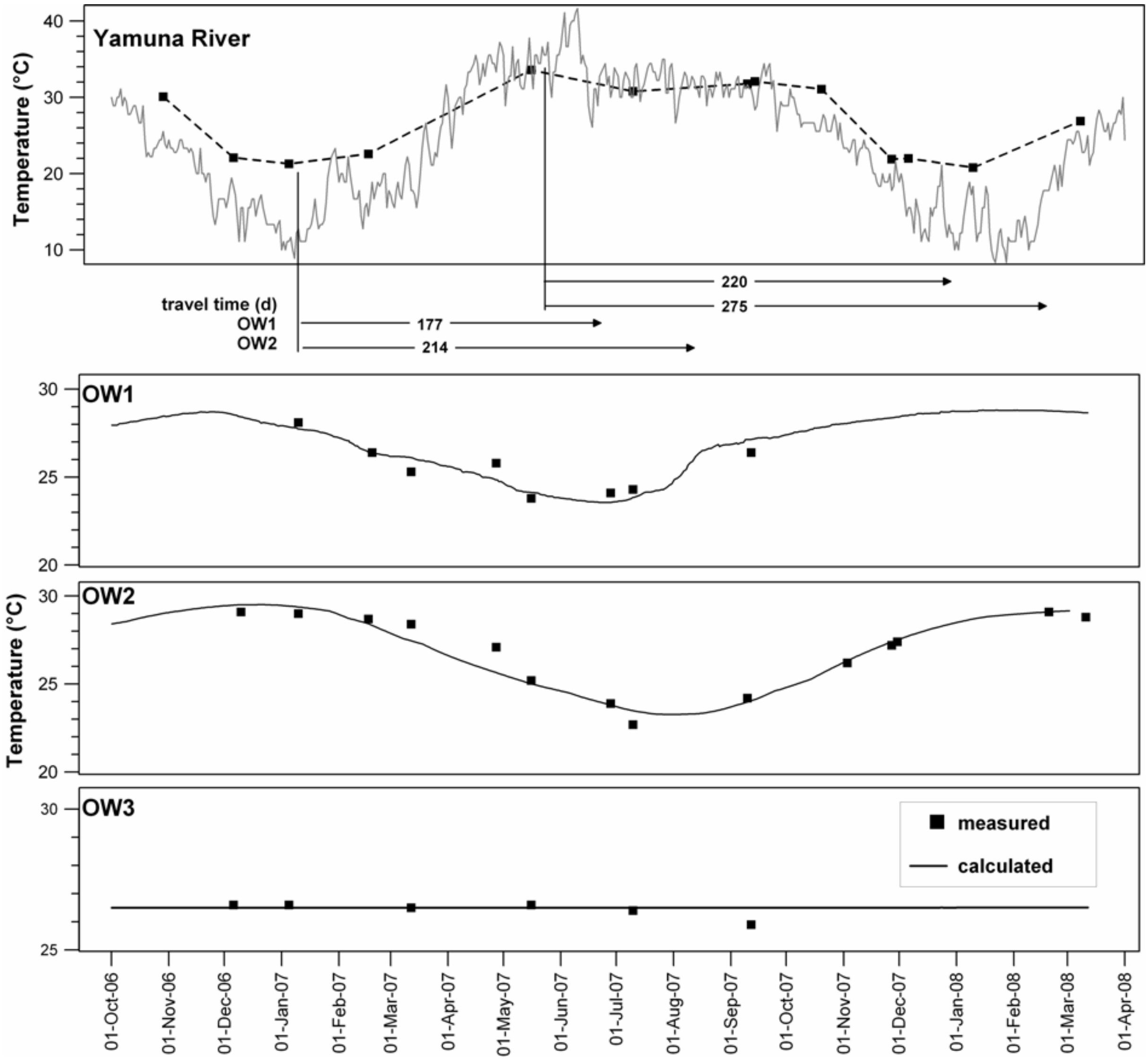

Figure 5.5 Measured temperature (square) with the calculated curves (line) in the shallow (OW1), medium (OW2) and deep observation wells (OW3) and the Yamuna River. The grey line at the upper part of the diagram indicates the mean air temperature.

Thermal properties for the simulation of heat transfer with MODFLOW/MT3DMS are based on data given in table 5.3. For water-saturated sand, the thermal properties vary only little compared to variations in hydraulic properties. Uncertainty in assessing proper thermal properties is more important in conduction-dominated environments, whereas under advection-dominated conditions the total heat flow is more influenced by hydraulic properties.

Compared to pure advective/dispersive flow the heat transfer is retarded. Here, we simulated the heat transport according to the diffusion equation (eq. 5.7) and the retardation factor (R) is expressed as the distribution coefficient $k_d = 1.4 \times 10^{-7}$ kg/m^3 (eq. 5.11). Thermal dispersivity was set at 5, which is equal to the 1/10 of total flow length. The diffusion coefficient, which corresponds now to the thermal diffusivity, was set to 2.7×10^{-5} m^2/day (eq. 5.7).

In the OW1, the lowest temperature (23.8 °C) was measured on 16.05.2007, but the calculated temperature course suggests a lower peak at the beginning of June. In the OW2 only one local minimum was observed on 2.08.2007, and one local maximum on 10.03.2008. The maximum temperature in December 2006 is a result of the 2005 summer period, which was before the start of the sampling campaign. The second maximum in March 2008 is from the 2007 summer peak, which results in retarded travel times between 214 - 275 days.

The temperature in the deep OW3 was almost constant (26.6 +/-0.1 °C) and 1.6 °C higher than the mean annual air temperature of Delhi. The depth of the surficial zone, which is influenced by the annual changes in surface water temperature, was approx. 23 mbgl (Lorenzen et al. 2010). This finding supports the idea that groundwater recharge was dominated during monsoon, when water temperatures were higher than the annual average.

Chloride

Chloride was used as a tracer substance to evaluate travel times at the SW/GW interface because it is highly mobile and conservative in its chemical behaviour. Travel time of bank filtrate was determined by comparing the seasonal signal in the Yamuna River with the shifted and attenuated signal in the observation wells. Four local minima/maxima in the Yamuna River and the observation wells were identified (Figure 5.6).

The Yamuna River showed a diluted (low) chloride concentration in the monsoonal season (~100 mg/L), whereas in the dry season the chloride content was higher (up to 240 mg/L). This input signal was transported by advection and thereby shifted and attenuated. The highly transient infiltration regime is reflected by variable travel times. Travel times to OW1 ranged from 61 days to 91 days, with a mean travel time of 75 days. Travel times increases with depth and range from 107 days to 137 days, with a mean travel time of 119 days, to the OW2.

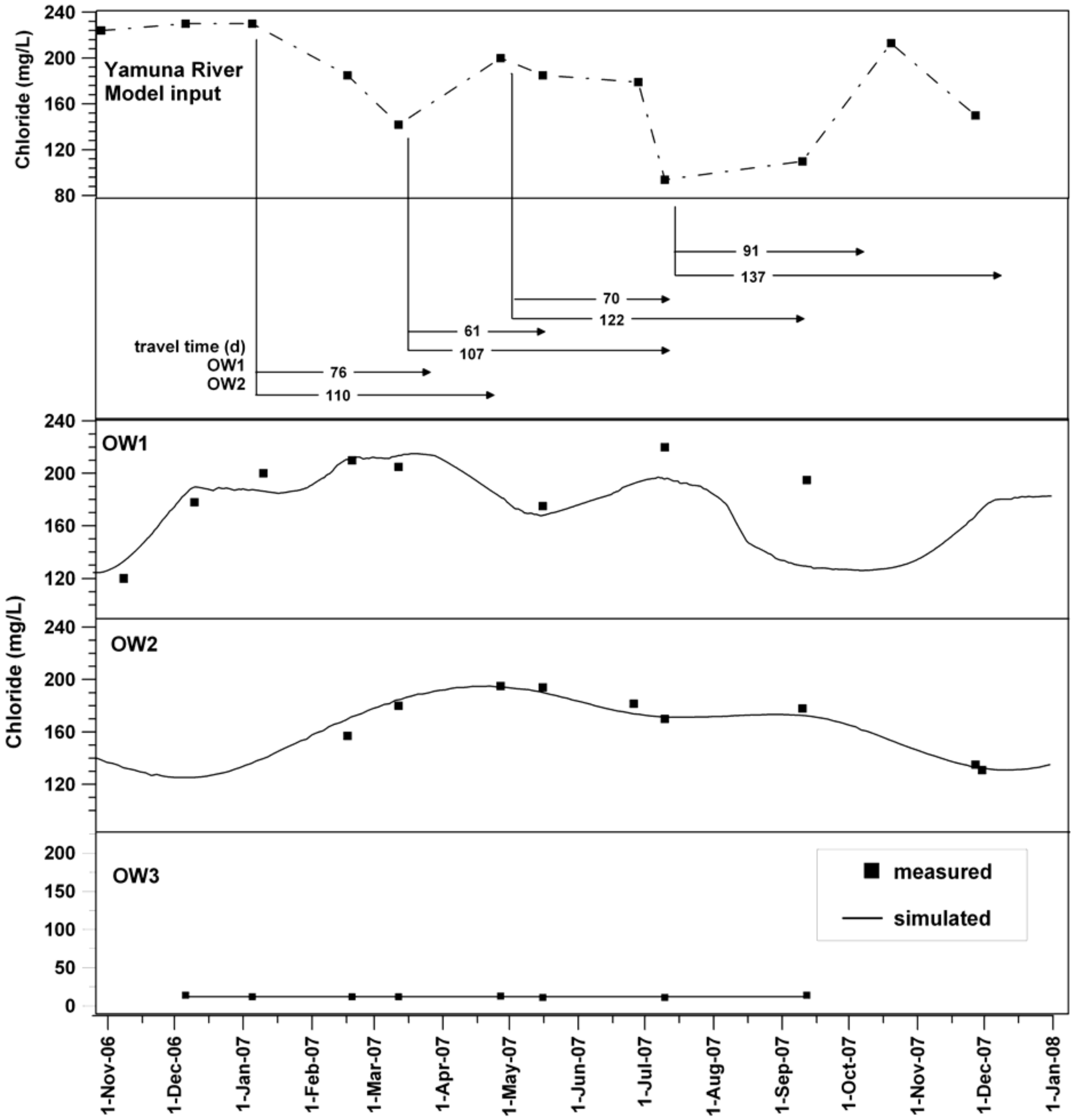

Figure 5.6 Measured chloride (square) with the calculated curves (line) in the shallow (OW1), medium (OW2) and deep observation wells (OW3) in combination with the Yamuna River.

The chloride concentrations in the shallow observation well (OW1) measured in August and September cannot be simulated accurately. The measured chloride concentrations were higher than the calculated concentrations. It is assumed that these findings indicate the influence of percolated flood water, which dissolves salts from the unsaturated zone. This effect is only observed in the shallow groundwater, while the chloride concentrations of the medium deep groundwater (OW2) can be simulated accurately.

In the OW3, chloride concentration was constant (13 mg/L) over time, reflecting the lack of any influence of river water on deep groundwater.

5.3.2 Sensitivity analysis

The sensitivity analysis demonstrates the relative importance of the individual parameters (porosity, riverbed clogging, hydraulic anisotropy and groundwater abstraction) to the overall accuracy of model in terms of infiltration rates and travel time to OW2. The parameters porosity, riverbed clogging, hydraulic anisotropy and groundwater abstraction were changed within plausible ranges and the effect on river infiltration rates and travel time to OW2 was investigated. Sensitivity analysis of the average infiltration rate of the Yamuna River indicates that changes in abstraction amount, aquifer anisotropy and riverbed clogging were causing the largest changes. Increasing the abstraction amount by 20 %, 50 % results in an increase in the infiltration rate of approx. 12 %, 25 %, respectively. A strong impact on the infiltration rate is also observed for the hydraulic anisotropy of the aquifer. If the hydraulic anisotropy is increased/decreased by one order of magnitude, the infiltration rate changes by +/- 17 %. Interestingly, the riverbed conductance was comparably insensitive within ranges of +/- 90%. A decrease of 90 % (from k = 3.6 m/d to 0.36 m/d) resulted in a decrease of the average infiltration rate of 4 %. Equalizing the hydraulic conductivity of the streambed and the aquifer yielded a calculated increase of 4%. As expected, a further increase had no impact on the infiltration rate. By decreasing the riverbed conductance by 99% (k= 3.6 m/d to 0.036 m/day) a strong impact on the infiltration rates was calculated with a decrease of 32 % (Figure 5.7).

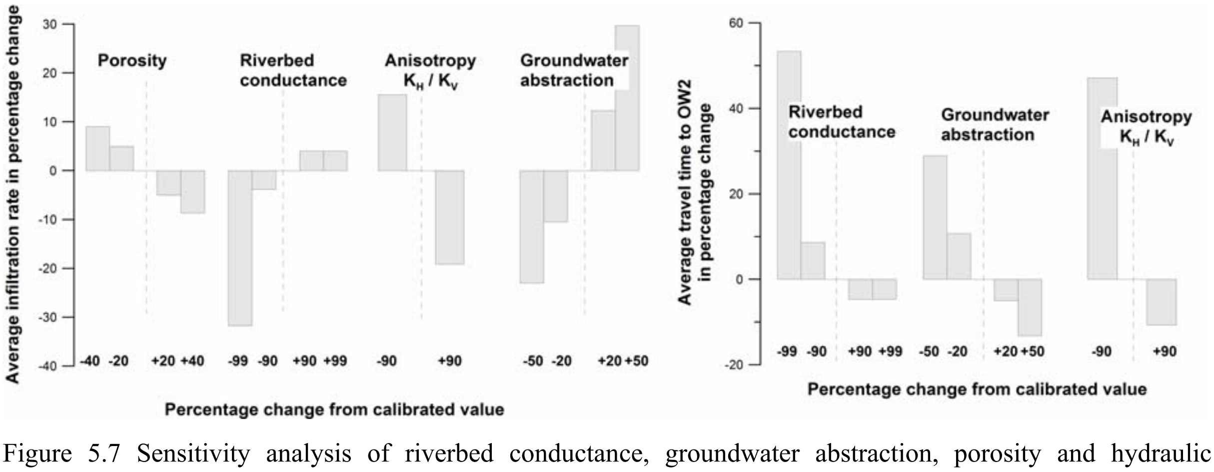

Figure 5.7 Sensitivity analysis of riverbed conductance, groundwater abstraction, porosity and hydraulic anisotropy on the average river water infiltration rate (left) and on the average travel time to the OW2 (right).

Sensitivity analysis of the effective porosity on groundwater travel time was not performed because of the linear dependency. The decrease of the riverbed conductance, hydraulic anisotropy and abstraction caused large changes in the average travel time to the OW2. Riverbed conductance was found to cause the largest changes within the investigated ranges (Figure 5.7). In general, the uncertainty of riverbed conductance and hydraulic gradient (caused by groundwater abstraction) has the largest impact on the modelling results of infiltration rates and travel time. Therefore, the riverbed conductance and the hydraulic gradient are key elements of SW/GW interactions and must be evaluated carefully.

5.3.3 Surface-/groundwater budget

Based on the modelling approach, the following water budget was developed for the Delhi flood plain aquifer. The surface-/groundwater flow system consists of inflow to the aquifer by river water infiltration, direct recharge during monsoon, lateral fluxes and changes in storage. Outflow from the flood plain aquifer consists of groundwater abstraction and changes in storage.

Water-budget calculations for the period from November 2006 to January 2008 indicate that river water infiltration was the most dominant inflow component. The average infiltration rate during monsoon was calculated with 5.5 m^3/day and for the non-monsoonal time with 3.6 m^3/day for the whole river width (Figure 5.8). Lateral fluxes to the flood plain aquifer were rather constant around 2 m^3/day over the whole study period and show only minor decline during monsoon. Only during phases of high river stage a positive balance in storage was calculated. Direct recharge by rainfall was only minor (0.15 m^3/d) during monsoon. The most dominant outflow component was groundwater abstraction given with 6.4 m^3/day. During phases of relative low river stages balance in storage was negative.

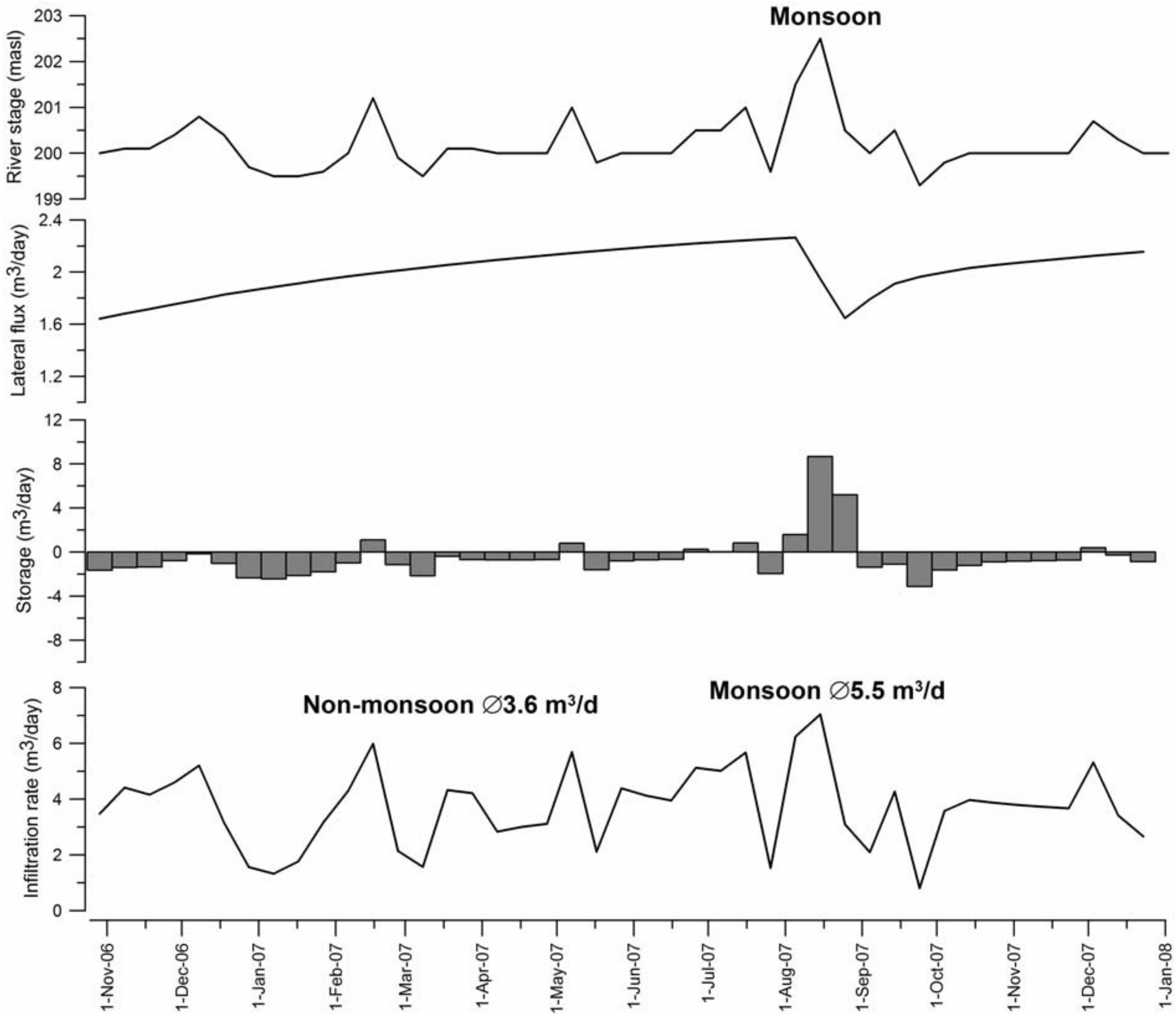

Figure 5.8 Temporal changes of river stage, infiltration rates, storage.

(Trisal et al. 2008) estimated the agricultural abstraction amount with 59 m^3/s for the whole urban stretch of the Yamuna flood plain. Converting this amount into areal abstraction per m^2 (urban flood plain area: 22 km x 3 km) will give an abstraction amount of 0.08 m^3/m^2d. This is 20 times more than the abstraction amount estimated in this study. Many areas in India suffer from unreliable or lack of data and unmetered and uncontrolled abstraction of groundwater is the main problem in calculating water budgets. However, the high abstraction amount for agriculture is causing the hydraulic gradient to be directed to the hinterland, resulting in permanently losing river conditions.

5.4 Conclusions

The following conclusions can be drawn from this study:

- The Yamuna River is in hydraulic contact to the adjacent flood plain aquifer and losing river conditions (influent conditions) dominates the eastern side of the Yamuna River
- Unsustainable groundwater abstraction volumes cause the hydraulic gradient indicating the flow from the river to the aquifer
- Reliable travel time evaluation is achieved by a combination of time variant environmental tracers (chloride and temperature)
- Since the chloride signal in the groundwater can be disturbed due to dissolution of salt from the unsaturated zone, temperature is considered to be more reliable as a tracer
- The greatest impact on infiltration rates are caused by changes in groundwater abstraction and riverbed conductance
- The greatest impact on travel times are caused by riverbed conductance and hydraulic anisotropy
- Infiltration rates of the Yamuna River during phases of high river stage (monsoon) is about 1.5 times higher than during phases of low river stage
- Data on spatial and temporal distribution of groundwater abstraction is poor and is the parameters with the highest uncertainty

6 Removal of bacteriophages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India)[9]

Abstract

Emerging countries, frequently afflicted by waterborne diseases, are in need of producing safe and cost-efficient drinking water; a task the more challenging, as many rivers carry a high degree of pollution. A study was conducted in Delhi (India) to ascertain if river bank filtration (RBF) can significantly improve the quality of the highly polluted surface water in terms of virus removal (bacteriophages, enteric viruses) and organic pollutants. A numerical model was used to describe the underground water flow and the transport and deposition of bacteriophages during RBF. A series of organic trace compounds including polar to non-polar substances from household, industrial and agricultural sources were considerably attenuated. Human adenoviruses and noroviruses, both present in the Yamuna at 10^5 genomes/100 ml, were undetectable after approx. 119 days of RBF passage. Indigenous somatic bacteriophages, used as surrogates of human pathogenic viruses, underwent approximately 5 $\log_{10}$ removal after only 3.8 m of RBF. The initial removal after 1 m was 3.3 $\log_{10}$, the removal between 1 and 2.4 meter and between 2.4 and 3.8 meter, 0.7 $\log_{10}$ each. RBF is therefore an excellent candidate to improve the water situation also in emerging countries.

---

[9] **Sprenger C**, Lorenzen G, Grunert A, Ronghang M, Dizer H, Selinka HC, Girones R, Lopez-Pila JM, Mittal A, Szewzyk R Journal of Water, Sanitation and Hygiene for Development (revised April 2011)

7 Vulnerability of bank filtration systems to climate change[10]

Abstract

Bank filtration (BF) is a well established and proven natural water treatment technology, where surface water is infiltrated to an aquifer through river or lake banks. Improvement of water quality is achieved by a series of chemical, biological and physical processes during subsurface passage. This paper aims at identifying climate sensitive factors affecting bank filtration performance and assesses their relevance based on hypothetical 'drought' and 'flood' climate scenarios. The climate sensitive factors influencing water quantity and quality also have influence on substance removal parameters such as redox conditions and travel time. Droughts are found to promote anaerobic conditions during bank filtration passage, while flood events can drastically shorten travel time and cause breakthrough of pathogens, metals, suspended solids, DOC and organic micropollutants. The study revealed that only BF systems comprising an oxic to anoxic redox sequence ensure maximum removal efficiency. The storage capacity of the banks and availability of two source waters renders BF for drinking water supply less vulnerable than surface water or groundwater abstraction alone. Overall, BF is vulnerable to climate change although anthropogenic impacts are at least as important.

---

[10] **Sprenger C**, Lorenzen G, Hülshoff I, Grützmacher G, Ronghang M, Pekdeger A (2010) Science of the Total Environment, Volume 409, Issue 4, 655-663, doi:10.1016/j.scitotenv.2010.11.002

References

Acharyya SK (2005) Arsenic levels in groundwater from quaternary alluvium in the Ganga Plain and the Bengal Basin, Indian subcontinent: insights into influence of stratigraphy. Gondwana Res 8(1): 55-66

Adams EE, Gelhar LW (1992) Field Study of Dispersion in a Heterogeneous Aquifer 2. Spatial Moments Analysis. Water Resour. Res. 28

Agarwal T, Khillare PS, Shridhar V (2006) PAHs contamination in bank sediment of the Yamuna River, Delhi, India. Environ Monit Assess 123:151-166

AGC (2001) Report on Evaluation study of soil conservation in seven watersheds of Sahibi catchment in Haryana and Rajasthan. Agricultural Finance Corporation Ltd., Northern Regional Office, sponsored by the Ministry of Agriculture, India: New Delhi; 154

Albinana-Gimenez N, Clemente-Casares P, Bofill-Mas S, Hundesa A, Ribas F, Girones R (2006) Distribution of human polyomaviruses, adenoviruses, and hepatitis E virus in the environment and in a drinking-water treatment plant. Environmental Science and Technoology, 40(23), 7416-7422

Alcala FJ, Custodio E (2008) Journal of Hydrology 359: 189– 207

Allard A, Albinsson B, Wadell G (2001). Rapid typing of human adenoviruses by a general PCR combined with restriction endonuclease analysis. Journal of Clinical Microbiology 39, 498-505

Ambast SK, Tyagi NK, Raul SK (2006) Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Agricultural Water Management 82(3):279–296

Andersen HE, Kronvang B, Larsen SE, Hoffmann CC, Jensen TS, Rasmussen EK (2006) Climate-change impacts on hydrology and nutrients in a Danish lowland river basin. Science of the Total Environment; 365: 223-237

Anderson MP (2005) Heat as a Ground Water Tracer. Ground Water 43(6):951–968

Appelo CAJ, Postma D (1993) Geochemistry, groundwater and pollution. Balkema, Rotterdam

Arnell N, Delaney E (2006) Adapting to climate change: Public water supply in England and Wales. Climatic Change; 78: 227-255

Ayoob S, Gupta AK (2006) Fluoride in drinking water: a review on the status and stress effects. Crit Rev Env Sci Tec 36:433–487

Bates BC, Kundzewicz ZW, Wu S, Palutikof JP (2008) Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat Geneva, pp 210

Banner JL, Wasserburg GJ, Dobson PF, Carpenter AB, Moore CH. (1989) Isotopic and trace element constraints on the origin and evolution of saline groundwaters from central Missouri Geochimica et Cosmochimica Acta 53: 383-398

Becker MW, Georgian T, Ambrose H, Siniscalchi J, Fredrick K (2004) Estimating flow and flux of ground water discharge using water temperature and velocity. Journal of Hydrology 296: 221-233

Bengtsson G, Annadotter H (1989) Nitrate reduction in a groundwater microcosm determined by 15N gas chromatography-mass spectrometry. Applied Environmental Microbiology 55(11):2861-2870

Berger P (2002) Removal of Cryptosporidium using bank filtration. NATO Advanced Research Workshop on Riverbank Filtration: understanding contaminant biogeochemistry and pathogen removal, Tihany, Hungary, pp. 85–121

Berman D, Rice EW, Hoff JC (1988) Inactivation of particle-associated coliforms by chlorine and monochloramine. Applied and Environmental Microbiology; 54: 507-512

Berner RA (1981) A new geochemical classification of sedimentary environments. Journal of Sedimentary Research; 51: 359-365

Beyer W (1964) On the determination of hydraulic conductivity of gravels and sands from grain-size distributions. Wasserwirtschaft-Wassertechnik 14: 165–169

Bhattacharya SK, Gupta SK, Krishnamurty RV (1985) Proc. Indian Acad. Sci (Earth Planet. Sci.) Vol. 94, No. 3: 283-295

BIS (1992) Indian Standard Specifications for Drinking Water. IS 10500 1983/1992. The Bureau of Indian Standards (BIS), New Delhi

Bloomfield JP, Williams RJ, Gooddy DC, Cape JN, Guha P (2006) Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater--a UK perspective. Science of The Total Environment; 369: 163-177

Böhlke JK, Smith RL, Miller DN (2006) Ammonium transport and reaction in contaminated groundwater: Application of isotope tracers and isotope fractionation studies. Water Resources Research; 42: p. W05411

Bouraoui F, Grizzetti B, Granlund K, Rekolainen S, Bidoglio G (2004) Impact of Climate Change on the Water Cycle and Nutrient Losses in a Finnish Catchment. Climatic Change; 66: 109-126

Bourg ACM, Bertin C (1993) Biogeochemical processes during the infiltration of river water into an alluvial aquifer. Environmental Science & Technology; 27: 661-666

Bourg ACM, Darmendrail D, Ricour J (1989) Geochemical filtration of riverbank and migration of heavy metals between the Deûle River and the Ansereuilles alluvion-chalk aquifer (Nord, France). Geoderma; 44: 229-244

Bradd JM, Milne-Home WA, Gates G (1997) Hydrogeology Journal 5: 51-67

Bradley PM, Chapelle FH (1998) Microbial Mineralization of VC and DCE Under Different Terminal Electron Accepting Conditions. Anaerobe; 4: 81-87

Brauch H-J (1988) Verhalten künstlicher, starker organischer Komplexbildner bei der Trinkwasseraufbereitung

Bredehoeft JD, Blyth CR, White WA, Maxey GB. (1963) AAPG Bulletin 47: 257-269

CGWB (2005) Basic data report of deposit wells drilled in Palla well fields of Yamuna flood plain area, north west district. Internal report, Central Groundwater Board

CGWB (2006) Ground Water Year Book 2005-2006, National Capital Territory, Delhi. Central Ground Water Board, Govt. of India, New Delhi

Champ DR, Gulens J, Jackson RE (1979) Oxidation- reduction sequences in ground water flow systems. Earth Science 16:12–23

Chave P, Howard G, Schijven J, Appleyard S, Fladerer F, Schimon W (2006). Groundwater protection zones. In: Protecting Groundwater for Health: Managing the Quality of Drinking-water Sources. Schmoll G, Howard J, Chilton I,Chorus (eds. ISBN: 1843390795. IWA Publishing, London, UK

Chorus I, Falconer IR, Salas HJ, Bartram J. (2000) Health risks caused by freshwater cyanobacteria in recreational waters. 3. Taylor & Francis, 323 - 347

Clark ID, Fritz P (1997) Environmental Isotopes in Hydrogeology CRC Press, Boca Raton

Clement, P (1997) A modular computer code for simulating Reactive Multi-species Transport in 3-Dimensional Groundwater Systems, U.S. Department of Energy, Washington

Cooper AH (2002) Halite karst geohazards (natural and man-made) in the United Kingdom Environmental Geology 42: 505-512

Courty MA, Fédoroff N (1985) Micromorphlogy of recent and buried soils in a semi-arid region of northwestern India Geoderma 35: 287-332

Cox MH, Constantz J, Su GW (2007) Comparison of Heat and Bromide as Ground Water Tracers Near Streams. Ground Water 45: 187-195

CPCB (2006) Water Quality Status of River Yamuna (1999-2005). ADSORBS/41/2006-07 Central Pollution Control Board, Govt. of India. Available via http://www.cpcb.nic.in. Accessed 15 Feb 2009

CSE (2007) Sewage canal - how to clean up the Yamuna. Centre for Science and Environment, New Delhi

Daga S(2003) Private supply of water in Delhi. Centre for Civil Society, New Delhi. Available via www.ccsindia.org. Accessed 15 Sept 2008

Das BK, Kakar YP, Moser H, Stichler W (1988) Deuterium and oxygen-18 studies in groundwater of the Delhi area, India. J Hydrol 98:133-146

Dash RR, Mehrotra I, Kumar P, Grischek T (2008) Lake bank filtration at Nainital, India: water-quality evaluation. Hydrogeol J 16:1089–1099

Datta PS, Tyagi SK, Chandrasekharan H (1991) Factors controlling stable isotope composition of rainfall in New Delhi, India. Journal of Hydrology 128: 223-236

Datta PS, Bhattacharya SK, Tyagi SK (1996a) ^{18}O studies on recharge of phreatic aquifers and groundwater flow-paths of mixing in Delhi area. Journal of Hydrology 176:25-36

Datta PS, Deb DL, Tyagi SK (1996b) Stable isotope (^{18}0) investigations on the processes controlling fluoride contamination of groundwater. Journal of Contaminant Hydrology 24:85-96

Datta PS, Deb DL, Tyagi SK (1997) Assessment of groundwater contamination from fertilizers in the Delhi area based on 180, NO3- and K+ composition. Journal of Contaminant Hydrology 27:249-262

Datta PS, Tyagi SK (2004) Evidences of climatic uncertainties linked groundwater variability in peri-urban agricultural areas of Delhi. Proceedings of the 1st Asia Oceania Geosciences Society (AOGS) Conference. 5-8 Jul 2004, Singapore

Davis SN, DeWiest RJM (1966) Hydrogeology. John Wiley & Sons: New York; 463

Davis S, Whittemore D, Fabryka-Martin J (1988) Uses of chloride/bromide ratios in studies of potable waterGround Water 36: 338-350

DeBorde DC, Woessner WW, Lauerman B, Ball PN (1998). Virus occurrence and transport in a school septic system and unconfined aquifer. Ground Water, 36(5), 825–834

Dennis JM (1959) 1955-56 infectious hepatitis epidemic in Delhi, India. J. Am. Water Works Association, 51, 1288-98

de Vet WWJM, van Genuchten CCA, van Loosdrecht MCM, van Dijk JC (2010) Water quality and treatment of river bank filtrate. Drinking Water Engineering and Science, 3: 79-90

Delpla I, Jung AV, Baures E, Clement M, Thomas O. (2009) Impacts of climate change on surface water quality in relation to drinking water production. Environment International; 35: 1225-1233

Diham SC (2007) Artificial recharge of aquifers. Proceedings of the national groundwater congress. 11 Sept 2007, New Delhi

Dillon PJ (2002) Managing Aquifer Recharge. Recharge in the water cycle. Brochure, sponsored by UNESCO-IHP; compiled by IAH-MAR with the support of the British Department for International Development (DFID). Adelaine, Australia. Available: http://unesdoc.unesco.org/images/0012/001278/127843e.pdf; Accessed: January 2011

Dillon PJ (2005) Future management of aquifer recharge. Hydrogeological Journal 13:313–316

Doussan C, Poitevin G, Ledoux E, Detay M (1997) River bank filtration: modelling of the changes in water chemistry with emphasis on nitrogen species. J Contam Hydrol 25:129-156

Doussan C, Toma A, Pari B, Poitevin G, Ledoux E, Detay M (1994) Coupled use of thermal and hydraulic head data to characterize river-groundwater exchanges. J Hydrol 153:215-229

Ducharne A, Baubion C, Beaudoin N, Benoit M, Billen G, Brisson N, (2007). Long term prospective of the Seine River system: Confronting climatic and direct anthropogenic changes. Science of the Total Environment; 375: 292-311

Duff JH, Triska FJ (1999) Nitrogen biochemistry and surface - subsurface exchange in streams. In: Jones JB, Mulholland PJ (eds) Streams and ground waters. Elsevier, New York

Duncan R, Bethune M, Christen E, Hornbuckle J (2005) A review of salt mobilisation and management in irrigated areas of the Murray-Darling Basin. Cooperative Research Centre for Catchment Hydrology, Monash University: Victoria, Australia

DVGW (1995) Code of Practice W101 for Drinking Water Protection Areas Part 1, Protective Areas for Groundwater. , German Association of Gas and Water Experts, Germany

Eckert P, Irmscher R (2006) Over 130 years of experience with Riverbank Filtration in Düsseldorf, Germany. J. Water SRT – Aqua, 55, 283-291

Eckert P, Lamberts R, Wagner C (2008) The impact of climate change on drinking water supply by riverbank filtration. Water Science & Technology: Water Supply; 8: 319-324

Eckhardt K, Ulbrich U (2003) Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range. Journal of Hydrology; 284: 244-252

Fontes DE, Mills AL, Hornberger GM, Herman JS (1991) Physical and chemical factors influencing transport of microorganisms through porous media

Foppen JWA, Naaman M, Schijven JF (2005) Managing urban water under stress in Sana'a, Yemen. Arabian Journal for Science and Engineering 30(2c), 69-83

Freeze RA, Cherry JA (1979) Groundwater, Prentice-Hall International, Hemel Hempstead

Frimmel FH (1998) Characterization of natural organic matter as major constituents in aquatic systems. Journal of Contaminant Hydrology 35: 201-216

Fukada T, Hiscock KM, Dennis PF, Grischek T (2003) A dual isotope approach to identify denitrification in groundwater at a river-bank infiltration site. Water Research 37:3070–3078

Gerecke AC, Schärer M, Singer HP, Müller SR, Schwarzenbach RP, Sägesser M, (2002) Sources of pesticides in surface waters in Switzerland: pesticide load through waste water treatment plants--current situation and reduction potential. Chemosphere; 48: 307-315

Gerritse RG, George RJ (1988). The role of soil organic matter in the geochemical cycling of chloride and bromide. Journal of Hydrology, 101: 83-95

Gilfedder M, Mein RG, Connell LD. (2000). Border Irrigation Field Experiment. II: Salt Transport J. Irrig. and Drain. 126: 92-97

Goedeke S, Weiß H, Geistlinger H, Fischer A, Richnow HH (2004) Strömungs- und Tracer-Transportmodellierung am Natural Attenuation-Standort Zeitz Grundwasser 9(1), 3-11

Goel PD, Datta PS, Tanwar BS (1977) Measurement of Vertical Recharge to Groundwater in Haryana State (India) Using Tritium Tracer. . Nordic Hydrology, 8: 211-224

Goldschneider AA, Haralampides KA, MacQuarrie KTB (2007) River sediment and flow characteristics near a bank filtration water supply: Implications for riverbed clogging. Journal of Hydrology; 344: 55-69

Greskowiak J, Prommer H, Massmann G, Nützmann G (2006) Modeling Seasonal Redox Dynamics and the Corresponding Fate of the Pharmaceutical Residue Phenazone During Artificial Recharge of Groundwater. Environmental Science & Technology; 40: 6615-6621

Grischek T, Schoenheinz D, Ray C (2002) Siting and design issues for riverbed filtration schemes. In: Ray C, Melin G, Linsky RB (eds) Riverbank Filtration, Kluwer, Dordrecht

Grischek T, Schoenheinz D, Ray C (2003) Riverbank Filtration. Ray, C., Melin, G. and Linsky, R.B. (eds), pp. 291-302, Kluwer Academic Publishers, New York, Boston, Dordrecht, London, Moscow.

Gross-Wittke A, Gunkel G, Hoffmann A (2010). Temperature effects on bank filtration: redox conditions and physical-chemical parameters of pore water at Lake Tegel, Berlin, Germany. Journal of Water and Climate Change; 1: 55–66

Grube A, Sschmalz B, Nachtigall K, Wichmann K (1999). Provisional Results of Investigations on Groundwater Salinization with Emphasis on the Region of Lübeck, Northern GermanyProceedings SWIM 15 Ghent. Naturweed. Tiddschr. 79: 164-171

Grünheid S, Amy G, Jekel M (2005) Removal of bulk dissolved organic carbon (DOC) and trace organic compounds by bank filtration and artificial recharge. Water Research 39:3219–3228

Grützmacher G, Böttcher G, Chorus I, Bartel H (2002) Removal of microcystins by slow sand filtration. Environmental Toxicology 17(4):386-94

Gruetzmacher G, Wessel G, Klitzke S, Chorus I (2009) Microcystin Elimination During Sediment Contact. Environmental Science & Technology

Guang-wei ZHU, Qiao-qiao CHI, Bo-qiang QIN, Wen-min W (2005) Heavy-metal contents in suspended solids of Meiliang Bay, Taihu Lake and its environmental significances. Journal of Environmental Sciences; 17: 672-675

Haberman DL (2006). River of Love in an Age of Pollution: The Yamuna River of Northern India. Univ. California Press; 1th edn, Berkeley, USA

Halling-Sørensen B, Nors Nielsen S, Lanzky PF, Ingerslev F, Holten Lützhøft HC, Jørgensen SE (1998) Occurrence, fate and effects of pharmaceutical substances in the environment- A review. Chemosphere; 36: 357-393

Harbaugh AW, Banta ER, Hill MC, McDonald MG (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 00-92. U.S. Geological Survey

Havelaar AH, van Olphen M, Schijven JF (1995) Removal and inactivation of viruses by drinking water treatment processes under full scale conditions. Water Science and Technology; 31: 55-62.

Hazen A (1893) Some physical properties of sand and gravel with special reference to the use in filtration. 4th Annual Report, State Board of Health, Boston

Heberer T (2002) Tracking persistent pharmaceutical residues from municipal sewage to drinking water. Journal of Hydrology; 266: 175-189

Heberer T, Mechlinski A, Fanck B, Knappe A, Massmann G, Pekdeger A, Fritz B (2004) Field studies on the fate and transport of pharmaceutical residues in bank filtration. Ground Water Monit R 24(2):70-77

Herczeg AL, Simpson HJ, Mazor E (1993) Transport of soluble salts in a large semiarid basin: River Murray, Australia Journal of Hydrology 144: 59-84

Herzberg A (1901) Die Wasserversordung einiger Nordseebäder Journal für Gasbeleuchtung und Wasserversorgung 44: 815-819, 842-844

Hiemstra P, Kolpa RJ, van Eekhout, JMJM, van Kessel TAL, Adamse ED, van Paassen JAM (2003). Natural recharge of groundwater: bank infiltration in the Netherlands, Journal of Water Supply: Research and Technology – Aqua, 52, 37-47

Hijnen WAM, Brouwer-Hanzens AJ, Charles KJ, Medema GJ. (2005) Transport of MS2 Phage, Escherichia coli, Clostridium perfringens, Cryptosporidium parvum, and Giardia intestinalis in a Gravel and a Sandy Soil. Environmental Science & Technology; 39: 7860-7868

Hiscock KM, Grischek T (2001) Attenuation of groundwater pollution by bank filtration. Journal of Hydrology 266 (3-4):139-144

Hoehn E (2002) Hydrogeological issues of riverbank filtration - a review. In: Ray C (ed) Riverbank filtration: understanding contaminant biogeochemistry and pathogen removal, Kluwer, Dordrecht

Holzbecher E (1998) Modelling Density-Driven Flow in Porous Media, Springer, Berlin.

Howard G, Charles K, Pond K, Brookshaw A, Hossain R, Bartram J (2010) Securing 2020 vision for 2030: climate change and ensuring resilience in water and sanitation services. Journal of Water and Climate Change; 1: 2–16

Hubbs SA (ed) (2006) Riverbank Filtration Hydrology. Impacts on system capacity and water quality. NATO Science Series IV: Earth and Environmental Sciences 60. Springer, Dordrecht

Hülshoff I, Greskowiak J, Wiese B, Grützmacher G (2009) Relevance and opportunities of RBF to provide safe water for developing and newly industrialised countries. TECHNEAU Integrated Project: D 5.2.3. European Commission. Available via www.techneau.org Accessed 28 Mar 2009

Hunt H, Schubert J, Ray C (2002) Conceptual design of riverbank filtration systems. In: Ray C, Melin G, Linsky RB (eds) Riverbank filtration: improving source-water quality, Kluwer, Dordrecht

IAEA/WMO (2009) Global Network of Isotopes in Precipitation. The GNIP database. Available via http://isohis.iaea.org. Accessed 03.12.2009

IPCC (2007) International panel for climate change Fourth Assessment Report: Climate Change 2007: Impacts, Adaptation and Vulnerability Summary for Policy-Makers

Jacks G, Bhattacharya P, Chaudhary V, Singh KP (2005) Controls on the genesis of some high-fluoride groundwaters in India. Appl Geochem 20:221–228

Jacobs LA, von Gunten HR, Keil R, Kuslys M.(1988) Geochemical changes along a river-groundwater infiltration flow path: Glattfelden, Switzerland. Geochimica et Cosmochimica Acta; 52: 2693-2706

Janakarajan S, Llorente M, Zérah M-H (2006) Urban water conflicts in Indian cities: Man-made scarcity as a critical factor. In: Janakarajan S, Llorente M, Zérah M-H (eds) Urban water conflicts: An analysis of the origins and nature of water-related unrest and conflicts in the urban context. UNESCO, Paris. Available via http://unesdoc.unesco.org/images/0014/001490/149032e.pdf Accessed 15 Sept 2008

Jekel M (2006) Organic Substances in Bank filtration and Groundwater Recharge - Process Studies. NASRI - Final Project Report. Technical University of Berlin, Berlin

Jolly ID, McEwan KL, Holland KL (2008) A review of groundwater-surface water interactions in arid/semi-arid wetlands and the consequences of salinity for wetland ecology.43-58

Jones GJ, Bourne DG, Blakeley RL, Doelle H (1994) Degradation of the cyanobacterial hepatotoxin microcystin by aquatic bacteria. Natural Toxins; 2: 228-235

Jüttner F (1999) Efficacy of bank filtration for the removal of fragrance compounds and aromatic hydrocarbons. Water Science and Technology; 40: 123-128

Jyrkama MI, Sykes JF (2007) The impact of climate change on spatially varying groundwater recharge in the grand river watershed (Ontario). Journal of Hydrology, 338: 237-250

Kale VS, Hire PS (2004) Effectiveness of monsoon floods on the Tapi River, India: role of channel geometry and hydrologic regime. Geomorphology; 57: 275-291

Karn SK, Harada H (2001) Surface water pollution in three urban territories of Nepal, India, and Bangladesh. Environ Manage 28(4):483–496

Käss W (2004) Geohydrologische Markierungstechnik., Gebrüder Bornträger, Berlin Stuttgart

Kaul BL, Pandit EMK (2004) Morphotectonic evaluation of the Delhi region in northern India, and its significance in environmental management. Environ Geol 46(8): 1118–1122

Kaushik CP, Sharma HR, Jain S, Dawra J, Kaushik A (2008) Pesticide residues in river Yamuna and its canals in Haryana and Delhi, India. Environ Monit Assess 144:329–340

Kedziorek MAM, Geoffriau S, Bourg ACM (2008). Organic Matter and Modeling Redox Reactions during River Bank Filtration in an Alluvial Aquifer of the Lot River, France. Environmental Science & Technology; 42: 2793-2798

Keery J, Binley A, Crook N, Smith JWN (2007) Temporal and spatial variability of groundwater–surface water fluxes: Development and application of an analytical method using temperature time series. Journal of Hydrology 336(1-2), 1-16

Kim S-B, Corapcioglu MY (2002) Contaminant transport in riverbank filtration in the presence of dissolved organic matter and bacteria: a kinetic approach. Journal of Hydrology; 266: 269-283

Kloppmann W, Négrel P, Casanova J, Klinge H, Schelkes K, Guerrot C (2001). Halite dissolution derived brines in the vicinity of a Permian salt dome (N German basin) Evidence from boron, strontium, oxygen, and hydrogen isotopes Geochimica et Cosmochimica Acta 65: 4087-4101

Kulkarni KM, Rao SM, Singhal BBS, Parkash B, Navada SV, Nair AR (1989) Origin of saline groundwaters of Haryana State In Regional Characterization of Water Quality. Proceedings of a workshop held during the Third IAHS Scientific Assembly at Baltimore, May 1989, Ragone S ed.: Baltimore

Kumar M, Sharma B, Ramanathan AL, Someshwar Rao M, Kumar B. (2008). Nutrient chemistry and salinity mapping of the Delhi aquifer, India: source identification perspective Environ Geol 14: 1431-2174

Kühn W, Brauch HJ (1988) Organische Mikroverunreinigungen im Rhein. Bestimmung und Aussagekraft für die Gewässerbeurteilung. Fresenius' Journal of Analytical Chemistry ; 330: 324-325-325

Kühn W, Müller U (2000) Riverbank filtration – an overview. Journal of the American Water Works Association: 60-69

Kumar V (2002) Water pollution of Yamuna. Nistads News 4(2):24-38

Kumar P (2004) Ecosystem services of floodplains: an exploration of water recharge potential of the Yamuna floodplain for Delhi. Proceedings of the conference on Market Development of Water & Waste Technologies through Environmental Economics. 28-29 May 2004. CERNA, Paris. Available via www.csh-delhi.com.Accessed 12 May 2008

Kumar M, Ramanathan A, Rao MS, Kumar B (2006) Identification and evaluation of the hydrogeochemical processes in the groundwater environment of Delhi, India. Environ Geol 50(7):1025-1039

Kumar M, Sharma B, Ramanathan AL, Someshwar Rao M, Kumar B (2008a) Nutrient chemistry and salinity mapping of the Delhi aquifer, India: source identification perspective. Environ Geol 14(7):1431-2174

Kumar V, Chakraborty A, Viswanath G, Roy P (2008b) Androgenic endocrine disruptors in wastewater treatment plant effluents in India: Their influence on reproductive processes and systemic toxicity in male rats. Toxicology and Applied Pharmacology 2008; 226: 60-73

Kundu MC, Mandal B, Hazra GC (2009) Nitrate and fluoride contamination in groundwater of an intensively managed agroecosystem: a functional relationship. Sci Total Environ 407(8):2771-2782

Kuypers MMM, Sliekers AO, Lavik G, Schmid M, Jorgensen BB, Kuenen JG (2003) Anaerobic ammonium oxidation by anammox bacteria in the Black Sea. Nature; 422: 608-611

Lalwani S, Dogra TD, Bhardwaj DN, Sharma RK, Murty OP, Vij A (2004) Study on arsenic level in ground water of Delhi using hydride generator accessory coupled with atomic absorption spectrophotometer. Indian J of Clin Biochem 19(2):135-140

Landmeyer JE, Chapelle FH, Bradley PM, Pankow JF, Church CD, Tratnyek PG. (1998) Fate of MTBE relative to benzene in a gasoline-contaminated aquifer (1993-98). . Ground Water Monitoring and Remeidiation; 18: 93-102

László F, Székely F (1989) Simulation of groundwater flow and redox processes around bank-filtration wells. Proceedings of the Symposium third IAHS scientific assembly. May 1989, Baltimore, MD. IAHS Publ. 185

László F, Literathy P (2002) Laboratory and field studies of pollutant removal. In: Ray, C (ed) Riverbank filtration: understanding contaminant biogeochemistry and pathogen removal, Kluwer, Dordrecht

Lawrence A, Gooddy D, Kanatharana P, Meesilp W, Ramnarong V (2000) Groundwater evolution beneath Hat Yai, a rapidly developing city in Thailand. Hydrogeology Journal 8(5), 564-575

Lindner K, Knepper TP, Mueller J, Karrenbrock F, Rörden O, Brauch H-J (2000) Entwicklung von Verfahren zur Bestimmung und Beurteilung der Trinkwassergängigkeit von organischen Einzelstoffen. Rhein-Themen 3

Lorenzen G, Sprenger C (2008) Preliminary report on data of all inorganic substances and physicochemical parameters listed in the Indian and German Drinking Water Standards from surface water and groundwater at the field sites. TECHNEAU Report D 5.2.2, p. 44, European Commission

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 Earth Sciences, 1419-1434

Lowenstein TK, Hardie LA (1985) Criteria for the recognition of salt-pan evaporites. Sedimentology 32: 627-644

Lovley DR (1991) Dissimilatory Fe(III) and Mn(IV) reduction. Microbiology and Molecular Biology Reviews; 55: 259-287

Maeng SK, Ameda E, Sharma SK, Grützmacher G, Amy GL (2010) Organic micropollutant removal from wastewater effluent-impacted drinking water sources during bank filtration and artificial recharge. Water Research; 44: 4003-4014

Maeng SK, Sharma SK, Amy GL (2009) Guidelines and prediction tool for pharmaceuticals removal during bank filtration. Switch scientific meeting, Delft, Netherlands

Markle JM, Schincariol RA (2007) Thermal plume transport from sand and gravel pits - potential thermal impacts on cool water streams. J Hydrol 338(3-4):174-195

Maria A (2004) The Role of Groundwater in Delhi´s Water Supply, p. 13, NATO Advanced Studies Institute on Urban Hydrogeology Baku, India / CERNA, Ecole Nationale Supérieure des Mines de Paris.

Maria A, Jaouen L (2004) Strategies for water supply in a planned urban extension - A case study of the Dwarka sub-city in Delhi, pp. 103, CERNA, Ecole Nationale Supérieure des Mines de Paris, Paris

Marshall E, Randhir T (2008) Effect of climate change on watershed system: a regional analysis. Climatic Change; 89: 263-280

Massmann G, Pekdeger A, Merz C (2004) Redox processes in the Oderbruch polder groundwater flow system in Germany. Applied Geochemistry 19:863–886

Massmann G, Knappe A, Richter R, Pekdeger A (2004) Investigating the Influence of Treated Sewage on Groundwater and Surface Water Using Wastewater Indicators in Berlin, Germany. Acta hydrochimica et hydrobiologica 32(4-5), 336-350

Massmann G, Greskowiak J, Dünnbier U, Zuehlke S, Knappe A, Pekdeger A (2006) The impact of variable temperatures on the redox conditions and the behaviour of pharmaceutical residues during artificial recharge. Journal of Hydrology; 328: 141-156

Massmann G, Sültenfuß J, Dünnbier U, Knappe A, Taute T, Pekdeger A (2008a) Investigation of groundwater residence times during bank filtration in Berlin: A multi-tracer approach. Hydrological Processes 22 (6):788-801

Massmann G, Dünnbier U, Heberer T, Taute T (2008b) Behaviour and redox sensitivity of pharmaceutical residues during bank filtration - Investigation of residues of phenazone-type analgesics. Chemosphere; 71: 1476-1485

Matthess G, Pekdeger A, Schroeter J (1988) Persistence and transport of bacteria and viruses in groundwater -- a conceptual evaluation. Journal of Contaminant Hydrology; 2: 171-188

Mehra A, Farago ME, Banerjee DK (2000) A study of eichhornia crassipes growing in the overbank and floodplain soils of the River Yamuna in Delhi, India. Environ Monit Assess 60:25–45

MFP (2008) Economic Survey of Delhi: Annual Report 2007/2008. Ministry of Finance and Planning, Govt. of NCT Delhi. Available via http://delhiplanning.nic.in Accessed 07 Aug 2008

Miettinen IT, Vartiainen T, Martikainen P (1996) Bacterial enzyme activities in ground water during bank filtration of lake water. Water Research; 30: 2495-2501

Misra AK, Mishra A (2007) Escalation of salinity levels in the quaternary aquifers of the Ganga alluvial plain, India Environ Geol 53: 47–56

Mukherjee A, von Brömssen M, Scanlon BR Bhattacharya P, Fryar AE, Hasan MA (2008) Hydrogeochemical comparison and effects of overlapping redox zones on groundwater arsenic near the Western (Bhagirathi sub-basin, India) and Eastern (Meghna sub-basin, Bangladesh) margins of the Bengal Basin. Journal of Contaminant Hydrology; 99: 31-48

Müller A (1998) The flood in the Oder River 1997 — impact on water quality. Ocean Dynamics; 50: 245-251

Naik SR, Aggarwal R, Salunke PN, Mehrotra NN (1992) A large waterborne viral hepatitis E epidemic in Kanpur, India. Bull. World Health Organ. 70, 597-604

Nema A, Agarwal L (2003) Wastewater management in Najafgarh drainage basin – key to water quality improvement in river Yamuna In Indian Association of Environment Management, Annual Conference. New Delhi

Neumann M, Schulz R, Schäfer K, Müller W, Mannheller W, Liess M (2002) The significance of entry routes as point and non-point sources of pesticides in small streams. Water Research; 36: 835-842

Noble P, Morgan P (2002) The Effects of Contamination Concentration on the Potential for Natural Attenuation. R&D Project P2-228, Technical Report P2-228/TR prepared by ABB Eutech & Geosyntec

Pant RK (1993) Spread of loess and march of desert in western India. Current Science 64: 841- 847

Pieper AP, Ryan JN, Harvey RW, Amy GL, Illangasekare TH, Metge DW (1997) Transport and Recovery of Bacteriophage PRD1 in a Sand and Gravel Aquifer:â€‰ Effect of Sewage-Derived Organic Matter. Environmental Science & Technology; 31: 1163-1170

Pollock DW (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. . In: Of 94-464 USGS (ed), Washington, D.C.

Post V, Kooi H, Simmons C (2007) Using hydraulic head measurements in variable-density ground water flow analyses. Ground Water 45 (6):664-671

Ramalingaswami V, Purcell RH (1988) Waterborne non-A, non-B hepatitis. Lancet 1, 571-573.

Rao SVN, Kumar S, Sinha SK, Shekhar S (2006) An operational model for groundwater pumping at palla well fields, NCT Delhi, p. 63, NIH - CGWB, Roorkee

Rao SVN, Kumar S, Shekhar S, Sinha SK, Manju S (2007) Optimal pumping from skimming wells from the Yamuna River flood plain in north India. Hydrogeological Journal 15(6):1157-1167

Ray C, Melin G, Linsky RB (eds) (2002a) Riverbank Filtration: Improving source-water quality, Water Science and Technology Library 34, Kluwer, Dordrecht

Ray C, Soong TW, Lian YQ, Roadcap GS (2002b) Effect of flood-induced chemical load on filtrate quality at bank filtration sites. Journal of Hydrology 266:235–258

Ray C, Melin G, Linsky R, Wang J (2003) Riverbank Filtration Case Study at Louisville, KentuckyRiverbank Filtration, Water Science and Technology Library:117-145

Reddersen K, Heberer T, Dünnbier U (2002) Identification and significance of phenazone drugs and their metabolites in ground- and drinking water. Chemosphere; 49: 539-544

Richert JG (1900) On Artificial Underground Water. C. E. Fritze's Royal Bookstore, Stockholm, Sweden

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460: 999-1002

Rohns H-P, Forner C, Eckert P, Irmscher R (2006) Efficiency of Riverbank Filtration Considering the removal of pathogenic Microorganisms of the River Rhine. . Recent Progress in Slow Sand and Alternative Biofiltration Processes; IWA Publishing: 539-546

Roy A (1999) Evolution of saline lakes in Rajasthan. Current Science 76: 290-295

Rozanski K, Araguas L, Gonfiantini R (1993) Isotopic patterns in modern global precipitation. Continental Isotope Indicatores of Climate

Sacher F, Brauch H-J (2002) Riverbank Filtration: Understanding Contaminant Biogeochhemistry and Pathogen Removal. Ray, C. (ed), Kluwer Academic, Dodrecht

Salama RB, Otto CJ, Fitzpatrick RW (1999) Contributions of groundwater conditions to soil and water salinizationHydrogeology Journal 7: 46-64

Sandhu C, Grischek T, Schönheinz D, Ojha CSP, Ray C (2006) Bank filtration as a source of drinking water in India. Everything About Water 03-04 2006:36-39

Schijven JF, Medema G, Vogelaar AJ, Hassanizadeh SM (2000). Removal of microorganisms by deep well injection. Journal of Contaminant Hydrology, 44, 301-327

Schijven JF, Hassanizadeh SM (2000) Removal of Viruses by Soil Passage: Overview of Modeling, Processes, and Parameters. 30. Taylor & Francis, pp. 49 - 127

Schijven J (2001) Virus Removal from Groundwater by Soil Passage: Modeling, Field and Laboratory Experiments, page 23-25. Ponsen & Looijen B. V, Wageningen

Schijven JF (2002) Virus removal by soil passage at field scale and groundwater protection. In: Ray C (ed) Riverbank filtration: Understanding contaminant biogeochemistry and pathogen removal. Kluwer, Dordrecht

Schijven J, Berger P, Miettinen I (2003) Removal of Pathogens, Surrogates, Indicators, and Toxins Using Riverbank Filtration. In: Ray C, Melin G, Linsky R, editors. Riverbank Filtration. 43. Springer Netherlands, pp. 73-116

Schmidt CK, Lange FK, Brauch H-J, Kühn W (2003) Experiences with riverbank filtration and infiltration in Germany. DVGW Water Technology Centre (TZW), Karlsruhe

Schmidt CK (2005) Ermittlung der potenziellen Reinigungsleistung der Uferfiltration/Untergrundpassage hinsichtlich der Eliminierung organischer Schadstoffe unter standortspezifischen Randbedingungen - Datenbank zum Verhalten organischer Spurenstoffe bei der Uferfiltration.

Schmidt CK, Lange FK (2006) Ermittlung der potenziellen Reinigungsleistung der Uferfiltration/Untergrundpassage hinsichtlich der Eliminierung organischer Schadstoffe unter standortspezifischen Randbedingungen. Technologiezentrum Wasser Karlsruhe (TZW), Karlsruhe

Schoenheinz D, Worch E (2006) DOC-Entfernung bei der Uferfiltration unter Berücksichtigung extremer Temperaturbedingungen und Belastungsschwankungen. Eigenverlag DVGW-Technologiezentrum Wasser Karlsruhe.

Schubert J (2002) Hydraulic aspects of riverbank filtration—field studies. Journal of Hydrology 266: 145–161

Schubert J (2006) Significance of Hydrologic Aspects on RBF Performance. Riverbank Filtration Hydrology, pp. 1-20

Schwarzenbach RP, Escher BI, Fenner K, Hofstetter TB, Johnson CA, von Gunten U (2006) The Challenge of Micropollutants in Aquatic Systems. Science; 313: 1072-1077

Schwarzenbach RP, Giger W, Hoehn E, Schneider JK (1983) Behavior of organic compounds during infiltration of river water to groundwater. Field studies. Environmental Science & Technology; 17: 472-479

Seiler KP, Müller E, Hartmann A, Trimborn P, Decarli F, Alvarado Rivas J, Jiriez A, Sajjad I (2001) Environmental Isotopes in the Hydrological Cycle, Principles and Applications.Volume 5: Man´s Impact on Groundwater Systems. UNESCO/IAEA: Paris

Selle B, Thayalakumaran T, Morris M (2010) Hydrological Processes 24: 3307-3321

Servais P, Anzil A, Ventresque C (1989) Simple method for determination of biodegradable dissolved organic carbon in water. Applied and Environmental Microbiology; 55: 2732-2734

Shamrukh M, Abdel-Wahab A (2008) Riverbank filtration for sustainable water supply: application to a large-scale facility on the Nile River. Clean Techn Environ Policy 10(4): 351-358

Sharma S, Singh I, Virdi JS (2003) Microbial contamination of various water sources in Delhi. Current science; 84

Sheets RA, Darner RA, Whitteberry BL (2002) Lag times of bank filtration at a well field, Cincinnati, Ohio, USA. J. Hydrol. 266, 162–174

Shekhar S (2006) An approximate projection of availability of the fresh groundwater resources in the South West district of NCT Delhi, India: A case study. Hydrogeology Journal 14:1330–1338

Shekhar S, Prasad R (2009) The groundwater in the Yamuna flood plain of Delhi (India) and the management options. Hydrogeology Journal 17: 1557-1560

Singh RB (1999) Urban impacts on groundwater quality in the Delhi region. In: Ellis JB (ed) Proceedings of the impacts of urban growth on surface water and groundwater quality. 18-30 July 1999, Birmingham, UK. IAHS Publ. 259

Singh M (2001). Heavy metal pollution in freshly deposited sediments of the Yamuna River (the Ganges River tributary): a case study from Delhi and Agra urban centres, India. Environmental Geology 40(6): 664-671

Singh NT (2005) Irrigation and Soil Salinity in the Indian Subcontinent - Past and Present. Lehigh Univ. Press: Cranbury, NJ, USA; 404

Singh P, Arora M, Goel NK (2006) Effect of climate change on runoff of a glacierized Himalayan basin; 20: 1979-1992

Smith M, Compton JS (2004) Origin and evolution of major salts in the Darling pans, Western Cape, South Applied Geochemistry 19: 645-664

Sontheimer H (1980) Experience with riverbank filtration along the Rhine River. Journal of the American Water Works Association 1980; 72: 386 - 390

Sonzogni W, Jocelyn H, Miel B, Steve G (2006) Occurrence of Estrogenic Endocrine Disruptors in Groundwater, 2006

Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal 10(1), 52-67

Sprenger C, Lorenzen G, Pekdeger A (2008) Occurrence and fate of microbial pathogens and organic trace compounds at riverbank filtration sites in Delhi, India. TECHNEAU Integrated Project: D 5.2.6. European Commission. Available via www.techneau.org Accessed 28 Mar 2009

Sprenger C, Lorenzen G, Hülshoff I, Grützmacher G, Ronghang M, Pekdeger A (2011) Vulnerability of bank filtration systems to climate change. Science of the Total Environment 409(4), 655-663

Srtvastava G, Singh I, Kulshrestha A (2006) Late quaternary geomorphic evolution of Yamuna-Sutlej interfluve: Significance of terminal fan. Journal of the Indian Society of Remote Sensing 34: 123-130

Srivastava SK, Ramanathan AL (2008) Geochemical assessment of groundwater quality in vicinity of Bhalswa landfill, Delhi, India, using graphical and multivariate statistical methods. Environ Geol 53(7):1509–1528

Stallmann RW (1963) Computation of ground-water velocity from temperature data. In: Bentall R (ed) Methods of Collecting and Interpreting Ground-Water Data USGS, Washington DC, 36-46

Standard Methods for the Examination of Water and Wastewater (1995) 19th edition. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC. (www.standardmethods.org).

Stockmarr J (1998) Danish Hydrological landscape planningHow to Cope with Degrading Groundwater Quality Swedish Council for Planning and Coordination of Research, Stockholm, 57-73

Stuer-Lauridsen F, Pedersen F (1997) On the influence of the polarity index of organic matter in predicting environmental sorption of chemicals. Chemosphere, 35(4): 761-773

Stuyfzand P, Juhàsz-Holterman M, Lange W (2004) Riverbank filtration in the Netherlands: well fields, clogging and geochemical reactions. NATO Advanced Research Workshop, Samorin, Slovakia. September 7–10

Stuyfzand PJ (1989) Hydrology and water quality aspects of rhine bank groundwater in The Netherlands. Journal of Hydrology; 106: 341-363

Suarez MP, Rifai HS (1999) Biodegradation Rates for Fuel Hydrocarbons and Chlorinated Solvents in Groundwater. Bioremediation Journal; 3: 337-362

Subramanian V, Saxena KK (1983) Hydrogeochemistry of groundwater in the Delhi region of India. In: Dun-In XF, Matthess G, Gras RA (eds) Relation of Groundwater Quantity and Quality. Proceedings of the XVIIIth General Assembly of the International Union of Geodesy and Geophysics at Hamburg, Germany. Aug 1983. IAHS Publ. 146

Sukhija BS, Reddy DV, Nandakumar MV, Rama (1997). A Method for Evaluation of Atrificial Recharge Through Percolation Tanks Using Environmental Chloride. Ground water Vol. 35, No.1: 161-165

Thussu JL (2004) Origin of Salinity in Groundwater in Haryana. Journal of the Geological Society of India Vol: 64: 165-190.

Thussu JL (2006) Geology of Haryana and Delhi. Geological Society of India, Bangalore

Tripathi JK, Rajamani V (1999). Geochemistry of the loessic sediments on Delhi ridge, eastern Thar desert, Rajasthan: implications for exogenic processes. Chemical Geology 155: 265-278

Trisal C, Tabassum, T, Kumar R (2008) Water Quality of the River Yamuna in the Delhi Stretch: Key Determinants and Management Issues. Clean 2008 36(3), 306 – 314

Tufenkji N, Ryan J, Elimelech M (2002) The promise of bank filtration. Environ Sci Technol 36(21):422A-428A

Tufenkji N, Elimelech M (2003) Correlation Equation for Predicting Single-Collector Efficiency in Physicochemical Filtration in Saturated Porous Media. Environmental Science & Technology 38(2), 529-536

Tufenkji N, Redman JA, Elimelech M (2003) Interpreting Deposition Patterns of Microbial Particles in Laboratory-Scale Column Experiments. Environmental Science & Technology 37(3), 616-623.

Tufenkji N, Miller GF, Ryan JN, Harvey RW, Elimelech M (2004) Transport of Cryptosporidium Oocysts in Porous Media: Role of Straining and Physicochemical Filtration. Environmental Science & Technology 2004; 38: 5932-5938

Tufenkji N (2006) Modeling microbial transport in porous media: Traditional approaches and recent developments. Advances in Water Resources 2006; 30: 1455-1469

Tuxen N, Tüchsen PL, Rügge K, Albrechtsen H-J, Bjerg PL (2000) Fate of seven pesticides in an aerobic aquifer studied in column experiments. Chemosphere 2000; 41: 1485-1494

Tyagi NK (1988) Managing salinity through conjunctive use of water resources. Ecological Modelling 40: 11-24

Umezawa Y, Hosono T, Onodera S, Siringan F, Buapeng S, Delinom R, Yoshimizu C, Tayasu I, Nagata T, Taniguchi M (2008) Sources of nitrate and ammonium contamination in groundwater under developing Asian megacities. Sci Total Environ 404 (2-3):361-376

UNDP (2006) Beyond scarcity: Power, poverty and the global water crisis. Human Development Report 2006. United Nations Development Programme. Available via http://hdr.undp.org Accessed: 15 Sept 2008

USEPA (2001) Method 1602: Male-specific (F+) and Somatic Coliphage in Water by Single Agar Layer (SAL) Procedure, April 2001 EPA 821-R-01-029.

USEPA (2003) National primary drinking water regulations: long term 2 enhanced surface water treatment rule. Federal Register 68, 154. In: Agency USEPA

USEPA (2006) The Groundwater rule. http://www.epa.gov/safewater/disinfection/gwr/regulation.html (accessed 25.06.2009)

Valdiya KS (2002) Saraswati: The River That Disappeared. Universities Press India Ltd.: Hyderabad; 128.

van der Wielen P, Senden W, Medema GJ (2008) Removal of bacteriophages MS2 and phiX174 during transport in a sandy anoxic aquifer. Environ. Sci. Technol. 42(12), 4589-4594.

Vennema H, de Bruin E, Koopmans M (2002). Rational optimization of generic primers used for Norwalk-like virus detection by reverse transcriptase polymerase chain reaction. Journal of Clinical Virology 25 (2), 233-235.

Verstraeten I, Heberer T, Scheytt T (2003) Occurrence, Characteristics, Transport, and Fate of Pesticides, Pharmaceuticals, Industrial Products, and Personal Care Products at Riverbank Filtration Sites. In: Ray C, Melin G, Linsky R, editors. Riverbank Filtration. 43. Springer Netherlands, pp. 175-227.

Vijay R, Sargoankar A, Gupta A (2007) Hydrodynamic simulation of River Yamuna for riverbed assessment: A case study of Delhi region. Environ Monit Assess 130:381–387

Villholth KG, Sharma BR (2006) Creating synergy between groundwater research and Management in South and South East Asia. In: Sharma BR, Villholth KG, Sharma KD (eds) Proceedings of IWMI-ITP-NIH International Workshop, Roorkee, India. 8-9 February 2005. Groundwater Governance in Asia Series - 1, International Water Management Institute, Colombo, Sri Lanka

Walia A, Mehra NK (1998). A seasonal assessment of the impact of coal fly ash disposal on the river Yamuna, Delhi. Water, Air, and Soil Pollution 103: 277–314

Wang J (2003) Riverbank Filtration Case Study at Louisville, Kentucky. In: Ray C, Melin G, Linsky R, editors. Riverbank Filtration. 43. Springer Netherlands, pp. 117-145.

Weert Fv, Gun Jvd, Reckman J (2009) Global Overview of Saline Groundwater Occurrence and Genesis. International Groundwater Resources Assessment Centre, UNESCO/WMO: Utrecht; 104

Weiss WJ, Bouwer EJ, Aboytes R, LeChevallier MW, O'Melia CR, Le BT, Schwab KJ (2005) Riverbank filtration for control of microorganisms: Results from field monitoring. Water Res 39:1990–2001

Wett B, Jarosch H, Ingerle K (2002) Flood induced infiltration affecting a bank filtrate well at the River Enns, Austria. Journal of Hydrology; 266: 222-234

WHO (2006) Guidelines for drinking-water quality, 3rd ed, incorp. 1st addendum. World Health Organization, Geneva

WHO (2007) A safer future - global public health security in the 21st century. World health report

Wilby RL, Whitehead PG, Wade AJ, Butterfield D, Davis RJ, Watts G. (2006) Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. Journal of Hydrology; 330: 204-220

Wilson AM, Fenstemaker T, Sharp JM. (2003). Abnormally pressured beds as barriers to diffusive solute transport in sedimentary basins Geofluids 3: 203-212

Wyn-Jones AP, Carducci A, Cook N, D'Agostino M, Divizia M, Fleischer J, Gantzer C, Gawler A, Girones R, Höller C, Husman AM, Kay D, Kozyra I, López-Pila JM, Muscillo M, Nascimento MS, Papageorgiou G, Rutjes S, Sellwood J, Szewzyk R, Wyer M (2011). Surveillance of adenoviruses and noroviruses in European recreational waters. Water Research 45(3), 1025-1038

Yadav DN (1997). Oxygen isotope study of evaporating brines in Sambhar Lake, Rajasthan (India) Chemical Geology 138: 109-118.

Yadav S, Rajamani V (2004) Geochemistry of aerosols of northwestern part of India adjoining the Thar desertGeochimica et Cosmochimica Acta 68: 1975-1988

Yao K-M, Habibian M, O´Melia C (1971) Water and Waste Water Filtration: Concepts and Applications. Environmental Science & Technology 5(11), 1105-1112

Ying G-G, Kookana RS, Ru Y-J (2002) Occurrence and fate of hormone steroids in the environment. Environment International; 28: 545-551

Ying G-G, Toze S, Hanna J, Yu X-Y, Dillon PJ, Kookana RS (2008) Decay of endocrine-disrupting chemicals in aerobic and anoxic groundwater. Water Research; 42: 1133-1141

Zafar M, Alappat BJ (2004) Environmental mapping of water quality of the River Yamuna in Delhi with landfill locations. Manage Environ Qual 15(6):608-621

Zérah M (2006) Urban Water and Waste Water. In: Zérah MH (ed) India Infrastructure Report 2006 - urban infrastructure. Oxford University Press, New-Delhi

Ziegler D (2001) Untersuchungen zur nachhaltigen Wirkung der Uferfiltration im Wasserkreislauf Berlins. Technical University Berlin

Zheng C, Wang PP (1999) A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion and Chemical Reactions of Contaminants in Groundwater Systems, p. Documentation and User’s Guide, Vicksburg, MS

Zheng C, Bennett GD (2002) Applied Contaminant Transport Modeling, Second Edition, John Wiley & Sons, New York

Appendix 1 List of publications arising from this thesis

-Order of appearance-

Chapter 2

Lorenzen G, **Sprenger C**, Taute T, Pekdeger A, Mittal A, Massmann G (2010) Assessment of the potential for bank filtration in a water-stressed mega city (Delhi, India). Environmental Earth Sciences, Volume 61, Number 7, 1419-1434

Chapter 3

Lorenzen G, **Sprenger C**, Baudron P, Gupta D, Pekdeger A (2011) Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and Haryana, India. Hydrological Processes (submitted)

Chapter 4

Sprenger C, Lorenzen G, Pekdeger A (2011) Environmental tracer application and purification capacity at a river bank filtration well in Delhi. Journal of Indian Water Works Association (accepted March 2011)

Chapter 6

Sprenger C, Lorenzen G, Grunert A, Ronghang M, Dizer H, Selinka HC, Girones R, Lopez-Pila JM, Mittal A, Szewzyk R (2011) Removal of bacteriophages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India). Journal of Water, Sanitation and Hygiene for Development (accepted March 2011)

Chapter 7

Sprenger C, Lorenzen G, Hülshoff I, Grützmacher G, Ronghang M, Pekdeger A (2010) Vulnerability of bank filtration systems to climate change. Science of the Total Environment, Volume 409, Issue 4, 655-663

Appendix 2 List of related publications

-Chronological order-

Grützmacher G, **Sprenger C**, Lorenzen G, Rustler M, Hülshoff I, Pekdeger A (2011) Techneau: Perspectives of river bank filtration for newly industrialized and developing countries. Blue facts - International Journal of Water Management. DVGW - Ausgabe für die Messe Wasser Berlin

Lorenzen G, **Sprenger C,** Pekdeger A (2010) A Simple Method to Hide Data Loggers Safely in Observation Wells. Ground Water, no. doi: 10.1111/j.1745-6584.2010.00771.x

Lorenzen G, **Sprenger C**, Pekdeger A (2010) Investigation of Riverbank filtration potential in developing and newly industrializing countries: Lessons learnt from the Delhi case studies. TECHNEAU Integrated Project Funded by the European Commission. Available: www.techneau.org

Sprenger C, Lorenzen G, van der Linden S, Schmidt W (2010) Endocrine disruptors and algal toxins during Riverbank Filtration passage in northern India TECHNEAU Integrated Project Funded by the European Commission. Available: www.techneau.org

Gruetzmacher G, Hülshoff I, Wiese B, Moreau-le Golvan Y, **Sprenger C,** Lorenzen G, Pekdeger A (2009) Function and relevance of aquifer recharge techniques to enable sustainable water resources management in developing or newly industrialized countries. In: van den Hoven, T., Kazner, C editors: TECHNEAU: Safe Drinking Water from Source to Tap - state of the art & perspectives. IWA Publishing: London pp. 121-132.

Sprenger C, Lorenzen G, Pekdeger A (2009) Preliminary report on data of all inorganic substances and physicochemical parameters listed in the Indian and German Drinking Water Standards from surface water and groundwater at the field sites. TECHNEAU Integrated Project Funded by the European Commission. Available: www.techneau.org

Sprenger C, Lorenzen G, Pekdeger A (2008) Occurrence and fate of microbial pathogens and organic trace compounds at riverbank filtration sites in Delhi, India.TECHNEAU Integrated Project of the European Commission. Available: www.techneau.org

Kohfahl C, Sprenger C, Herrera JB, Meyer H, Chacón FF, Pekdeger A (2008) Recharge sources and hydrogeochemical evolution of groundwater in semiarid and karstic environments: A field study in the Granada Basin (Southern Spain). Applied Geochemistry 23: 846-862

Appendix 3 Tables

Table A.1 Physicochemical properties and ion concentrations of the water samples (selected parameters).

		Najafgarh Drain					Central Delhi					Palla				
		Naj. Drain	shallow	medium	deep	distal	Yamuna	shallow	medium	deep	distal	Yamuna	shallow	medium	deep	distal
Physicochemical parameters:																
EC [µS/cm]	*Feb:*	2520	3740	10520	15600	5000	1277	1527	1051	847	-	738	601	734	420	928
	May:	349	3480	12830	17300	4370	1196	1429	1274	838	-	452	406	704	398	-
	Sep:	350	4030	13370	19700	7620	724	1353	1160	791	1027	862	495	537	377	951
pH	*Feb:*	8.3	6.8	6.7	6.7	8.6	7.3	6.7	7.3	8.0	6.7	8.8	8.2	7.6	8.2	7.2
	May:	9.0	6.9	6.8	6.5	7.2	7.6	6.8	7.4	8.1	-	9.6	7.9	7.6	7.9	7.4
	Sep:	7.5	6.8	6.7	6.7	7.3	7.4	6.7	7.4	8.0	7.1	9.1	7.7	7.7	7.9	7.1
Major ions:																
Ca [mg/L]	*Feb:*	71	187	477	723	240	87	131	83	15	-	49	39	55	18	144
	May:	38.8	146	539	737	151	65	125	100	15	-	31	41	58	27	-
	Sep:	38.7	80.8	478	844	225	49.2	159	30.9	14.1	113	35.6	50.3	40	22.2	76.7
Na [mg/L]	*Feb:*	360	605	1940	3180	795	141	158	58	210	-	75	61	58	62	69
	May:	38	535	2150	3400	625	146	154	151	199	-	45	31	58	48	-
	Sep:	22	685	2575	3600	1180	80	154	122	200	102	122	34	56	41	67
Mg [mg/L]	*Feb:*	35	69	233	427	180	31	33	23	6	-	17	15	25	10	36
	May:	12.2	53	278	458	134	28	31	30	6	-	11	14	25	15	18
	Sep:	12	71.4	335	520	205	18.8	41.3	37.7	5.94	31.3	25.5	15.7	18.5	18.2	32.2
K [mg/L]	*Feb:*	30	2	18	36	15	14	12	18	2	-	8	5	4	3	6
	May:	4	2	20	40	12	16	12	16	2	-	6	6	4	3	4
	Sep:	3.3	2.7	25	42	32	9.5	13	12.3	1.6	8	9.5	7.5	3.3	2.5	6
Cl [mg/L]	*Feb:*	370	850	3200	6000	1400	185	196	157	12	-	90	58	95	10	20
	May:	47	750	3940	6700	1050	185	200	194	11	-	45	18	85	12	7
	Sep:	42	960	4700	7330	1860	110	195	178	14	117	132	44	73	19	21
HCO_3 [mg/L]	*Feb:*	702	519	342	275	702	366	699	372	531	-	223	183	220	220	488
	May:	134	513	317	244	708	366	732	519	519	-	214	159	189	217	-
	Sep:	128	537	305	214	751	214	775	543	506	531	226	201	177	195	506
SO_4 [mg/L]	*Feb:*	56	360	1200	1340	470	123	46	3	50	-	51	50	68	29	98
	May:	50	270	1300	1390	270	90	32	58	43	-	36	34	86	32	70
	Sep:	35	340	1410	1520	620	70	55	<1	50	15	110	40	61	35	110
NO_3 [mg/L]	*Feb:*	<1	<1	-	5	20	<1	<1	<1	<1	-	6	3	<1	<1	<1
	May:	<1	<1	4	3	6	<1	<1	<1	<1	-	<1	<1	3	<1	1
	Sep:	0.3	1	0.8	2.7	6	34	70	0.4	0.2	7	0.9	0.1	0.3	<1	1
Selected trace ions:																
NH_4 [mg/L]	*Feb:*	40	0.4	<0,05	-	<0,05	16	16.5	30	<0,05	-	0.1	0.05	0.45	0.1	0.6
	May:	-	-	<0,05	-	-	4	-	-	-	-	0.05	-	0.4	<0,05	0.05
	Sep:	0.2	0.01	<0,05	0.5	0.1	7	33	32	0.05	23	<0,05	0.25	0.4	0.1	0.5
F [mg/L]	*Feb:*	1.4	1	1	1	2	1.4	1	1.3	3	-	1.1	1	1.2	2.1	1.1
	May:	1.1	1.1	1	1.9	1.9	1.6	1.1	1.2	3.4	-	1.1	1	1.2	2.2	1.4
	Sep:	1.1	1	1.2	<1	2.6	1.2	1	1.5	3.6	1.4	1.2	1	1.2	2	1.2
Fe [mg/L]	*Feb:*	0.2	0.4	<0.05	0.2	0.1	0.4	30.1	3.2	0.2	-	0.3	0.2	0.3	0.2	1.3
	May:	0.2	0.2	0.1	0.2	0.3	0.5	28.9	3.5	0.6	-	0.2	0.3	0.3	0.5	0.1
	Sep:	0.4	1.2	-	-	0.1	0.7	12.1	4.0	0.5	7.9	0.2	<0.05	0.3	<0.05	0.7
Mn [mg/L]	*Feb:*	0.2	0.4	0.7	0.6	<0.01	0.5	2.4	1.6	0.1	-	<0.01	0.3	0.9	0.4	1.0
	May:	<0.01	0.4	0.8	0.3	0.1	0.5	1.8	1.3	0.1	-	<0.01	0.2	0.6	0.3	0.5
	Sep:	0.1	0.3	-	-	0.4	0.2	1.6	1.4	0.1	0.7	<0.01	0.2	0.3	0.1	0.5
As [µg/L]	*Feb:*	<1	3	<1	3	2	2	35	56	3	<1	-	<1	2	4	11
	May:	<1	<1	<1	<1	<1	2	31	46	<1	-	-	<1	<1	<1	-
	Sep:	1	1	-	-	<1	3	27	35	1	95	5	2	1	1	10

Table A.2 Groundwater samples and the results of hydrogeochemical and stable isotope analysis.

no	SITE	Type	date	Na^+	Ca^+	Mg^+	Cl^-	SO_4^{2-}	HCO_3^-	Br^-	NO_3^-	$\delta^{18}O$	δ^2H	TDS
A) Delhi Field Site														
1a	shallow I	OW	12/06	555	169	61	890	290	506	-	0.1	-1.39	-22.1	2487
1b	shallow I	OW	05/07	535	146	53	750	270	512	-	0.1	-1.21	-20.3	2281
1c	shallow I	OW	02/08	876	260	103	1350	323	-	2	3.6	-1.93	-24.62	2934
2a	medium	OW	12/06	2060	499	264	3800	1250	317	-	0.5	-3.99	-32.8	8223
2b	medium	OW	05/07	2150	539	278	3940	1300	317	8	4	-3.84	-30.6	8559
2c	medium	OW	02/08	2610	628	330	4680	1350	-	5.9	24	-3.82	-32.0	9657
3a	deep	OW	12/06	3200	680	442	6600	1450	256	-	0.5	-4.71	-38.0	12677
3b	deep	OW	05/07	3400	737	458	6700	1390	244	9	3	-4.53	-38.3	12983
3c	deep	OW	02/08	4750	867	553	9320	1500	-	8.5	2	-5.01	-38.4	17053
4a	distal	DW	12/06	800	193	185	1500	400	732	-	22	-3.15	-28.7	3862
4b	distal	DW	05/07	625	151	134	1050	270	708	-	6.00	-3.41	-31.10	2965
4c	distal	DW	02/08				1460	472	-	2.3	14	-3.07	-29.54	1974
B) Haryana groundwater sampling points														
5	Ismailpur	TW	04/08	54	69	42.5	87	8	336	0.4	37	-6.15	-48.67	648
6	Bridge 8-1	TW	04/08	284	153	61.5	524	183	-	1.6	2	-	-	1223
7	Bamlad	TW	04/08	5430	893	1335	10500	4270	232	21	15	-4.99	-45.66	22703
8	Budhera	TW	04/08	27	35	24	6	5	214	0.2	21	-5.85	-52.69	346
9	Center	HP	04/08	148	62	43	45	17	702	0.3	1	-4.25	-39.64	1032
10	DAD FW	TW	04/08	429	78	67	370	270	506	1.6	67	-4.93	-37.36	1802
11	Daria	TW	04/08	1230	168	356	2080	1160	403	5	45	-4.88	-35.69	5466
12	HP Drain	HP	04/08	232	78	91	470	103	482	1.4	0.7	-5.76	-43.81	1467
13	Kurk	TW	04/08	763	394	374	2600	760	349	6	71	-4.01	-36.72	5359
14	LAG-DE	TW	04/08	687	341	227	1800	380	354	4	17	-3.12	-30.4	3824
15	Mubarik	HP	04/08	207	169	158	580	136	358	2.8	150	-5.38	-40.64	1811
16	Munur	TW	04/08	147	32	52	90	36	488	0.5	23	-4.86	-41.06	888
17	Pelpa	HP	04/08	683	100	156	1000	278	775	3.7	72	-5.56	-46.91	3084
18	Sondhi	TW	04/08	1217	262	392	3100	608	738	12	91	-5.48	-36.84	6070
19	Sultanpur1	TW	04/08	151	66	55	270	31	329	0.6	60	-5.97	-46.47	978
20	Sultanpur2	HP	04/08	310	33	35	98	192	592	0.4	50	-5.64	-42.32	1322
21	Weir-FW	TW	04/08	358	196	164	1280	110	336	3	6	-5.27	-38.84	2464
22	Weir-HP	HP	04/08	224	59	55	275	34	513	0.7	20	-5.50	-45.19	1192
23	Workers	TW	04/08	315	26	44	205	186	-	0.6	0.1	-	-	795
24	Dadri	HP	04/08	253	67	55	320	193	342	2	35	-	-	1280
C) Additional sample:														
25	Tiki Kalan	TW	04/08	1920	845	733	5550	2000	244	6	9	-5.55	-43.3	11338

Units: concentrations in ppm; stable isotope ratios in ‰ (vs. V-SMOW)

Sample type: OW = observation well, TW = private tube well (motor pump), HP = hand pump, DW = traditional open dug well

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.