# Riverbank filtration in Delhi, India:
# Insights from hydrogeological field investigations and perspectives for a water-stressed megacity

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# Preface

The present study was conducted at Freie Universität Berlin (FUB) within the framework of TECHNEAU, an integrated project funded by the European Commission. Bank filtration (BF) studies in Delhi, India, were part of the work package 5.2 under the coordination of the Kompetenzzentrum Wasser Berlin (KWB) and co-funded by Veolia Water (period: 2006–2010). The project reports have been published as deliverables D5.2.x on the project website (www. TECHNEAU.org). Preliminary investigations and project preparation were carried out in 2005–2006 in cooperation with KWB and FUB as part of the feasibility study IDB-India (International development of bank filtration: Case study India), with the financial support of Veolia Water.

All scientific and management activities at FUB were supervised by Prof. Dr. A. Pekdeger and Prof. Dr. M. Schneider. The planning and organisation of all activities was supported by KWB. Field work and sampling was to some extent supported by the Indian Institute of Technology Delhi. Project preparation, setup of field sites, organisation of field work, and scientific experiments were initially supported by Dr. T. Taute. Microbiological sampling and analysis were carried out under the guidance of Prof. Dr. Lopez Pila and A. Grunert (Umweltbundesamt Berlin) and consultancy for the interpretation of GC–MS scans was given by M Ricking (FUB). Laboratory analyses were carried out by scientists, technicians, and students of the following institutions:

- Faculty of Geosciences, FUB: Analysis of sediment samples, inorganic ions, stable isotopes, and organic pollutants.
- Department of Microbiology of the University of Barcelona: Analysis of enteric viruses.
- Environmental Engineering Laboratory of the Indian Institute of Technology, Delhi: Analysis of bacteriophages and bacteria.

The main chapters of this thesis have been published or submitted for publication in different research papers, to which I contributed either as the first author or as a co-author. The papers include results from the field investigations conducted in Delhi as well as reviews on the water stress in the metropolitan area, the hydrogeological and environmental conditions in the study region, groundwater salinity, surface water–groundwater interaction, bank filtration systems, and climate change. The setup of the field sites, organisation and performance of field work, and data management and analysis were carried out in equal measures by C. Sprenger and me. Other co-authors have mainly played an advisory and supervisory role.

My contribution as the first author or a co-author in the individual papers can be summarised as follows:

***Chapter 2: A simple method to hide data loggers safely in observation wells***

It was my idea to conceal the data loggers as described in the paper, and I assembled all tools and equipment and tested the setup. The method was successfully applied by C. Sprenger and me at the field sites in Delhi, and the data were used by both of us for different applications, as mentioned in the paper. The description of the method and exemplary datasets, including the design of the figures and writing of the manuscript, was my responsibility.

***Chapter 3: Assessment of the potential for bank filtration in a water-stressed megacity (Delhi, India)***

As the first author, I had the idea for the paper and was responsible for the composition of the scientific content, the configuration of the individual parts, and the development of the manuscript. Literature review, interpretation of the data, preparation of figures and tables, and manuscript writing were done by me. All work was carried out in consultation and with an interchange of ideas with C. Sprenger, especially the section about iron and arsenic. The development and editing of the manuscript was supported by Dr. G. Massmann.

***Chapter 4: Removal of coliphages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India)***

With respect to the pathogens, I was involved in the setup of field sites and preparation of sampling campaigns. My main contribution to this paper was related to the analysis of organic compounds. The organisation and performance of the sampling campaign in Delhi was done by me. After the GC–MS analysis at FUB laboratories, I was responsible for the interpretation of the raw data with the HP Chemstation Data Analyzer software, as well as the literature review, preparation of the figures, and description of the corresponding sections in the manuscript. I further assisted in the development of the groundwater model and the research paper, including reviews and discussions on the configuration and presentation of the results.

***Chapter 5: Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and adjacent territories of Haryana State, India***

It was my idea to further investigate groundwater salinity and publish the results. I was responsible for the composition of scientific content and the development of the manuscript.

Literature review, interpretation of the data, preparation of figures and tables, and manuscript writing were done by me. All work was carried out in consultation and with an interchange of ideas with C. Sprenger. The paper includes data from the master thesis of co-author P. Baudron, who carried out parts of the sampling in the Haryana area under the guidance of C. Sprenger and me.

***Chapter 6: Vulnerability of bank filtration systems to climate change***

My commitment to this article was mainly limited to the discussion of the manuscript configuration and presentation of results with the first author as well as reviewing the draft versions of the paper. Furthermore, I provided some ideas and text modules for the organic compounds section.

# Abstract

Under favourable site conditions, bank filtration (BF) is a cost-effective and robust method for managed aquifer recharge and (pre-)treatment of surface water. In many European cities, BF systems have been used for drinking water production for more than a century and are today an essential component for integrated water resources management. In developing and newly industrializing countries, BF has significant potential for development. This study analyses the potential for BF in the water-stressed metropolitan area of Delhi.

Delhi lies on the river Yamuna, in the semiarid alluvial plains of the Himalayan foreland. In the plains, agriculture is very productive but relies on extensive canal and groundwater irrigation. In Delhi, the water demand is rising continuously along with population growth and industrialisation. Yet, the supply infrastructure of the megacity is deficient, and local water resources are highly stressed from overexploitation and contamination. The only perennial river in the region, the Yamuna, gets severely polluted in Delhi, by urban runoff and often untreated wastewater. Groundwater quality does not fit drinking water standards in large parts of the territory, and salinity ingress is a major concern. As a consequence of the uncontrolled exploitation of the aquifers, an alarming decline in groundwater levels is observed.

In the Indian National Capital Territory of Delhi, three field sites have been selected and equipped with observation wells. The sites cover a broad variety of environmental conditions: The Palla field site is situated on the western banks of the Yamuna, upstream of the urban parts of Delhi. The river water quality is still relatively good, and the municipal water supplier is operating a large well field on a broad fluvial terrace. A second lies on the Yamuna floodplain in central Delhi (at the Nizamuddin Bridge), where the river is highly polluted from urban effluents. The third site is located in the rural western part of Delhi at the Najafgarh Drain. In the canalised stream, considerable flow is mainly restricted to the monsoon season, and ambient groundwater is mostly brackish.

For the analysis of hydrogeological conditions and processes in the riverbank aquifers, regular sampling campaigns were carried out, and water levels and temperatures were measured manually and monitored with data loggers. To minimise the urgent risk of losing loggers and data through vandalism or theft at the remote sites, a simple yet effective method was invented to conceal the instruments inside the observation wells.

Hydraulic gradients, temperature profiles, and time series were used for surveying the actual flow pattern in the surface water–groundwater interaction zone. The results show that BF takes place at both sites at the Yamuna: at the Palla well field, groundwater abstraction induces a rapid and deep infiltration of river water, and at Nizamuddin Bridge, seepage from the Yamuna recharges the overexploited urban aquifer. At the Najafgarh Drain site, in contrast, gaining river conditions prevail most of the year, and BF takes place only in the dry season when the ambient groundwater level is lowered considerably.

Water samples were analysed for quality parameters as well as for tracer and indicator substances. Concentrations of undesired substances were assessed; potential sources and attenuation processes were identified; and relevant processes were discussed.

The investigation of inorganic ions and physico-chemical parameters revealed both positive and negative effects of BF on source water quality: undesired substances in groundwater often originate from natural sources, for instance, arsenic, fluorite, or dissolved salts. Anthropogenic pollutants are another major concern at the sites, especially nitrogen compounds from agriculture or sewage. Nitrate can naturally be attenuated by denitrification in the aquifer, whereas ammonium from the seepage of highly polluted anoxic river water remains largely persistent. An important process during BF is the oxidation of organic matter and formation of carbon dioxide by the consumption of oxygen and subsequently the reduction of other redox partners. The reductive dissolution of iron/manganese-(hydr)oxides leads to the mobilisation of associated arsenic in central Delhi. The formation of carbon dioxide in the riverbank aquifer, along with pH decrease, also enables the dissolution of calcite and thereby may trigger the precipitation of fluorite. These results make clear, that problems associated with undesired inorganic substances at BF facilities largely depend on site-specific conditions.

Investigations of further quality parameters, namely of organic compounds and human pathogenic microorganisms are focused on the Central Delhi field site. A high pollution load of the Yamuna gives the opportunity to investigate BF with unique data from virtually a worst case scenario. Human pathogenic viruses and bacteriophages were detected in surface water, in high concentrations, indicating large shares of untreated sewage. After only 3.8 m of underground passage a 5 $\log_{10}$ removal of coliphages was detected, and at a distance of 50 m (~120 days of subsurface passage), viruses and phages were not detectable in the bank filtrate. The transport and removal of bacteriophages were simulated with a numerical groundwater model. The high attenuation rates confirm that BF is a robust barrier for pathogenic germs, even under such extreme conditions. Organic substances were analysed in a non-target GC–MS screening in the river water and the bank filtrate in order to identify critical substances and compare the pollutant load in a semi-quantitative approach. A large number of contaminants from household, industrial, and agricultural sources were identified in the Yamuna water. After a travel distance of about 50 m, polar to non-polar bulk organic compounds were either completely removed or largely attenuated. Hence, attenuation through BF worked effectively on site, even under completely anoxic conditions along the entire flow path.

Groundwater salinity in the region was further investigated because it was identified as a potential risk for BF sites in Delhi. Field investigations were carried out along the Najafgarh Drain in Delhi and the neighbouring Haryana State. The interpretation of the field and laboratory data was based on comprehensive reviews on possible drivers of salinity ingress in shallow inland aquifers and on environmental conditions in the study region. Groundwater salinity mapping revealed that the drain partly acts as a hydraulic barrier. Multi-level monitoring and temperature logging indicated density stratification and local upconing of saline waters at Najafgarh Drain field site. Stable isotope ($\delta^2H$, $\delta^{18}O$) investigations show that groundwater is generally influenced by evaporation, which is sometimes linked to the irrigation return flow with increased nitrate-content. However, most saline waters were found in relatively deep aquifer sections. In the corresponding samples, limited enrichment in the heavy isotopes and carbon dioxide excess suggested that the high mineralization is a result of the dissolution of salts at this depth. Overall, it was concluded that the natural conditions, especially warm and dry climate, and water influx into a poorly drained basin with shallow groundwater table favoured the accumulation of salts in soil and groundwater. Human-induced changes in environmental conditions, especially the implementation of traditional canal and modern groundwater irrigation, augmented evapotranspiration and led to waterlogging in large areas. In addition, groundwater level fluctuations and perturbation of the natural hydraulic equilibrium favoured the mobilisation of salts from salt stores in the unsaturated zone and relatively deep aquifer sections.

Apart from regional development, global environmental changes may have a significant impact on local water resources and supply systems. The vulnerability of BF facilities to climate change is therefore assessed by a universal review, considering both quantitative and qualitative aspects. Sensitive factors affecting the BF performance are listed, and their relevance is discussed for hypothetical ‘drought’ and ‘flood’ scenarios. Droughts are found to promote anaerobic conditions during BF passage, while flood events can drastically shorten the travel time and enhance the risk of the breakthrough of pathogens, metals, suspended solids, dissolved organic carbon, and organic micro-pollutants. It is concluded that BF systems are climate sensitive. However, the mixing of water from different sources, relatively large residence times, and multiple barriers make them relatively robust systems in terms of contaminant removal.

In the outlook, future perspectives for BF in Delhi are considered, taking into account the development options of the water sector in the metropolitan area. At the Palla site, further optimisation of the well field should be a priority, and critical parameters, especially salinity, should be monitored thoroughly. In central Delhi, BF wells would not deliver potable water under present conditions, so extensive post treatment would be mandatory. However, if current efforts to improve the water quality of River Yamuna are effective, BF could be an attractive future option for drinking water production and reclamation in a semi-closed urban water cycle. At the Najafgarh Drain, groundwater salinity and limited surface water availability do not permit drinking water production with conventional BF schemes. Yet, BF could be incorporated in an integrated management approach for water resources as a potential tool for the banking of flood water, dilution of brackish groundwater for desalination, and the reclamation of treated wastewater in a semi-closed cycle.

# Zusammenfassung

Uferfiltration gilt bei günstigen Standortbedingungen als kostengünstige und robuste Methode zur gesteuerten Grundwasseranreicherung (Managed Aquifer Recharge) und (Vor-)Aufbereitung von Oberflächenwasser. In vielen europäischen Städten werden Uferfiltrationsanlagen seit mehr als einem Jahrhundert zur Trinkwasserproduktion verwendet und stellen heute eine wesentliche Komponente im integrierten Wasserressourcenmanagement dar. In Entwicklungs- und Schwellenländern besteht ein erhebliches Entwicklungspotential für Uferfiltration. In dieser Arbeit wird das Potential für Uferfiltration im wasserwirtschaftlich beanspruchten Metropolenraum Delhi analysiert.

Delhi liegt am Fluss Yamuna, in den semiariden alluvialen Ebenen des Himalayavorlandes. Die landwirtschaftliche Produktivität in den Ebenen ist sehr hoch, beruht aber auf einer extensiven Bewässerung aus Kanälen und Grundwasser. In Delhi steigt der Wasserbedarf mit Bevölkerungswachstum und Industrialisierung kontinuierlich an. Die Infrastruktur der Wasserversorgung ist jedoch unzulänglich, und die lokalen Wasserressourcen sind durch Raubbau und Kontamination überbeansprucht. Der Yamuna - der einzige perennierende Fluss in der Region – wird in Delhi durch die Einleitung urbaner Abflüsse und oft unbehandelten Abwassers schwer verunreinigt. Die Grundwasserqualität entspricht in großen Teilen Delhis nicht den Trinkwasserrichtlinien, und Grundwasserversalzung stellt eine erhebliche Herausforderung dar. In Folge der unregulierten Ausbeutung der Grundwasserleiter wird eine alarmierende Absenkung der Grundwasserstände beobachtet.

Innerhalb des Unionsterritoriums Delhi wurden drei Feldstandorte errichtet und mit Grundwassermessstellen ausgestattet. Die Lokationen decken ein breites Spektrum an Umweltbedingungen ab: Der Standort Palla liegt stromaufwärts von Delhi, am westlichen Ufer des Yamuna. Die Flusswasserqualität ist hier noch relativ gut und der städtische Wasserversorger betreibt ein großes Brunnenfeld auf einer breiten Flussterrasse. Ein zweiter Standort wurde auf der Überflutungsebene des Yamuna im Zentrum von Delhi (an der Nizamuddin Brücke) aufgebaut, wo der Fluss von urbanem Abwasser hochgradig verunreinigt ist. Der dritte Standort befindet sich im ländlich geprägten westlichen Teil von Delhi, am Najafgarh Drain. In dem kanalisierten Wasserlauf ist nennenswerter Durchfluss fast ausschließlich auf die Monsunzeit beschränkt und das umgebende Grundwasser ist meist brackig.

Zur Analyse der hydrogeologischen Rahmenbedingungen und Prozesse in den ufernahen Grundwasserleitern, wurden regelmäßige Probenahmekampagnen durchgeführt und

Wasserstände und Temperaturen wurden manuell sowie mit Datenloggern beobachtet. Um an den abgelegenen Standorten ein akutes Verlustrisiko von Loggern und Daten durch Diebstahl oder Vandalismus zu minimieren, wurde eine einfache aber effektive Methode entwickelt, mit der die Instrumente innerhalb der Grundwassermessstellen verborgen werden.

Hydraulische Gradienten, Temperaturprofile und -zeitreihen wurden verwendet, um das gegenwärtige Fließregime im Wechselwirkungsbereich Oberflächenwasser-Grundwasser zu erkunden. Die Ergebnisse zeigen, dass Uferfiltration an den beiden Lokationen am Yamuna stattfindet: Am Brunnenfeld in Palla bewirkt die Grundwasserentnahme eine rasche, tiefreichende Infiltration von Flusswasser und an der Nizamuddin Brücke wird der überbeanspruchte urbane Grundwasserleiter von versickerndem Oberflächenwasserwasser angereichert. Im Gegensatz dazu wird das Najafgarh Drain am Standort den größten Teil des Jahres vom Grundwasser gespeist. Uferfiltration findet nur in der Trockenzeit statt, wenn die Grundwasserstände in der Umgebung deutlich tiefer liegen.

Die Wasserproben wurden auf qualitative Parameter, aber auch auf Tracer- und Indikatorsubstanzen analysiert. Die Konzentrationen von unerwünschten Stoffen wurden bewertet und mögliche Quellen sowie Abbau- und Rückhalteprozesse wurden erkannt und diskutiert.

Bei der Untersuchung der anorganischen Stoffe und physiko-chemischen Parameter wurden sowohl positive als auch negative Einflüsse der Uferfiltration auf die Rohwasserqualität aufgezeigt: Im Grundwasser unerwünschte Gehalte an anorganischen Substanzen, wie zum Beispiel Arsen, Fluorid oder gelösten Salzen, stammen oft aus natürlichen Quellen. Außerdem sind anthropogene Belastungen an den Standorten problematisch, insbesondere Stickstoffverbindungen aus der Landwirtschaft oder aus Abwässern. Während Nitrat im Grundwasserleiter durch Denitrifikation natürlich abgebaut werden kann, bleibt mit hoch belastetem, anoxischem Flusswasser infiltrierendes Ammonium weitgehend persistent. Ein wichtiger Prozess bei der Uferfiltration ist die Oxidation von organischer Substanz unter Sauerstoffzehrung und anschließender Reduzierung weiterer Redoxpartner. Die reduktive Lösung von Eisen/Mangan-(Hydr-)Oxiden führt zur Mobilisierung von gebundenem Arsen im Zentrum von Delhi. Die Bildung von Kohlendioxid im ufernahen Grundwasserleiter mit pH-Wert-Senkung ermöglicht außerdem die Lösung von Kalk und kann damit die Ausfällung von Fluorit bewirken. Die Ergebnisse zeigen, dass Probleme mit unerwünschten anorganischen Substanzen an Uferfiltrationsanlagen vor allem von standortspezifischen Bedingungen abhängen.

Die Untersuchung weiterer qualitativer Parameter, der organischen Verbindungen und humanpathogenen Mikroorganismen, ist auf den Standort im Zentrum Delhis fokussiert. Durch die hohe Belastung des Flusswassers kann Uferfiltration hier mit einzigartigen Daten unter extrem ungünstigen Rahmenbedingungen (nahezu Worst-Case-Szenario) untersucht werden. Humanpathogene Viren und Bakteriophagen wurden im Flusswasser mit hohen Konzentrationen nachgewiesen, die auf einen großen Anteil an unaufbereitetem Abwasser hinweisen. Nach nur 3,8m Fließweg wurde ein Rückhalt von $5\log_{10}$ bei den Coliphagen festgestellt und nach 50m (~120 Tage Untergrundpassage) waren Viren und Phagen im Uferfiltrat nicht mehr nachweisbar. Transport und Rückhalt der Phagen wurde in einem numerischen Grundwassermodell simuliert. Die hohe Reinigungsleistung bestätigt, dass Uferfiltration auch unter den extremen Bedingungen eine effektive Barriere für pathogene Keime darstellt. Organische Substanzen in Flusswasser und Uferfiltrat wurden mit einem „nicht gezielten“ (non target) GC-MS Screening analysiert, um kritische Substanzen zu erkennen und den Belastungsgrad in einem semiquantitativen Ansatz zu vergleichen. Im Yamunawasser wurde eine große Anzahl von Kontaminanten aus Haushalten, Industrie und Landwirtschaft identifiziert. Nach etwa 50m Fließweg, war der Großteil der polaren bis apolaren organischen Stoffe nicht mehr oder kaum noch nachweisbar. Rückhalt und Abbau durch Uferfiltration funktioniert am Standort also effektiv, selbst unter vollständig anoxischen Bedingungen entlang des gesamten Fließweges.

Grundwasserversalzung in der Untersuchungsregion wurde näher untersucht, weil sie als mögliches Risiko für Uferfiltrationsstandorte erkannt wurde. Felduntersuchungen wurden entlang des Najafgarh Drains in Delhi und im Nachbarstaat Haryana durchgeführt. Die Interpretation der Gelände- und Labordaten beruht auf umfassenden Literaturstudien zu möglichen Ursachen der Binnenversalzung in flachen Grundwasserleitern und Umweltbedingungen in der Untersuchungsregion. Eine Kartierung der Grundwasserversalzung verdeutlicht, dass das Drain teilweise als hydraulische Barriere wirkt. Teufenorientiertes Monitoring und Temperaturlogs zeigten Dichteschichtung und lokalen Salzaufstieg am Feldstandort Najafgarh Drain an. Untersuchungen der stabilen Isotopen ($\delta^2H$, $\delta^{18}O$) zeigen, dass das Grundwasser generell von Verdunstung beeinflusst ist, die teilweise im Zusammenhang mit der Infiltration von nitratreichen Bewässerungslösungen steht. Die Wässer mit den höchsten Salzgehalten wurden jedoch in tieferen Grundwasserleiterabschnitten angetroffen. In den entsprechenden Proben deuteten eine begrenzte Anreicherung an schweren Isotopen sowie Kohlendioxidüberschuss darauf hin, dass die Mineralisation aus der Lösung von Salzen in der Tiefe hervorgeht. Die Ergebnisse führten letztlich zu der Schlussfolgerung, dass die natürlichen Bedingungen - insbesondere warmes und trockenes Klima und Wasserzufluss in eine schlecht entwässerte Senke mit geringem Grundwasserflurabstand - zur Anreicherung von Salz in Boden und Grundwasser führten. Anthropogen verursachte Änderungen der Umweltbedingungen, vor allem die Einführung der traditionellen Kanal- und der modernen Grundwasserbewässerung haben zu einer Erhöhung der Evapotranspiration und der Ausbildung von Staunässe in weiten Gebieten beigetragen. Außerdem fördern Grundwasserstandsschwankungen und die Störung des natürlichen hydraulischen Gleichgewichts die Mobilisierung von Salzen aus Reservoiren aus der ungesättigten Zone und aus tieferen Grundwasserleiterabschnitten.

Nicht nur regionale Entwicklungen, sondern auch können Änderungen der globalen Umweltbedingungen können einen erheblichen Einfluss auf lokale Wasserressourcen und die Wasserversorgungssysteme haben. Die Vulnerabilität von Uferfiltrationsanlagen im Bezug auf den Klimawandel wurde daher ausgehend von einer umfassenden Literaturstudie bewertet. Berücksichtigt wurden sowohl qualitative als auch quantitative Aspekte. Sensible Faktoren, welche die Leistung von Uferfiltration beeinflussen können, wurden aufgeführt und ihre Relevanz für die hypothetischen Szenarien „Hochwasser“ (flood) und „Trockenheit“ (drought) diskutiert. In Trockenperioden stellen sich bei der Uferfiltration eher anoxische Bedingungen ein, während Hochwasserereignisse die Fließzeiten drastisch verkürzen können und damit das Risiko eines Durchbruchs von Pathogenen, Metallen, gelösten Feststoffen, gelöstem organischem Kohlenstoff und organischen Mikroschadstoffen erhöhen. Schlussfolgernd wurde festgestellt, dass Uferfiltrationssysteme klimasensitiv sind. Durch die Mischung von Wässern aus verschiedenen Quellen, relativ lange Aufenthaltszeiten und mehrfache Barrieren stellen sie aber im Bezug auf den Rückhalt von Schadstoffen relativ robuste Systeme dar.

Im Ausblick werden Zukunftsperspektiven für Uferfiltration in Delhi aufgeführt, wobei Entwicklungsmöglichkeiten im Metropolenraum berücksichtigt werden. Am Standort Palla sollte die Priorität auf der Optimierung des Brunnenfeldes liegen und kritische Parameter, insbesondere Salinität, sollten sorgfältig beobachtet werden. Am Standort Nizamuddin würden Uferfiltrationsbrunnen unter den gegenwärtigen Bedingungen kein Trinkwasser fördern, daher wäre eine erhebliche Nachbereitung notwendig. Wenn allerdings die aktuellen Bemühungen zur Verbesserung der Wasserqualität des Yamuna Erfolg zeigen, könnte Uferfiltration eine attraktive Zukunftsoption zur Trinkwasserproduktion und -wiedergewinnung in einem halbgeschlossenen städtischen Kreislauf sein. Am Najafgarh

Drain ist wegen der Grundwasserversalzung und der eingeschränkten Oberflächenwasserverfügbarkeit eine Trinkwassergewinnung mit konventionellen Uferfiltrationssystemen nicht möglich. Uferfiltration könnte aber in einem Ansatz zum integrierten Wasserressourcenmanagement eingebunden werden und als mögliches Instrument zum Rückhalt von Monsunwasser, zur Verdünnung von brackigem Grundwasser für anschließende Entsalzung, sowie zur Rückgewinnung von aufbereitetem Abwasser in einem halbgeschlossenen Kreislauf dienen.

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# 1 Introduction

## 1.1 Managed aquifer recharge by bank filtration

On a global scale, around 98% of the fresh liquid water is stored as groundwater (BOUWER 2000). It is naturally formed by direct recharge when excessive rainfall (total precipitation minus surface runoff and evapotranspiration) percolates through the vadose zone down to an aquifer (BOUWER 2000). Indirect recharge occurs, when surface water infiltrates into an aquifer, through the bed of a river or lake (DE VRIES & SIMMERS 2002). Groundwater recharge can also be human induced either in a managed way (e.g. by contour ploughing and building of bunds, dams, ponds, diversion channels, and recharge wells), or incidental (e.g. as a consequence of irrigation, waste water disposal, or leaky pipes) (DILLON 2002).

Subterranean water resources have always played an important role for human water supply and development. For many millennia, groundwater use was limited by the delivery of natural springs and the capacity of primitive wells, and the exploitation was tiny compared to the availability of the resource (FOSTER & CHILTON 2003). During the 20th century, advances in geological knowledge and well construction, as well as the introduction of motorised pumps, have enabled a heavy exploitation of the aquifers worldwide (FOSTER & CHILTON 2003, VILLOTH & SHARMA 2006). Today, nearly half of the world's population directly depends on groundwater resources for drinking water supply and for other uses (OKI & KANAE 2006). While in some regions, groundwater supply systems can be regarded as largely sustainable, in other regions, a mismanagement of the resources leads to groundwater depletion and water scarcity (UNDP 2006).

Managed aquifer recharge (MAR) can be an option to maximise the available subsurface water resources and benefit from the storage and purification potential of natural soil/rock. When groundwater demand exceeds natural recharge, MAR techniques can help to equalise the water balance and progress towards sustainability. They can also be a tool in an integrated water resources management approach and help to reduce costs and increase the security and quality of water supply systems (DILLON 2002).

Bank filtration (BF; percolation of surface water to the groundwater table), which can be a natural process under loosing river conditions, is considered an MAR technique when it is human induced. Therefore, an abstraction well is placed in the vicinity of a river or lake with the intention of lowering the groundwater table locally and thereby increasing surface water seepage into the aquifer (RAY 2008). During infiltration, a series of attenuation processes takes place in the river/lake bed sediments and aquifer rock, as shown in Figure 1.1 and further specified in **Chapter 3**. BF wells extract a mixture of ambient groundwater and infiltrated surface water (bank filtrate) that is relatively consistent in quality and is often easy to treat to higher levels of finished quality (TUFENKJI *ET AL.* 2002).

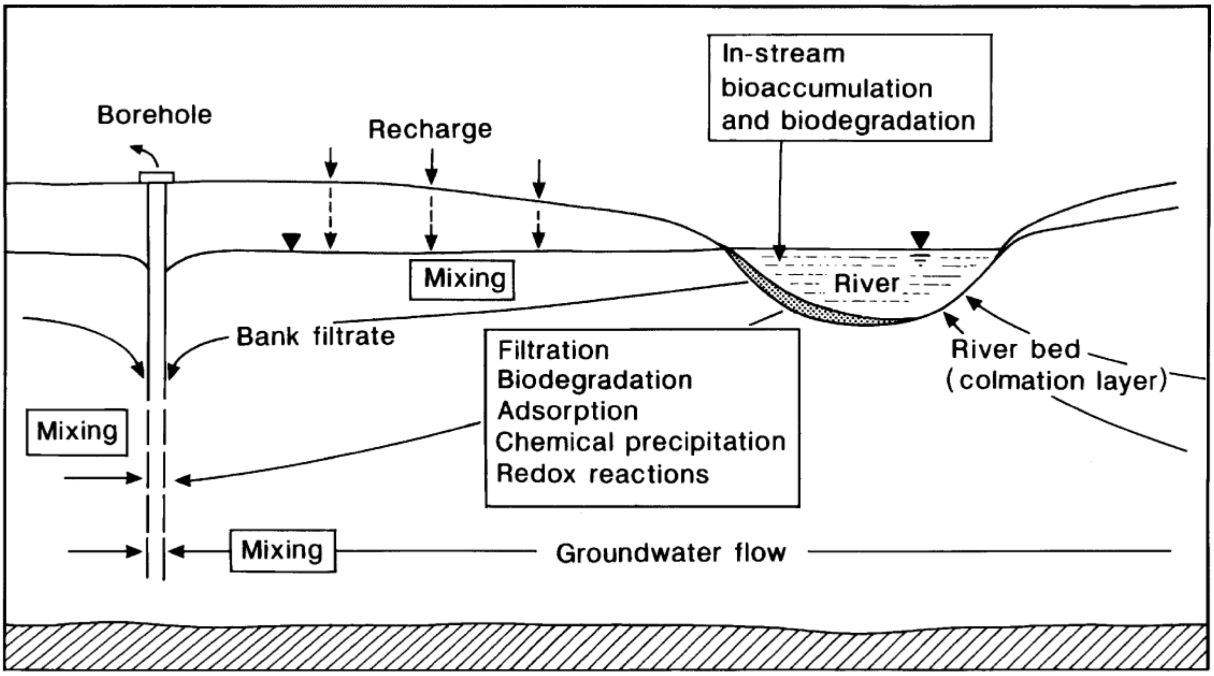


**Figure 1.1 Schematic diagram of a bank filtration system and processes affecting water quality. (HISCOCK & GRISCHEK 2001)**

BF is appreciated as an effective and relatively inexpensive means for (pre-)treatment of surface water in many cities in Europe and has a long tradition (DURHAM *ET AL.* 2002, TUFENKJI *ET AL.* 2002). It has been used for drinking water production in communities along the rivers Rhine, Elbe, Danube, and Seine for more than a century (RAY 2008). Bank filtrate provides around 50% of potable supplies in the Slovak Republic, 45% in Hungary, 16% in Germany, and 5% in the Netherlands (HISCOCK & GRISCHEK 2002). In the city of Düsseldorf, for example, water from the river Rhine has been systematically treated by BF since 1870 (SCHUBERT 2002). The water supply for the city of Berlin, with about 3.4 Mio. inhabitants, is more than 90% covered from underground resources of the capital's own territory (892 $km^2$). This is only possible in a semi-closed water cycle, with high shares of bank filtrate (~60%) and seepage from artificial recharge ponds (~10%), supplementing natural recharge (~30%) (MÖLLER & BURGSCHWEIGER 2008).

## 1.2 International development of bank filtration

Historical examples show that the benefits of BF for the supply of safe water have been recognised in different parts of the world since the ancient times. For instance, when the water of the river Nile was contaminated by an algae bloom in ancient Egypt, the Egyptians dug wells around the river and abstracted bank-filtrated drinking water that was free of the toxins (‘*The Bible: Exodus 7:2*’, as referred to in DEININGER *ET AL.* 2002).

In Delhi, attempts to establish riverbank filtration (RBF) for water supply have been documented since the $19^{th}$ century (MANN 2007): In 1869, a British engineer suggested to avoid the polluted surface water from the Yamuna River for drinking water supply and instead abstract water from ‘wells sunk in the sandy bed of the river, where a clear, cool, undercurrent of very pure water is to be found at all seasons of the year’ (Report on the Sanitary Administration of Punjab 1869, as cited in MANN 2007). After initial tests, BF wells were built and regular pumping started in 1892, but the water supply was deficient as a consequence of well clogging with sand and silt and the executive engineer of the Delhi Water Works refused to take over the system (MANN 2007).

Today, BF is common in Europe but far less developed in other continents, although the worldwide potential of BF is significant (RAY 2008, SANDHU 2011, RAY & SHAMRUK 2011). One reason for this situation is the fact that the sustainable water treatment capacity of natural aquifers is often under-estimated (DILLON 2005). In North America, however, many utilities are interested in using BF to improve raw water quality and reduce the costs of in-plant conventional treatment (TUFENKJI *ET AL.* 2002). According to recent estimates, BF could potentially supply water to 120 million people in the US alone (RAY 2008). Information about the use of BF and experiences from developing and newly industrializing countries is scarce, but it has to be considered that many facilities are extracting water from alluvial aquifers without referring to the bank filtrate (GRÜTZMACHER *ET AL.* 2009). SANDHU (2011) has identified a number of Indian cities that are already using BF for the water supply (and in most of them, no significant additional treatment is provided), but there still is a great potential (SANDHU 2011).

More of this worldwide potential could be exploited by fostering the international development of BF for a more responsible water resources management (DILLON 2005, RAY 2008). Water scarcity is increasing worldwide, and overcoming the crisis in water and sanitation is considered one of the great human development challenges of the early 21st century (UNDP 2006). In many communities, particularly in semiarid and arid zones, the use of groundwater has gained fundamental importance for urban, industrial, and agricultural water requirements (DE VRIES & SIMMERS 2002). Groundwater abstraction often exceeds natural recharge (FOSTER & CHILTON 2003). The depletion of groundwater resources not only increases water scarcity, endangers human development, and leads to water conflicts, but it also transfers the costs to the environment and to future generations (UNDP 2006). Integrated management principles for surface water and groundwater resources are the best solution for developing sustainable systems and prevent catastrophes (BOUWER 2000, DURHAM *ET AL.* 2002). BF, as an efficient low-cost and low-tech method, is considered to be very attractive for countries with limited socioeconomic resources (DURHAM *ET AL.* 2003, RAY 2008, GRÜTZMACHER *ET AL.* 2009, LORENZEN *ET AL.* 2010a, SANDHU *ET AL.* 2011 RAY & SHAMRUK 2011). It relies on water storage and treatment in a natural aquifer and is generally robust with respect to the removal of human pathogens, a dominant concern to human health (DILLON *ET AL.* 2006).

Over the last decade, the scientific community, policy makers, water suppliers, and development organisations have shown a growing interest to investigate and establish artificial recharge methods, including BF in developing and newly industrialised countries (e.g. DILLON 2002/2005B, UNDP 2006, VILLOUTH & SHARMA 2006, RAY 2008, HUELSHOFF *ET AL.* 2009, SANDHU 2011). For the development of a BF site, it is recommended to evaluate the feasibility of the site by carrying out preliminary investigations and consider environmental conditions as well as logistical and economical aspects (LORENZEN *ET AL.* 2010a). Hydrological and hydrogeological variables and controls must be investigated in detail so field tests are irreplaceable and should be accompanied with laboratory investigations and model calculations (LÁSZLÓ & LITERATHY 2002, HOEHN 2002, RAY 2011). The surface water (river, canal, or lake) must have enough discharge or storage, and the bottom sediment must be sufficiently permeable to allow the desired infiltration rates (LORENZEN *ET AL.* 2010a). The quantity of infiltration water must be of a certain magnitude to justify the cost and efforts for the installation, operation, and maintenance of the BF facilities. On the other hand, the seepage losses should not endanger the ecosystem stability or provoke conflicts with other stakeholders (LORENZEN *ET AL.* 2010a).

The metropolitan area of Delhi is today a prominent example for water scarcity (UNDP 2006). The water demand is rising along with industrialisation, rapid population growth, and increasing wealth, while the surface and groundwater resources are getting degraded dramatically in terms of quality and quantity (CGWB 2006, ZÉRAH 2006, CSE 2007). There may be options for the development of BF because from a hydraulic point of view, the minimum requirements are given, namely a river that provides considerable recharge potential and a hydraulically connected aquifer (HUNT *ET AL.* 2002, LORENZEN *ET AL.* 2010a). For a feasibility analysis, however, hydrogeological conditions and quality aspects have to be investigated in detail.

## 1.3 Background and aims of this study

The basic concept of the TECHNEAU project is to approach towards a 'technology-enabled universal access to safe water' by promoting research and development activities. This dissertation was carried out within the frame of work package 5.2, which aims to foster the international development of BF as a managed aquifer recharge strategy, with a main focus on the situation in Delhi, India (LORENZEN *ET AL.* 2007).

The objective of this study is to explore the potential of BF in Delhi at field scale. Detailed reviews are carried out for further taking into account natural environmental realities in the study region, human-induced water stress, and development options. Field studies are conducted at three investigation sites (Figure 3.1) that were built with the aim to analyse the local hydrogeological conditions and the surface water–groundwater interaction. The general setup considerations for the field sites are shown in Appendix 1. The characteristics of individual observation wells are specified in the methods part of each chapter. The main focus of the investigations lies on quality concerns, namely the occurrence, sources, and fate of undesired substances in surface water and groundwater, attenuation potential for different contaminants, and the identification of associated processes.

The planning and execution of the scientific investigations in India required not only a good understanding of the hydro(geo)logical processes and a broad knowledge of research methods but also a well-organised management of the activities, a good infrastructure, and a fruitful communication with project partners, end users, local authorities, and other stakeholders (LORENZEN *ET AL.* 2010a). A major challenge of the project was the work in remote and unattended areas, with the requirement to get high-quality data, according to the state of the scientific and technical knowledge. For field work, creativity had a significant value, and improvisation helped to manage all kinds of challenges. One example is a new method that was invented to hide data loggers in observation wells for protecting them from vandalism or theft at the remote, unattended sites. A detailed description, along with exemplary data, was published as a 'methods note' in the journal "Ground Water" journal and incorporated as **Chapter 2** of this thesis.

**Chapter 3** initially provides an overview of BF for the managed aquifer recharge, with special emphasis on the possible benefits for water supply systems in newly industrialising and developing countries. An introduction to the study area is given, with a detailed review on geological, geographical, and environmental conditions in water-stressed Delhi. The three field sites are presented, and local hydraulic conditions are assessed for different seasons with the help of water level data and temperature profiles. Based on this information, hydrogeochemical data (inorganic ions and physico-chemical parameters) from the sampling campaigns are discussed. Different geogenic and anthropogenic sources of these contaminants are identified, and mobilisation processes as well as attenuation processes are discussed for individual substances.

The fate of pathogens and organic pollutants is analysed in **Chapter 4**. Sampling for these parameters was carried out at the field site in Central Delhi, where the Yamuna River is most polluted. Human pathogenic viruses, as well as indicator organisms (bacteriophages), were analysed. The fate and removal of the phages was further simulated with a numerical groundwater flow and transport model calibrated with the field data. Organic substances were analysed in non-target GC–MS screenings of the river water and bank filtrate in order to identify critical substances and compare the pollutant load by a semi-quantitative approach. Potential sources and attenuation processes during BF are discussed.

**Chapter 5** discusses the subject of groundwater salinity, which is a widespread problem in the study area and identified as a major concern at two of the three field sites (results of Chapter 3): Upconing of deep saline groundwater is a threat for existing BF facilities in northern Delhi (Palla) and limiting factor for the capacity of the well field. At the field site in west Delhi (at the Najafgarh Drain, close to the Haryana border), brackish groundwater is present even at shallow depths, and saline water was found in relatively deep aquifer sections; hence, a BF well at the drain would pump a mixture of brackish/saline groundwater and bank filtrate. At both the sites, it is important to understand the processes that lead to groundwater salinity and salinity ingress in the shallow aquifers in order to adopt water resources management strategies in the future. **Chapter 5** therefore presents a study on the sources of the salts in the regional context. Geographic conditions, as well as human-induced modifications of the natural water cycle, are taken into account. Field data, including temperature logs and hydrogeochemical and stable isotope analyses, are used for investigating the local patterns of groundwater salinity for understanding the relevant processes. The work on salinity is complemented by considerations for the installation of BF facilities at the Najafgarh Drain in chapter 7.2.

For future considerations of water management strategies, not only the understanding of present conditions is important, but also a consideration of the possible changes in the water cycle due to climate change. Surface water resources in Delhi are mainly derived from rivers originating from the Himalayan glaciers, and the major source of groundwater recharge is monsoonal rain. The catchment can be considered to be sensitive to climate change (MALL *ET AL.* 2006). **Chapter 6** provides a review of the potential influences of climate change on BF systems, considering both quantitative and qualitative aspects. Sensitive factors affecting BF performance are listed, and their relevance is discussed on the basis of hypothetical 'drought' and 'flood' scenarios.

In **Chapter 7**, the major outcomes of the individual chapters are summarised, and overall conclusions are drawn for the evaluation of the potential of BF in Delhi. Future development options in the emerging metropolitan area are considered because upcoming environmental consciousness and investment potential in the water sector may have a decisive impact on the perspectives in the near future.

# 2 A simple method to hide data loggers safely in observation wells


## Abstract

Submersible data loggers are widely used for groundwater monitoring, but their application often runs the risk of hardware and data loss through vandalism or theft. During a field study in India, the authors of this article experienced that well locks attract the attention of unauthorized persons and do not provide secure protection in unattended areas. To minimize the risk of losing data loggers, a cheap and simple solution has been invented to hide the instruments and associated attachments below ground surface, inside observation wells. It relies on attaching the logger to a length of small-diameter pipe that is submerged at the bottom of the well, instead of attaching it to the top of the well. The small-diameter pipe with the logger is connected to a small bottle containing a magnet that floats on the water surface of the well and can be recovered using another bottle also with a magnet. A logger that is concealed in this way is difficult to detect and access without knowledge of the method and adequate removal tools. The system was tested and successfully applied for monitoring shallow observation wells at three field sites in Greater Delhi, India.



Lorenzen G, Sprenger C and Pekdeger A (2011) A simple method to hide data loggers safely in observation wells. Methods Note. ***Ground Water*** 49(3): 450–453.

http://dx.doi.org/10.1111/j.1745-6584.2010.00771.x

# 3 Assessment of the potential for bank filtration in a water-stressed megacity (Delhi, India)


## Abstract

In the densely populated semi-arid 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 resources 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 megacity 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.



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

http://dx.doi.org/10.1007/s12665-010-0458-x

# 4 Removal of coliphages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India)


## 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 riverbank filtration (RBF) can significantly improve the quality of the highly polluted surface water in terms of virus removal (coliphages, enteric viruses) and organic pollutants. A numerical model was used to describe the underground water flow and the transport and deposition of coliphages 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 105 genomes/100 ml, were undetectable after approx. 119 days of RBF passage. Indigenous somatic coliphages, used as surrogates of human pathogenic viruses, underwent approximately 5 log10 removal after only 3.8 m of RBF. The initial removal after 1 m was 3.3 log10, the removal between 1 and 2.4 meter and between 2.4 and 3.8 meter, 0.7 log10 each. RBF is therefore an excellent candidate to improve the water situation also in emerging countries.


Sprenger C., Lorenzen G, Lopez-Pila JM, Grunert A, Ronghang M, Dizer H, Selinka HC, Girones R, Mittal A and Szewzyk R *(under review)* Removal of coliphages, enteric viruses and organic pollutants during riverbank filtration under anoxic conditions in Delhi (India). ***Journal of Water, Sanitation and Hygiene for Development*** [submitted 04/2011].

# 5 Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and adjacent territories of Haryana State, India


## Abstract

Groundwater salinity is a widespread problem and a challenge to water resources management. It is an increasing concern in the alluvial plains of Delhi and neighbouring Haryana state as well as a risk for agricultural production, water supply and sustainable development. This study aims to identify potential sources of dissolved salts and the driving mechanisms of salinity ingress in the shallow aquifer. It combines a comprehensive 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 groundwaters and dissolution/precipitation dynamics. Density stratification and local upconing of saline waters were 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 region. 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. Human induced changes of environmental conditions, especially the implementation of traditional canal and modern groundwater irrigation, have augmented evapotranspiration and led to waterlogging in large areas. In addition, water level fluctuations and perturbation of the natural hydraulic equilibrium favour the mobilisation of salts from salt stores in the unsaturated zone and deeper aquifer sections. The holistic approach of this study demonstrates the importance of various salinity mechanisms and provides new insights into the interference of natural and anthropogenic influences.


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Lorenzen G, Sprenger C, Baudron P, Gupta D and Pekdeger A (2011) Sources and dynamics of groundwater salinity in Delhi, India: New insights from geomorphologic analysis, stable isotope and geochemical data. ***Hydrological Processes*** (Early View 12/2011).

http://dx.doi.org/10.1002/hyp.8311

# 6 Vulnerability of bank filtration systems to climate change


## 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 (BF) 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 BF 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.



Sprenger C, Lorenzen G, Hülshoff I, Grützmacher G, Ronghang M and Pekdeger A (2011) Vulnerability of bank filtration systems to climate change. ***Science of the Total Environment*** 409(4): 655-63.

http://dx.doi.org/10.1016/j.scitotenv.2010.11.002

# 7 Combined conclusions, synthesis, and outlook

## *7.1 Major outcomes and conclusions from individual chapters*

***Chapter 2: A simple method to hide data loggers safely in observation wells***

Data loggers have become standard instruments for groundwater monitoring, but during the field studies in Delhi, researchers were apparently confronted with either resigning the use of these instruments or running the risk of losing valuable hardware and data. A relatively simple method that was invented and tested during the project, made it possible to achieve a high-quality time series of groundwater level and temperature fluctuations. The method was published to the scientific community so that the technical expertise can be used in other projects to minimise the risks of vandalism and theft.

***Chapter 3: Assessment of the potential for bank filtration in a water-stressed megacity (Delhi, India)***

The comprehensive review highlights the importance of a better management of integrated water resources in water-stressed regions such as Delhi. BF is identified as a potential (pre-) treatment method for drinking water production. Investigations at three field sites demonstrate that very different environmental conditions control the hydraulics and water chemistry in the surface water–groundwater interaction zone. Water level monitoring and temperature profiles can be used for analysing the groundwater flow pattern in the riverbank aquifers. At the Palla field site, these parameters indicate the relatively rapid and deep infiltration of the surface owing to the operation of drinking water production wells. At the Nizamuddin field site, hydraulic gradients indicate that BF takes places as a consequence of a lowered groundwater table in urban Delhi. At the Najafgarh field site, the excavated channel is draining the territory, except in the dry season, when a lowered groundwater table leads to the seepage of surface water.

Hydrogeochemical data allow us to identify the sinks and sources of inorganic contaminants in the surface water and the groundwater and to draw conclusions regarding the mobilisation and attenuation processes.

- When the surface water meets certain quality standards (e.g. at the Palla field site), bank filtration is a robust method for drinking water production.

- The discharge of untreated sewage into a river (like in Central Delhi) is typically associated with a high nitrogen load in the surface water and the river-bottom sediment. Anoxic conditions in the surface water and bank filtrate inhibit the oxidation of ammonia (and the subsequent denitrification).
- The oxidation of dissolved organic matter during bank filtration triggers a series of redox reactions, with a decrease in pH and an increase in the $CO_2^-$ pressure in the aquifer. At the Nizamuddin field site, the oxidation of high loads of organic matter leads to the reductive dissolution of $Fe^{2+}$ and $Mn^{2+}$ (hydr)oxides with associated As. An increase in the $CO_2$-pressure triggers the dissolution of $CaCO_3$ and the precipitation of $F^-$, subsequently.
- Mixing with the bank filtrate can dilute the concentrations of contaminants from the ambient groundwater. At the Palla well field, this process reduces the natural concentrations of As and $F^-$ from the aquifer. At the Nizamuddin field site, bank filtration could be used for diluting the shallow brackish groundwater.
- Mixing and/or upconing of ambient brackish to saline groundwater would impair the water quality discharged from bank filtration wells at the Najafgarh Drain field site. Field data from Palla field site provide no evidence of salinity ingress, but reports from the well field indicate that an overexploitation of the aquifer can trigger saline intrusions.
- At all the field sites, distal groundwater must be expected to be polluted with substances from the urban or agricultural sources (e.g. $NH_4^+$, $NO_3^-$, and $F^-$).
- Other inorganic ions (e.g. $PO_4^{3-}$ or heavy metals other than $Fe^{2+}$ and $Mg^{2+}$) were not detected in health-relevant concentrations.

***Chapter 4: Removal of coliphages, enteric viruses and organic pollutants during river bank filtration under anoxic conditions in Delhi (India)***

With large shares of untreated sewage in the Delhi's surface water, the bank filtration sites at the Yamuna cannot be compared with the well-investigated sites in central Europe. Samples from the Yamuna water and bank filtrate from the Central Delhi site confirm a high pollution load of human pathogenic microorganisms (enteric viruses and somatic bacteriophages) and organic pollutants from household (e.g. food additives, drugs, and fatty acids), industrial/technical (e.g. bisphenol A and alkanes), and agricultural (herbicides) effluents. An analysis of bank-filtrated water reveals the following:

- Complete removal or extensive attenuation of polar to non-polar bulk organic compounds after approximately 50 m or 119 days of aquifer passage.

- Complete removal of human adenoviruses and noroviruses and somatic coliphages after approximately 50 m or 119 days of bank filtration passage.
- Approximately 5 $\log_{10}$ removal of indigenous somatic coliphages after only 3.8 m of bank filtration (~8 days of travel time).

The transport and deposition of bacteriophages could be simulated with a numerical groundwater model that helps to understand hydraulic conditions and to further constrain the removal processes in the aquifer. High efficiency in terms of pathogen removal shows that bank filtration is well suited to places where highly fecally polluted raw water overburdens the capacity of conventional treatment techniques. The attenuation of organic compounds takes place under anoxic conditions along the entire flow path. A future improvement of surface water quality to oxic conditions or a simple post treatment (aeration and filtration) would activate aerobic degradation processes and improve treatment capacity.

***Chapter 5: Origin and dynamics of groundwater salinity in the alluvial plains of western Delhi and adjacent territories of Haryana State, India***

Brackish-to-saline groundwater is observed in large parts the study area. The salinity ingress in shallow aquifers is a threat to the existing drinking water production facilities and groundwater-irrigation-based agriculture. Geogenic groundwater salinity in shallow inland aquifers can be caused by the concentration of salts through evaporation, dissolution of salts, and/or mobilisation of saline groundwater. An analysis of geomorphological and hydrological conditions and field data from the study area indicate that salinity ingress in the study area is caused by various processes, owing to the following reasons:

- The study area is situated in a poorly drained basin with a constant inflow of surface water (and dissolved solids).
- Warm and dry climate and shallow groundwater lead to high evaporation rates, especially from irrigated fields and waterlogged areas.
- In the geologic past, when the monsoon weakened or failed, arid conditions may have lead to the formation of salt reservoirs (e.g. salt clay) within the basin.
- There is no indication of the presence of massive rock salt and dissolution of marine evaporites.

- Salinity generally increases with an increase in depth; at the field site, density stratification and temperature profiles suggest the upconing of saline water in the discharge zone (artificially excavated drainage canal).
- $HCO_3^-$ is the dominant ion in fresh water, and $Cl^-$ and $SO_4^{2-}$ are dominant in the saline samples.
- Evaporation from the soil surface or waterlogged areas is indicated by enrichment in heavy isotopes ($^2H$, $^{18}O$), along with increased salinity of groundwater samples.
- Elevated nitrate concentrations in evaporated groundwater are interpreted to be a result of irrigation return flow.
- Most saline groundwater samples have not undergone extreme evaporation; hence, high mineralization originates from the dissolution of salts.
- $HCO_3^-$ depletion and excess $CO_2$ pressure in deep saline water are interpreted as a consequence of $SO_4^{2-}$ dissolution in relatively deep aquifer sections, triggering the precipitation of $Ca(HCO_3)_2$.

It can be concluded that natural environmental conditions in the basin have favoured the built-up of salinity and salt reservoirs in groundwater, unsaturated soil, and low-permeability sediments. The human-induced perturbation of the hydraulic system and the natural salt-water-balance can lead to increased evaporation and to the mobilisation of solid or dissolved salts. The construction of canals in the semiarid plains, surface and groundwater irrigation, and changes in land use pattern have triggered the salinity ingress.

***Chapter 6: Vulnerability of bank filtration systems to climate change***

Climate change on a global scale is expected to have an impact on water supply systems. The consequences of the increasing temperatures and increasing weather extremes on the bank filtration facilities can be assessed from hypothetical flood and drought scenarios. The following possible consequences have been identified:

- A dryer climate leads to decreasing discharge and flow velocities, more anoxic conditions, increasing algae growth, and possibly eutrophication. It may lead to the concentration of many contaminants (e.g. pathogens and disinfection by products) and limit the aerobic degradation potential, which controls the attenuation of certain substances (e.g. bulk DOC, $HN_4$, and disinfection by products or PAHs).

- A flood scenario can increase deposition from diffuse sources, e.g. through wash off from urban or agricultural pollutants or combined sewer overflow. Increased hydraulic gradients and flow velocities may have a negative impact on the attenuation capacity of a site.

Overall, bank filtration facilities rely on two different sources. Mixing, relatively large residence times, and multiple barriers make them relatively robust systems, often less vulnerable than systems relying on only one source and conventional treatment methods. Further, bank filtration systems are vulnerable to climate change, but anthropogenic impacts are at least as important.

## 7.2 Synthesis and outlook: Perspectives for bank filtration in Delhi

In the water-stressed metropolitan area of Delhi, the water demand is rising, while resources are getting degraded by overexploitation and pollution. While economy has been developing rapidly, deficient water supply still incorporates the vast majority of the population and plays a central role in persistent poverty (GREY & SADOFF 2007). However, efforts for better resources management are currently increasing, and industrial growth itself creates a demand for environmental innovations (JÄNICKE 2009). The results of this study have shown that the conditions in Delhi cannot be compared to those at bank filtration (BF) sites in Europe. However, in the semiarid environment, with overexploited aquifers and high pollution loads in surface water, even small or qualitatively degraded resources can be valuable for their contribution in conjunctive resources management. It is therefore important to consider the rapid development in Delhi with an emerging economy, high investment potential, and probable future advances in pollution management and environmental conditions.

***The Yamuna River, upstream the urban parts of Delhi***

Upstream the urban part of Delhi, groundwater abstraction in the Palla well field is boosting the seepage of Yamuna water into the floodplain aquifer. The Yamuna is not yet contaminated by the effluents of the megacity, and relatively low pathogens contents can be expected to be safely retained during BF. Sorption of As from surface water and denitrification during BF improves the source water quality. Meanwhile, increased concentrations of As, $NO_3^-$, and $F^-$ from the ambient ground water can be diluted in production wells by mixing with the bank filtrate. However, there is currently no indication of health-relevant concerns from inorganic ions. Saline intrusions, reported from other parts of the well field (RAO *ET AL.* 2007), are not observed at the BF site but could be confirmed by salinity mapping (Appendix 2). For future considerations, the prevention of salinity ingress and well field optimisation will be the major challenges. Quality parameters (including As, $NO_3^-$, $F^-$ and salinity) and hydraulic conditions should be monitored. Further, BF wells could be constructed for drinking water production and the partial substitution of surface water treatment plants. Infiltration ponds (recharged with Yamuna water) could be installed to activate the recharge potential, minimise drawdown, and prevent salinity ingress in the southern and eastern parts of the well field (more distant from the active river channel). Climate change may lead to a degradation of source water but is possibly less important than the human-induced impacts in the Yamuna catchment.

***The Yamuna River in urban Delhi and downstream***

The Central Delhi (Nizamuddin Bridge) field site represents the situation in urban Delhi and downstream, where surface water is highly polluted and seeps into the aquifer. Human pathogenic viruses, bacteria, and bacteriophages are present in the mostly anoxic Yamuna in large amounts but get completely retained during approximately 50 m (or 119 days) of subsurface passage. A large number of most distinct organic pollutants get considerably or even fully attenuated during seepage and underground passage. However, under the anoxic conditions, removal is not confirmed for all organic substances. Reducing conditions also inhibit the nitrification of ammonia and lead to the release of considerable amounts of $Fe^{2+}$, $Mn^{2+}$, and As from the aquifer matrix. Under the present conditions, BF is confirmed as a robust treatment step for the removal of pathogens, but residues of persistent organic pollutants and inorganic ions would make further treatment steps mandatory.

For future planning, it should be considered that local stakeholders and policy makers in Delhi today give prime importance to a better management of this polluted Yamuna segment (UPADHYAY 2011). Large investments have initially failed to improve the river water quality (CSE 2007) but may help to significantly reduce the pollution of Yamuna in the future (UPADHYAY 2011). When bulk pollutants decrease and water conditions become oxic, BF will be much more attractive. Ammonia could naturally get oxidised to nitrate in surface water, which could again be reduced by denitrification during BF (as described by DOUSSAN *ET AL.* 1997). A more pronounced redox-zonation along the flow path is further expected to have positive effects on the degradation of bulk organic matter. Under such conditions, BF in central Delhi could deliver raw water with a much better quality, and efforts for post treatment could eventually be minimised. The major advantage of the installation of BF facilities in central or south Delhi would be the possibility to reclaim water in a semi-closed cycle, when treated sewage enters the Yamuna upstream of the sites. BF could help to replenish Delhi's scarce water resources, and the reclamation of treated sewage through managed aquifer recharge in BF systems has the benefit of providing a multi-barrier system against micro-pollutants; the public acceptance of this technique is generally better than that of technical treatment solutions for wastewater recycling (RYGAARD *ET AL.* 2011).

***Najafgarh Drain in western Delhi and Haryana***

At first glance, there seem to be few options for the development of BF at the Najafgarh Drain field site. Surface water discharge is only considerable in the monsoon season, and ambient groundwater quality is largely impaired by salinity. Yet, in the transition zone towards the warm and dry area, there are no alternative water sources, except from the water transfer and harvesting of scarce rainwater. Under such conditions, floodwater or even brackish groundwater can be a feasible resource for implementation in the integrated resources management planning. At a similar site in Haryana, TYAGI (2006) promotes the conjunctive use of partly saline groundwater with canal water for irrigation purposes. The author sees the opportunity of increasing production and minimizing the risk of water logging (TYAGI 1996). BF could be used as a tool to bank flood water in the wet season, to replenish resources, and to improve the quality of ambient groundwater through dilution (DILLON 2006, RAY & SHAMRUK 2011). According to the findings of Chapter 5, major challenges would be to increase the residence time of flood water in the drain, maximise surface infiltration rates, avoid overexploitation of the shallow aquifer, and prevent the upconing of the relatively deep saline water as well as the intrusion of brackish/saline water from the north. Efforts would be needed for realizing the potential gains of conjunctive water management at both government and farmer levels (TYAGI 2006).

Recently, the industrial sector has also discovered the Haryana territories beyond the western border of Delhi as an attractive investment location. A location at the Najafgarh Drain was for instance considered to be a potential site for the development of a major industrial enclave (Haryana Special Economic Zone, PALIT 2009). Water scarcity must be considered a limitation for the development and local self sufficiency of the region. Under such circumstances, even wastewater reclamation, desalination, and rainwater collection may be profitable options to augment water resources (RYGAARD *ET AL.* 2011). Considering the currently rapid development in membrane technologies and decreasing costs for desalination (RYGAARD *ET AL.* 2011), brackish groundwater becomes an increasingly attractive resource for industrial use or water supply. An exemplary sketch for a holistic management scheme of local resources drafted during the TECHNEAU project is shown in Appendix 3. In this scheme, BF plays a key role for conjunctive use of surface water and groundwater and enables the reclamation of treated wastewater.

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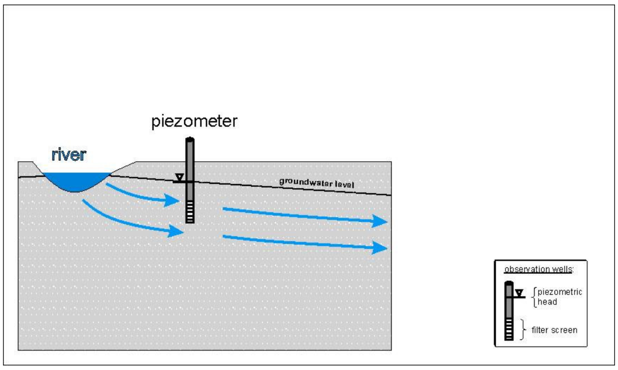
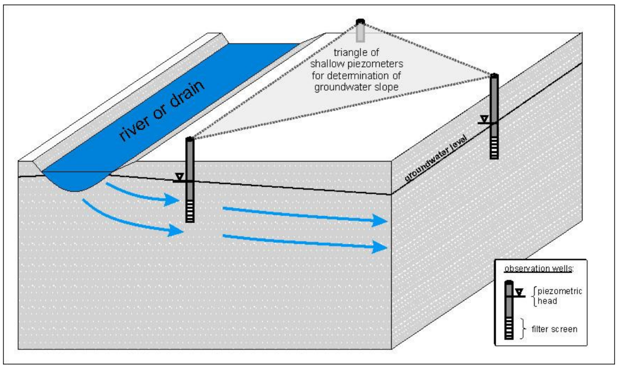
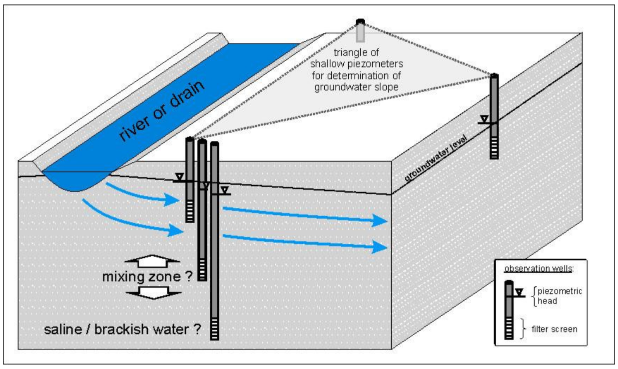
# Appendix



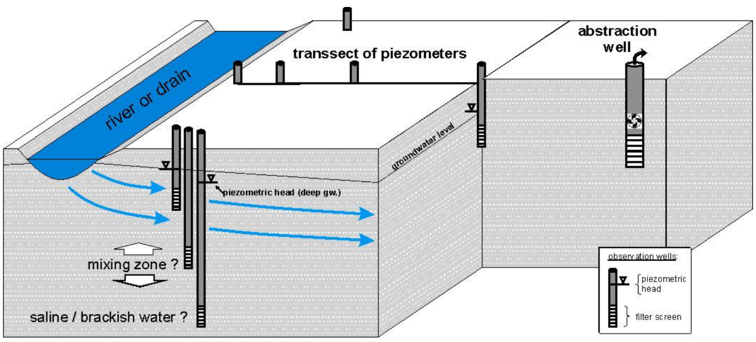

(A) Observation well close to the surface water can be used for determining the hydraulic gradient (gaining river/loosing river). Groundwater can be sampled to get an impression of water chemistry or can be used for tracer tests.




(B) Triangle of shallow observation wells will allow determining the inclination of the groundwater surface. Several samples can be taken to identify the scattering of different parameters or to estimate the attenuation of contaminants during bank filtration with an increase in distance and travel time.

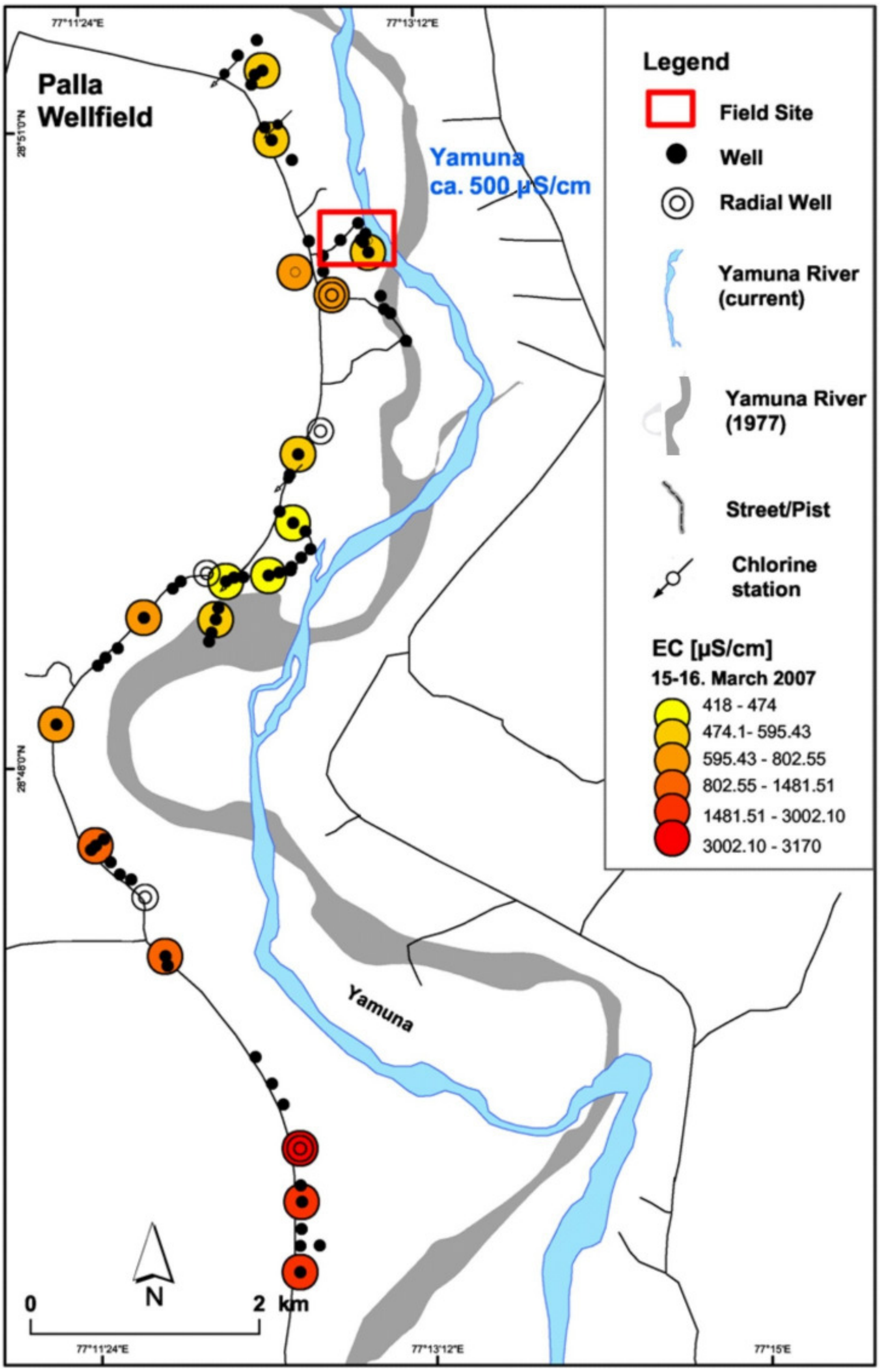



(C) At least one multi-level monitoring point should be available for determining the vertical hydraulic gradient. The multi-level wells also give the possibility to test whether the water properties change with a change in depth. This is a crucial aspect in areas affected by groundwater salinity.



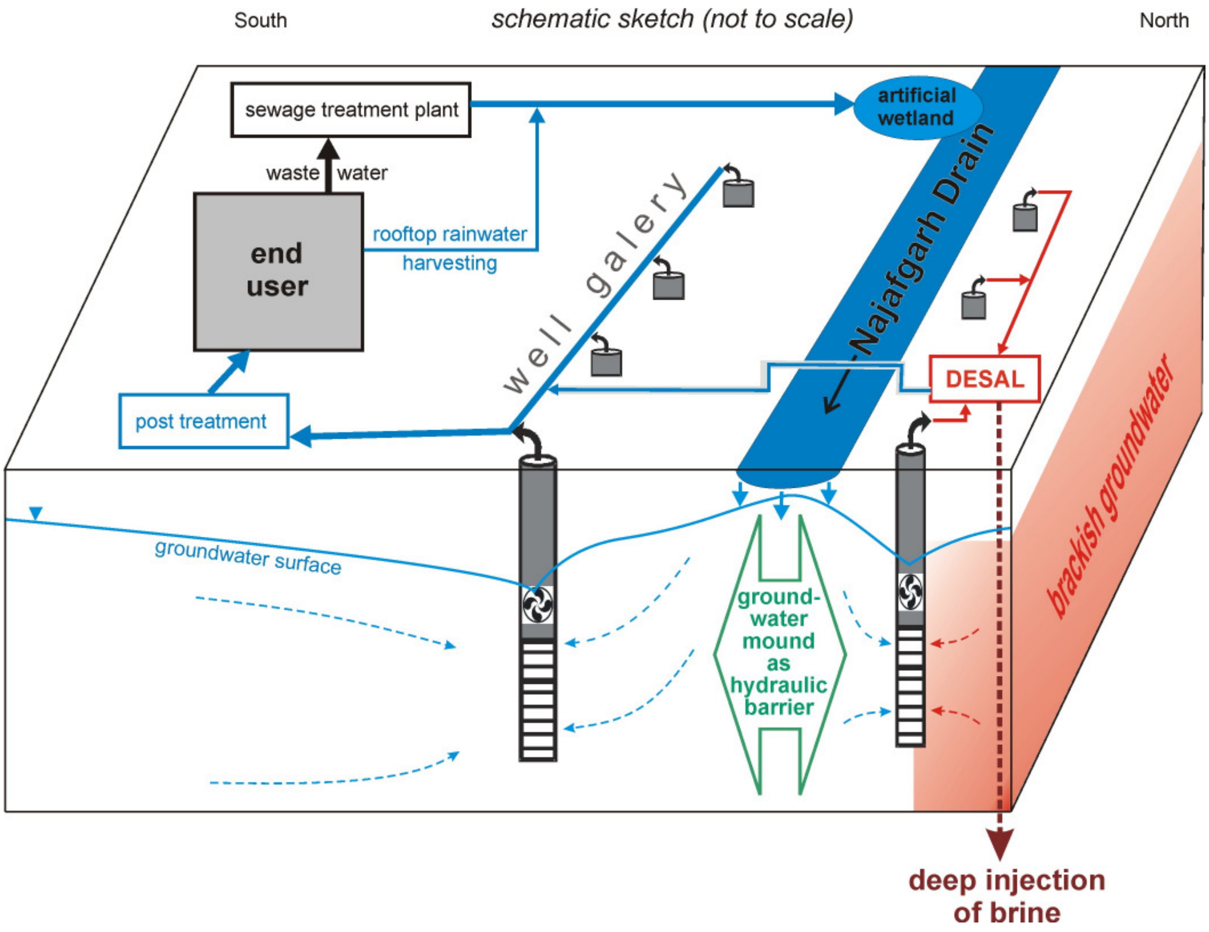

(D) Adding an abstraction well allows investigating bank filtration under realistic operation conditions in real time. This well can be further used for pumping tests. A transect of shallow observation wells between the river and the well can be used for investigating water quality changes during bank filtration, e.g. due to natural attenuation in the aquifer.

**Appendix 1.** Exemplary design for the setup of a field site for investigations of bank filtration processes. For the first test, one shallow well can provide a lot of useful information (A). Developing a site with additional wells (B–D) will increase the possibilities for groundwater. [Source: LORENZEN *ET AL.* 2010a]




**Appendix 2.** Salinity mapping of selected wells at the Palla well field in March 2007. Electrical conductivities range from ~400 µS/cm to more than 3000 µS/cm. High values are frequently measured in the southern and western parts of the well field. In these sections, the wells are more distant from the Yamuna at the present state. These distal parts of the well field are more vulnerable to salinity ingress because aquifer recharge by bank filtration decreases with an increase in the distance from the river. Bank filtration shares are therefore relatively low, and the dilution of the ambient groundwater with fresh water from the Yamuna decreases. Drawdown rates can be expected to be relatively high, increasing the risk of the upconing and mobilisation of brackish or saline water from deeper aquifer sections or from the west.

[Source: TECHNEAU project; Sprenger & Lorenzen; not published]




**Appendix 3.** Exemplary sketch for a holistic management scheme for local resources at the Najafgarh Drain. Bank filtration plays a key role in the conjunctive use of surface water and groundwater and enables the reclamation of treated wastewater. According to the findings given in Chapter 5, the drain partially acts as a hydraulic barrier, separating fresh to slightly brackish groundwater in the south from the more saline groundwater in the north. South of the drain, bank filtration wells could be built with the intention to deliver water with a relatively low content of dissolved solids. On the opponent banks of the drain, wells could be constructed to prevent brackish/saline intrusions from the north. More saline water from these (northern) wells could become an utilizable resource for desalinisation because due to the dilution with bank filtrate, it could become fresher than the ambient groundwater in the north. Brackish resources are becoming more attractive for water supply because membrane technologies are currently developing very rapidly and desalination costs are decreasing (RYGAARD *ET AL.* 2011). After industrial or domestic use, wastewaters should be treated and discharged into the drain at a location upstream from the facilities in order to enable reclamation by bank filtration. An artificial wetland at the discharge point of treated sewage could be installed to increase the residence time of treated sewage in surface water and maximise biological degradation processes under oxic conditions in the biosphere. Rooftop rainwater harvesting should be integrated into the system, and if necessary, additional water could be supplied by an inter-basin transfer. Such a scheme would have to be evaluated thoroughly in a feasibility study, including a cost-benefit analysis and pilot studies on a field scale. A major challenge for further hydrogeological investigations and planning and operation of wells would be to avoid the upconing of deep saline water.

[Source: Lorenzen et al. 2009]

## Curriculum Vitae

For reasons of data protection,
the curriculum vitae is not included in the online version.