

# Chapter 1

## Introduction to natural water treatment systems in the Indian context

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### 1.1 INTRODUCTION TO SAPH PANI

It is well known that groundwater is the largest source of fresh water in the world. Domestic, agricultural and industrial activities require water, and in most parts of the world the requirement is met by pumping groundwater. Even though it is a renewable resource, today, the availability of fresh water has become a vital issue in almost all parts of the world. Due to increased population, the demand for water is greater than the recharge of the groundwater sources. The demand for water is reported to increase even more by 2050 as the population is expected to rise to 9 billion by this time (FAO, 2007). In this context, water conservation needs priority attention to manage the existing water resources and to ensure sufficient availability of water for future generations. With these aspects in mind, a multi-disciplinary and multi-institutional pilot study based project was conceived. This project, given the acronym Saph Pani, on the ‘Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India’ was co-funded by the European Commission within the 7th Framework Programme. The project was carried out at several study sites in India during the period 2011–2014. The project partners include academic institutions, research institutes, water supply agencies, and small and medium level companies. The institutions are located in Australia, Austria, France, Germany, India, Sri Lanka, The Netherlands, and Switzerland. The project consortium consisted of investigators with varied level of expertise and disciplines of study including economists, social scientists, geologists, hydrogeologists, chemical engineers, biologists, microbiologists, hydrologists, civil engineers, chemists, geophysicists, environmental engineers etc. The project highlights are field based pilot level studies in northern, central, western and southern parts of India. Aspects related to natural water treatment systems such as Managed Aquifer Recharge (MAR) by ponds and check dams, Soil Aquifer Treatment (SAT) and River Bank Filtration (RBF) were closely investigated at those sites.

#### 1.1.1 Water resources in India

India possesses 18% of the world’s population i.e., 1.25 billion, but accounts for only 4% of the world’s water resources. There are different estimates reported about India’s water budget in terms of available resources and current use. Table 1.1 gives a comparison of different estimates considering two evapotranspiration scenarios (UNICEF *et al.* 2013).

Depending on the scenario it becomes more or less obvious how strained the given resources are. However, not only is the total country perspective relevant but also the geographical and temporal distribution as well as variability of water availability. This can be illustrated by the fact that annual rainfall can range from around 3,700 mm in Karnataka to around 500 mm in Rajasthan (CWC, 2014). In many river basins 80% of the run-off occurs during the few months of monsoon and cannot be captured effectively but rather can lead to flooding and destruction (Mishra *et al.* 2009). The agricultural sector is

## 2 Natural Water Treatment Systems for Safe and Sustainable Water Supply in the Indian Context

the biggest water user in India with around 90% use of the total water resources. 80% of the irrigation water in agriculture is abstracted from groundwater, due to water pollution in rivers (World Bank Report, 2005). Although domestic (8%) and industrial supply (2%) are currently smaller water users (Aquastat, 2010), strong growth is expected based on the increasing population. This problem is particularly acute for India's urban population which makes up more than 28% of the total population. The potable water supply increased from  $3 \times 10^9$  m<sup>3</sup>/year in 1990 to  $56 \times 10^9$  m<sup>3</sup>/year in 2010 and is estimated to reach  $110 \times 10^9$  m<sup>3</sup>/year by 2050 according to FAO data. Similarly, the "India Vision 2020" (2002) report predicts that total water consumption in India is expected to rise by 20–40% until 2020. Wherever urbanization has been growing, the quantity of water infiltrating from the rains has decreased due to construction of impervious surfaces such as buildings, cemented pavements and roads.

**Table 1.1** General water management data for India (UNICEF *et al.* 2013).

	<b>Analysis Based on MoWR* (Values in BCM**)</b>	<b>Analysis Based on MoWR* Estimates Based on Worldwide Comparison (Values in BCM**)</b>
Annual rainfall	3,840	3,840
Evapotranspiration	$3,840 - (1,869 + 432) = 1,539$ (40%)	2,500 (65%) World-wide comparison
Surface run-off	1,869 (48.7%)	Not used in estimate
Groundwater recharge	432 (11.3%)	Not used in estimate
Available water	2,301 (60%)	1,340 (35%)
Utilisable water	1,123 (48.8% of 2,301)	654 (48.8% of 1,340)
Current water use	634	634

\*Ministry of Water Resources

\*\*BCM = Billion Cubic Meters

In many cases these pressures result in a scarcity of safe drinking water supply, sanitation problems, urbanisation of wetlands, and encroachment of urban areas onto swamp and floodplain areas of rivers. The people living in these suburban areas generally have neither organized potable water supply systems nor adequate sewerage facilities. The National Water Policy of India (NWP, 2002), among other government mandates and regulations, emphasizes drinking water (section 8) and water quality (section 14) as important priorities to be addressed. The Central Pollution Control Board (2009) estimates only a third of the collected urban wastewater is actually treated in India's class I cities (the biggest 498 cities in India) and class II towns (CPCB, 2009).

Climate change, causing frequent failure of monsoons and resulting in limited surface water resources, has led to increased dependence on groundwater resources (Lal, 2001). Hence, the health of populations that depend entirely on groundwater as their sole source of drinking water (Ragunath, 1987) are particularly vulnerable due to groundwater depletion and water quality degradation. Thus, future supplies of water for urban areas will depend on the quantity and quality of the groundwater available (McIntosh, 2003).

Faced with poor water supply services, farmers and urban dwellers alike have resorted to pumping groundwater through tube wells. For example, as many as 10.2 million dug wells, 5.4 million private production (tube) wells, and 60,000 deep production wells became operational in the country in the four decades before 1999 (Nagaraj, 1999).

Groundwater levels are rapidly declining in most states in India. In the regions south of the Ganga and the Sutlej Rivers (the Indo-Gangetic alluvial plain) up to the southern margin of the Deccan Plateau (Nagaraj, 1999), which includes the nations bread basket Punjab (Brown, 2005), levels declined by more than 0.2 m/year between 1981 and 2000. In Tamil Nadu, a state with more than 62 million people in southern India, falling water tables are very common which has resulted in many wells drying up (The Economic Times, 2007). Associated crop yields are also decreasing. Declining water tables lead to land subsidence and make surface water flows less reliable since many rivers are maintained in the dry season by the groundwater discharge. Furthermore, groundwater helps to maintain other surface water bodies such as ponds, lakes and wetlands, which are also threatened by excess pumping. In coastal cities like Chennai unregulated pumping has led to seawater intrusion, which forces the abandonment of well fields progressively inwards, away from the sea (Elango, 2009).

Groundwater management today involves many facets – it is not just the science of groundwater hydrology and water quality, but includes other issues such as sustainability and integration of social, economic and ecological aspects (Campana, 2007).

### 1.1.2 The role of natural treatment technologies in mitigating water scarcity in India

There is a growing need to address the water scarcity problems not only in India but all over the world. Natural treatment processes utilising the attenuation and buffering capacity of natural soil-aquifer and plant-root systems are particularly suited for this as they can be implemented by using locally available resources both in terms of the initial investment needed and operational effort (e.g., in terms of energy and chemicals). Natural treatment processes are considered most relevant for the Indian context and have huge, undeveloped potential to address water scarcity issues (UN Water, 2006).

MAR is a very suitable technique which includes rainwater harvesting, construction of infiltration wells, percolation tanks, recharge pits and shafts and managing run-off water to facilitate recharge of suitable aquifers. Some of the advantages of MAR include floodwater mitigation, control of saltwater intrusion, storage of water to reduce pumping and piping costs, temporary regulation of groundwater abstraction, and water quality improvements (Asano, 1985). A subset of the MAR concept is SAT, RBF or bank filtration (BF, common usage for rivers or lakes), which enables the utilisation of surface water sources after passing through the natural porous sub-surface (aquifer) to the production well. The porous media serves as a natural filter and also biochemically attenuates potential contaminants present in the surface water. BF is also recognised by the WHO (World Health Organisation) as a natural treatment method for drinking water (WHO, 2011). Similarly, constructed and natural wetland systems can be used for water resources protection and provision of non-potable water, e.g., for irrigation applications both in the agricultural and urban context.

Several studies have shown that MAR can be effective in raising groundwater levels (Athavale *et al.* 1992; CGWB, 2000; Karanth & Prasad, 1979; Muralidharan *et al.* 2007; Parthasarathi & Patel, 1997; Raju, 1998; Shivanna *et al.* 2004). Effective groundwater recharge through the construction of subsurface barriers was also studied by Elango and Senthilkumar (2006) in Tamil Nadu, India. These studies demonstrated that MAR is a potent solution to overcoming water scarcity. Gale (2005) states that in India, MAR in rural areas is typically performed as part of a package of measures aimed at developing or rehabilitating watersheds. Such watershed development programmes combine a range of land development/protection, soil moisture conservation, afforestation, pasture development and horticultural activities, as well as explicit water resource conservation/augmentation measures. Those measures additionally emphasize the potential role of RBF as an element of MAR and groundwater banking (Sandhu *et al.* 2011).

While numerous studies on BF exist for Europe and North America, there have been very few holistic and comprehensive studies on RBF in India. For example, the quality of bank filtrate abstracted for domestic use was studied in Nainital, Haridwar, Delhi and Mathura. Bank filtrate was found to have lower concentrations of turbidity, coliforms (especially during the monsoon) and dissolved organic carbon compared to directly abstracted surface water (Dash *et al.* 2008, 2010; Gupta *et al.* 2014b; Lorenzen *et al.* 2010; Pekdeger *et al.* 2008; Singh *et al.* 2010; Sprenger *et al.* 2008). A summary of preliminary studies of RBF systems within a description of the potential for RBF in India (Sandhu *et al.* 2011), demonstrates that such systems already play a significant role in providing drinking water to urban areas. RBF (along with more limited post-treatment chlorination) is generally accepted as the sole drinking water treatment at some sites such as in Haridwar, Nainital and Srinagar in the State of Uttarakhand. Bank filtrate monitored in recent years has shown a significantly higher quality compared to water abstracted directly from surface sources (JIWWA, 2012; Sandhu & Grischek, 2012; Bartak *et al.* 2015; see also Chapters 2 and 3). With these techniques there is great potential for improved treatment of surface water. Hence, due to the need to augment ground water quantity in order to sustainably meet India's future water needs it is sensible and essential to adopt and implement natural water systems and treatment technologies.

### 1.1.3 Saph Pani project objectives

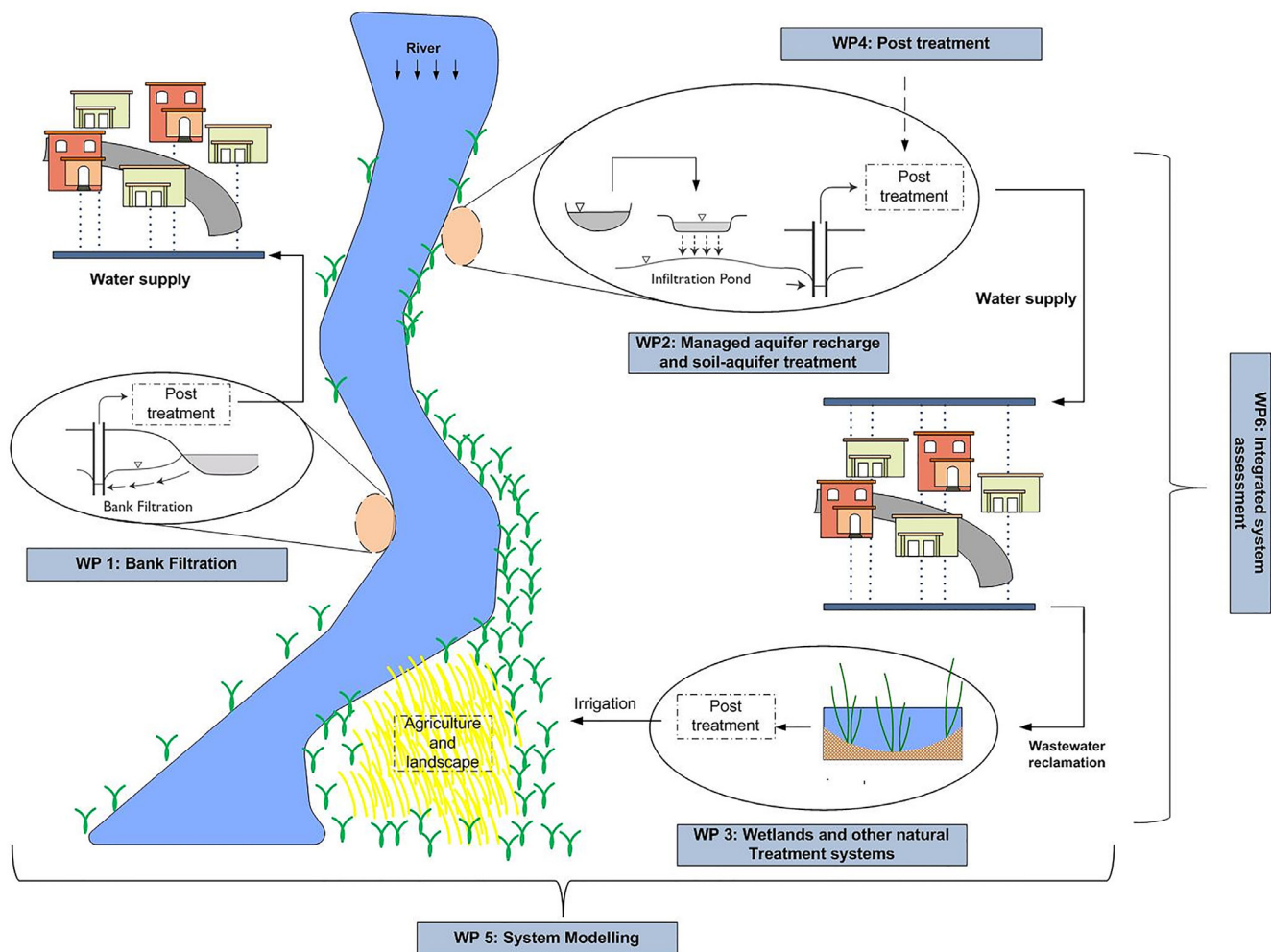
The Saph Pani project aimed to improve natural water treatment systems such as BF, MAR and wetlands in India. The project considered particularly water resources and water supply in water- stressed urban and peri-urban areas in different parts of the Indian sub-continent.

The objective was to strengthen the scientific understanding of the performance-determining processes occurring in the root, soil and aquifer zones of the relevant regions and considered the removal and fate of important water quality parameters

such as pathogenic microorganisms and respective indicators, organic substances, nutrients and metals. The hydrologic characteristics (infiltration and storage capacity) were also investigated to strengthen local or regional water resources management strategies (e.g., by providing buffering of seasonal variations in supply and demand). The socio-economic value of enhanced utilisation of the treatment and storage capacity of natural systems was evaluated taking into account sustainability and system risk management.

### 1.1.4 Saph Pani approach and methodology

The project focused on a set of case studies in India (see Section 1.1.5). These included a range of natural water systems and treatment technologies investigated by different work-packages (WP) such as BF (WP1), MAR (WP2) and constructed wetlands (CWs) (WP3) as illustrated in Figure 1.1.



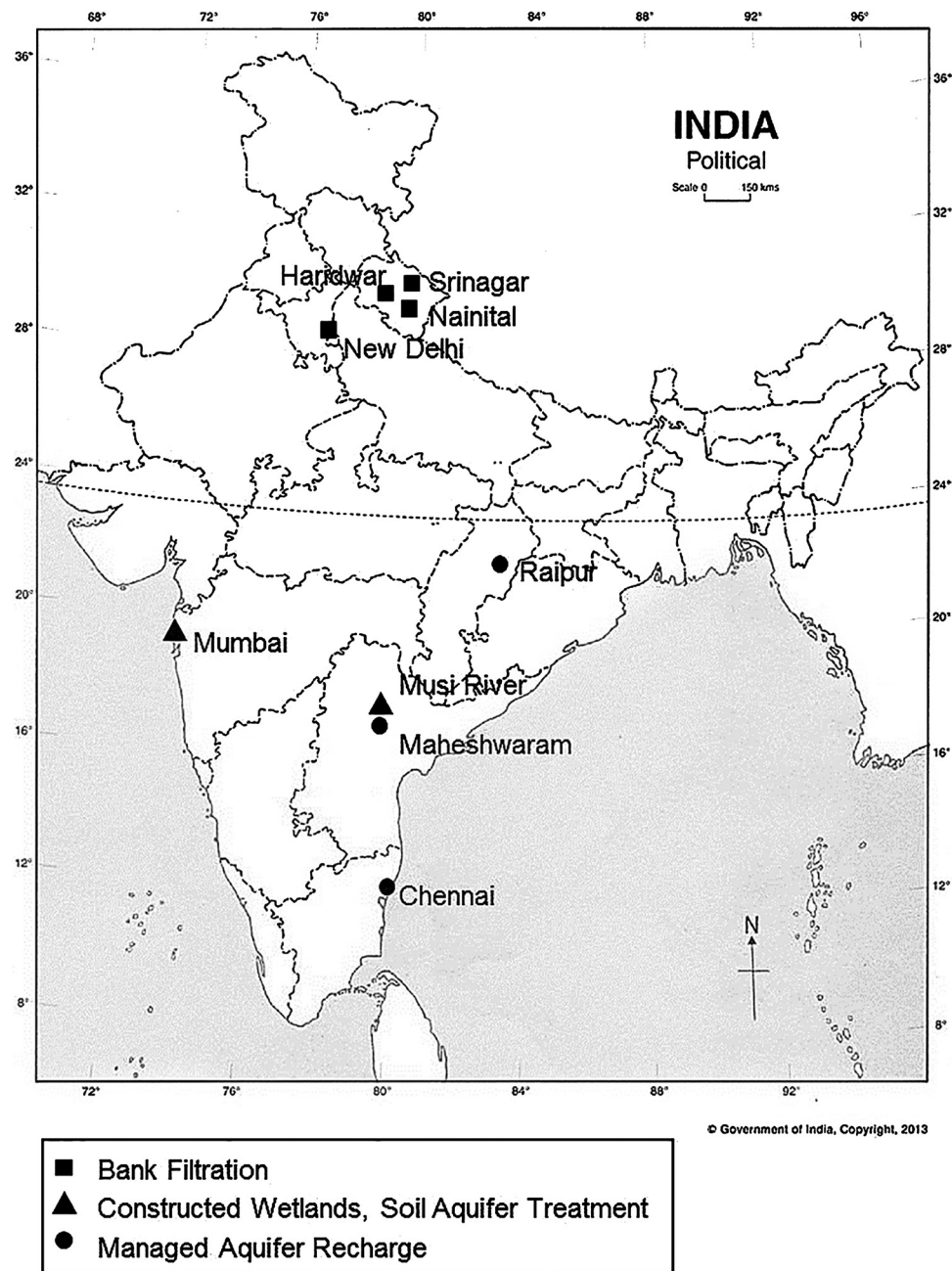
**Figure 1.1** Overall Saph Pani approach showing main technology areas and relation to work package.

The field site investigations included hydrogeological, hydrological and geochemical characterisation and in some cases water quality monitoring or pre-feasibility studies for new treatment schemes. In addition, recommendations regarding appropriate pre- and post-treatment (WP4) to produce potable water quality and to avoid clogging of the sub-surface structures was given. The experimental and conceptual studies were supported by modelling (WP5) which improved the theoretical understanding of the sites and enhanced the transferability of results. Furthermore, a sustainability assessment was performed, covering health, environmental, economical, institutional and social aspects (WP6).



## 1.2 SAPH PANI CASE STUDY SITES

Saph Pani has performed case studies on eight different sites. In WP1 BF as a natural water system and (pre-)treatment technology was addressed in four case studies in urban areas in North India, namely Haridwar, Srinagar (Uttarakhand), Nainital and Delhi (see Figure 1.2, Table 1.2 and Chapter 2 and 4). In WP 2 MAR was investigated in the rural site Maheshwaram and the urban sites Chennai and Raipur (see Table 1.3). In work package 3 a natural wetland with SAT near Hyderabad (Musi River Watershed) and a specially designed and CW in Mumbai have delivered “hands-on” knowledge and data for further interpretation. The case study sites are situated in different geographic and climatic situations, addressing natural phenomena such as drought, flood and saltwater infiltration. The main characteristics of the study sites are briefly described in the paragraphs below.



**Figure 1.2** Location of the Saph Pani case study sites (Source Map: © Government of India, 2013).

**Table 1.2** Features of case studies on bank filtration (BF) in Uttarakhand and NCT Delhi.

Case Study Site	Haridwar	Srinagar	Nainital	Delhi
<b>Population</b>	>225,000 (plus 5,000 pilgrims daily & occasionally 8.2 million)	~80,000 (Gupta <i>et al.</i> 2014)	>41,000 (plus 5,000 tourists in summer months)	~16,000,000 (Census of India, 2011)
<b>Source-water quality</b>	<b>Good</b>	<b>Good</b>	<b>Moderate</b>	<b>Poor</b>
Current raw water source	Bank filtrate & groundwater	Surface water, groundwater & bank filtrate	Bank filtrate & groundwater	Surface water, groundwater & bank filtrate
Issues relevant to natural water systems & treatment technologies addressed in the case studies on BF	<ul style="list-style-type: none"> <li>• Removal of pathogens and turbidity</li> <li>• Reliable drinking water disinfection</li> <li>• Flood protection of wells</li> <li>• High nitrate concentration in land-side groundwater (in Srinagar)</li> <li>• Adaptation of management of RBF schemes (Srinagar)</li> <li>• Catchment area and well head protection of wells</li> </ul>		<ul style="list-style-type: none"> <li>• Removal of pathogens and organics</li> <li>• Sustainability of existing bank filtration system</li> <li>• Discharge of partially treated to untreated urban wastewater via sewer canals entering lake</li> </ul>	<ul style="list-style-type: none"> <li>• High Ammonium in groundwater</li> <li>• High pollution from wastewater in Yamuna</li> <li>• Identification of suitable remediation options for existing RBF wells</li> </ul>

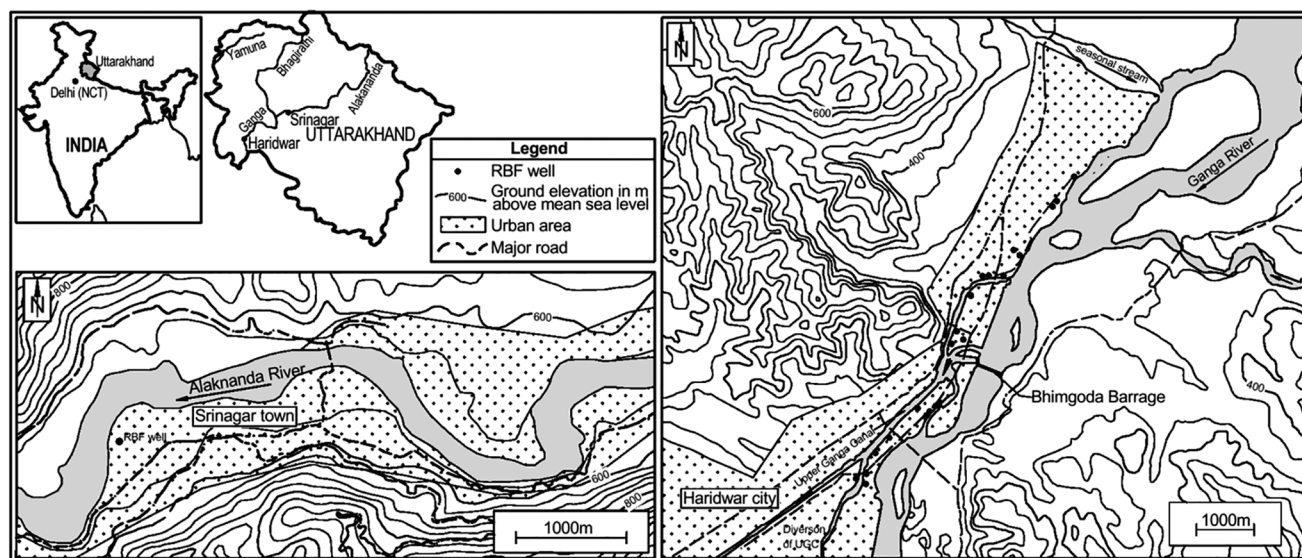
### 1.2.1 Field site in Haridwar by Ganga River

Haridwar is located in the state of Uttarakhand next to the Ganga River and is one of the most important Hindu pilgrimage sites in the world. In addition to the permanent residents of around 225,235 residing in the main part of the city (Census of India, 2011), about 50,000 pilgrims come to Haridwar daily with up to 8.2 million people during specific religious festivals such as the Kumbh Mela (Gangwar & Joshi, 2004) for the ritual of bathing in the Ganga. Hence the city's drinking water supply, managed by the Uttarakhand State Water Supply and Sewerage Organisation – Uttarakhand Jal Sansthan (UJS), both quantitatively and qualitatively, is difficult because of the highly varying demand. As of 2013, around 59,000 to 67,000 m<sup>3</sup>/d of water for drinking purposes is abstracted from 22 RBF wells (Figure 1.3), which account for around two-thirds of the total drinking water supply to Haridwar city; the remainder is abstracted from groundwater production wells. The abstracted water only requires disinfection by chlorination, and can provide safe drinking water even when facing high variations in water demand and during monsoons. However, in September 2010 during one of the severest monsoons in North India, the Ganga River rose to an unprecedented level of 296 m above sea level (CWC, 2014) inundating the ground surface around some of the nearby RBF wells. Consequently, high turbidity and coliform counts were observed in these wells. In WP1, water quality and hydrogeological site data from Haridwar was collected and analysed. Subsequently, and supported by column experiments, the need for flood-proofing RBF wells was elucidated and guidelines for mitigation of the risk of floods on RBF wells were formulated (Saph Pani D1.2, 2013; see also chapter 2). In conjunction with WPs 4, 5 and 6 the current disinfection (post-treatment) of RBF water was assessed and suggestions for improvement were made, a numerical groundwater flow modelling study was conducted to obtain an improved understanding of the travel time, flow path and portion of bank filtrate abstracted by the RBF wells, and an integrated assessment of technical and socio-economic aspects (Essl *et al.* 2014) as well as a risk-based assessment of the RBF site were conducted (Bartak *et al.* 2015).

### 1.2.2 Field site in Srinagar by Alaknanda River

The town of Srinagar is located along the road to the important Hindu shrine of Badrinath in the Himalayas. It is the main commercial and administrative centre of the district of Pauri in Uttarakhand, and is one of the largest towns along the Alaknanda River. However, the production of drinking water has not been able to match the growing demand. Around 90% of the drinking water is conventionally treated surface water from Alaknanda River (produced from directly abstracted Alaknanda River water followed by conventional treatment), with the remainder being supplied by groundwater and RBF

wells. During the severe Monsoons of 2010, 2011 and 2013 the surface water supply had to be discontinued for several days due to excessive turbidity and damage to water abstraction structures. To determine whether RBF could serve as an alternative to surface water treatment for the year-round production of drinking water and to address the deficit between demand and supply, UJS constructed an RBF well in 2010 (Kimothi *et al.* 2012; Figure 1.3). However, extreme events like the highest ever-recorded flood of June 2013 resulted in the RBF well being completely inundated and a fine sand layer of more than 1 m thickness was deposited over the well, even though the site was considered to have an elevation above the previous highest recorded flood level (see also Chapter 2). In WP1 the water quality of the RBF system was investigated at this site (Saph Pani D1.1, 2012). Nitrate in excess of the Indian drinking water limit of 45 mg/L was found in the water abstracted by the RBF well. The source might be the leaching of nitrate from geogenic phyllite present in the bedrock (Gupta *et al.* 2015a) and as such is an extremely rare case for an RBF site. Using the primary field data collected in WP1, a groundwater flow modelling study was conducted in WP5 to optimise the operation of the RBF site in order to lower the nitrate concentration in the abstracted water (Saph Pani D5.2, 2012). Furthermore, the breakthrough of bacteriological indicators was assessed to mitigate the risk of floods and a sanitary sealing was constructed for the RBF well (Saph Pani D1.2, 2013; see also Chapter 2).



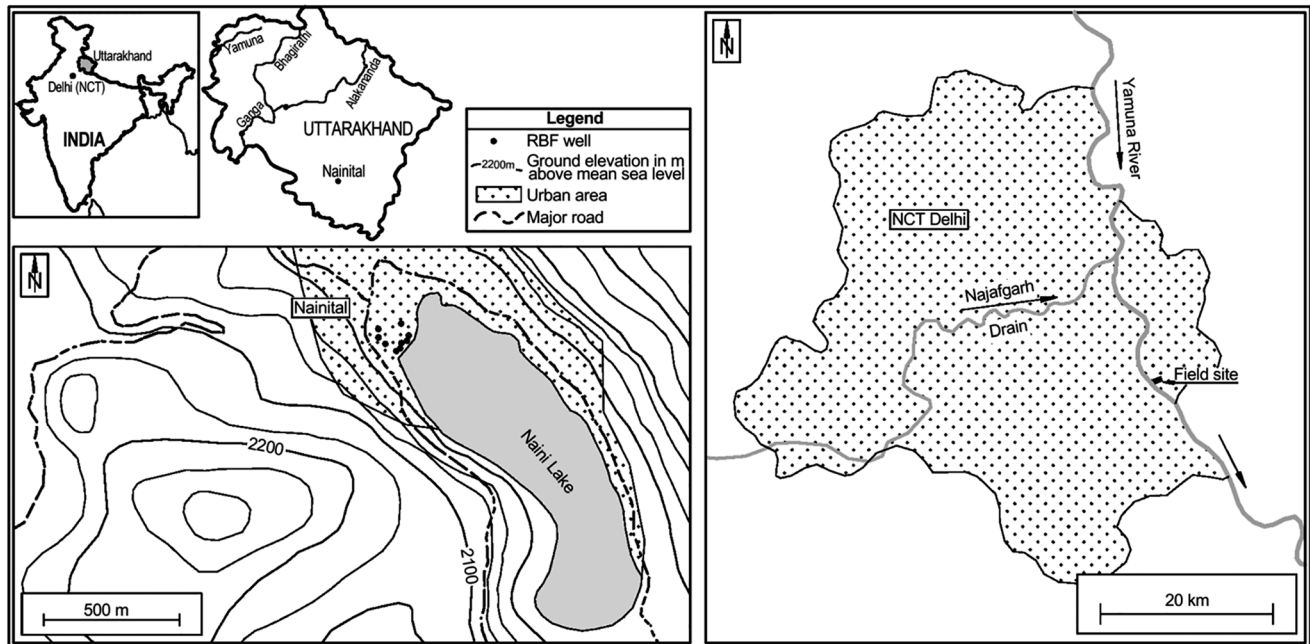
**Figure 1.3** Location of riverbank filtration (RBF) wells at Srinagar (left) and Haridwar (right), Uttarakhand (HTW Dresden and IIT Roorkee, 2014).

### 1.2.3 Nainital by Nainital Lake

Nainital, located around the Naini Lake in the foothills of the Himalayas in the Kumaon region of Uttarakhand, is the administrative headquarters of the district of Nainital and is a popular tourist destination especially in summer and by virtue of the lake. From 1955 up to around 2007, lake water was directly abstracted and conventionally treated to supplement the existing water supply from springs (Dash *et al.* 2008). The BF system was subsequently developed in stages at the bank of Lake Naini (Figure 1.4) starting in 1990 and by around 2007 had completely replaced the direct abstraction of surface water on account of the superior treatment by BF (Dash *et al.* 2008). However, over the past decades anthropogenic activities in Nainital led to severe degradation of the Naini Lake, which became increasingly eutrophic (Pant *et al.* 1981). Since 2007, several measures have been taken to conserve the lake and check its eutrophication, including upgradation of the town's sewer system to prevent wastewater from entering the lake, cleaning and prohibiting solid waste disposal into the lake and introduction of hypolimnetic aeration in the lake (Gupta *et al.* 2015b). In WP1, the water quality of the BF wells, lake and groundwater was investigated by Gupta *et al.* (2015b; see also Chapter 3) to assess BF performance after recent changes in the Naini Lake and its catchment (see chapter 3). Stable isotope analysis was conducted to assess the portion of groundwater and bank filtrate in each well. The results were compared with previous data (Dash *et al.* 2008) to assess the long-term changes in water quality. This study also revealed important insights into the groundwater hydrology of the BF well field in



Nainital and showed that bank filtrate has better water quality than groundwater in terms of inorganic ion concentrations throughout the year. The water quality data was used to determine options for post-treatment in conjunction with WP4.



**Figure 1.4** Location of bank filtration (BF) wells at Nainital (left) and study area in National Capital Territory (NCT) Delhi (right) (HTW Dresden and IIT Roorkee, 2014).

#### 1.2.4 National Capital Territory (NCT) Delhi by Yamuna River

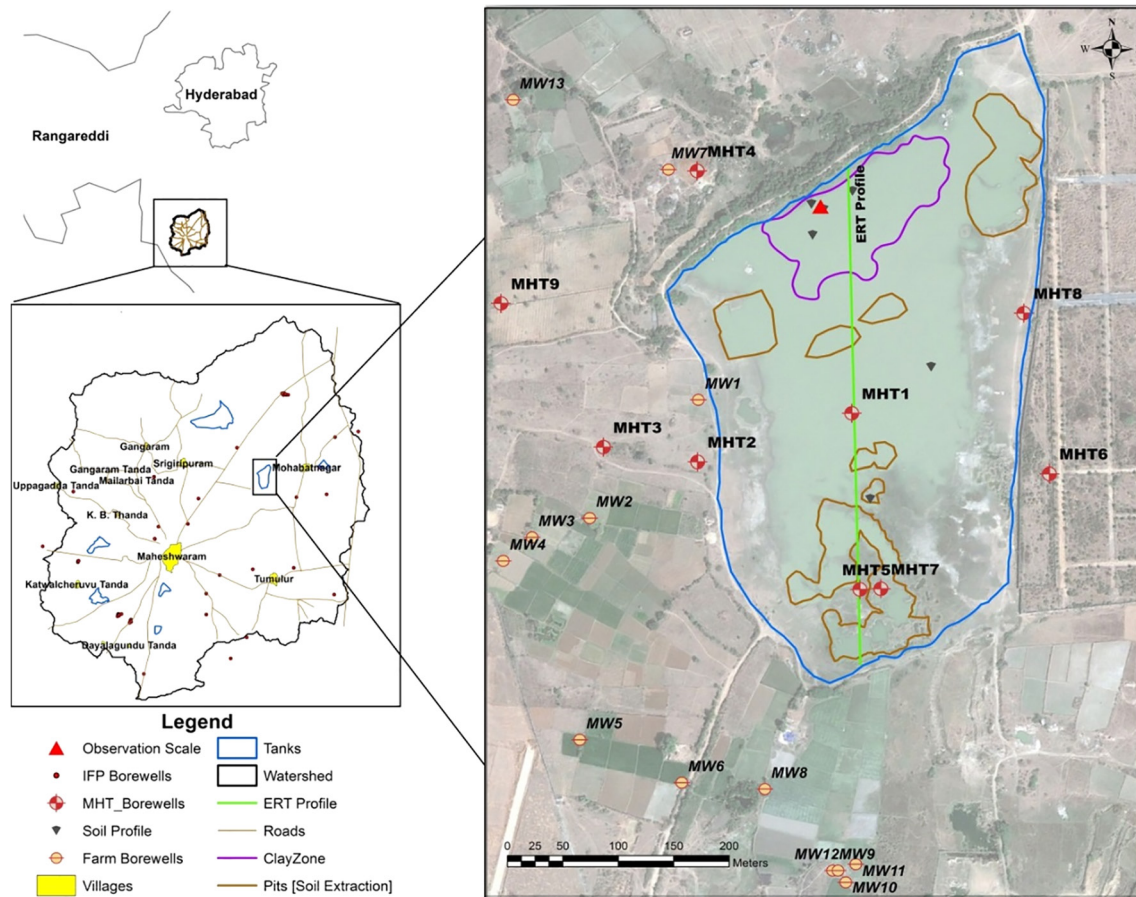
The study site is located on the eastern bank of the Yamuna River in Delhi opposite the Nizamuddin area on the western bank of the river (Figure 1.4). Here, the Yamuna River is heavily polluted by poorly treated and untreated urban wastewater and the existing drinking water production wells close to the river produce bank filtrate of low quality. The high concentration of nitrogen (mostly ammonium) makes the abstracted groundwater unfit for drinking water purposes and one of the production wells is not used for the water supply most of the time (Groeschke, 2013). Furthermore, the groundwater is used by urban dwellers and small scale farmers. Before distribution, the bank filtrate is mixed with surface water to reduce the ammonium concentration. If the ammonium concentration is too high the distribution is stopped. In order to understand the behaviour of ammonium in aquifers at BF sites with surface waters highly polluted by untreated sewage, field data have been collected and laboratory column studies have been conducted with aquifer material from Delhi. Results of the analyses and experiments were used as the basis for recommendations about the application of BF in nitrogen contaminated aquifers (see also Chapter 4). The removal of pollutants (nitrogen species and trace organic compounds) was studied and appropriate post-treatment was suggested in WP4.

#### 1.2.5 Maheshwaram

One of the main experimental watersheds relevant for MAR studies in WP2 is located around the town of Maheshwaram (Figure 1.5) near Hyderabad. With a total area of 54 km<sup>2</sup>, the watershed is located in a semi-arid hard-rock context typical of the entire region where the saprolite, a chemically weathered rock, layer (10–20 m thick) is usually unsaturated. It is a watershed with a high density of groundwater production wells (>700) mostly for paddy irrigation. Changes in land use have occurred since 2006 because of the new Hyderabad international airport located less than 10 km away. It is expected to become a peri-urban area within the coming years as significant housing projects are planned. Over the last decade MAR has been implemented throughout the watershed in the form of percolation tanks, check dams, etc. (see Chapter 7). Intensive groundwater exploitation for irrigation and domestic use has resulted in aquifer over-exploitation and deterioration of groundwater quality. The fluoride level is above the maximum permissible limit of 1.5 mg/L and salinization and agricultural inputs have been observed. MAR is an attractive concept for groundwater augmentation and enhanced groundwater quality.



The objective of the tasks in WP2 for the case study site was to investigate the potential of percolation tanks to enhance recharge and groundwater quality in the over-exploited hard-rock aquifer by implementing a sophisticated monitoring strategy for groundwater levels and quality, conducting hydro-geochemical analysis, and investigating the hydrodynamics with the support of a conceptual groundwater balance model developed in cooperation with WP5.



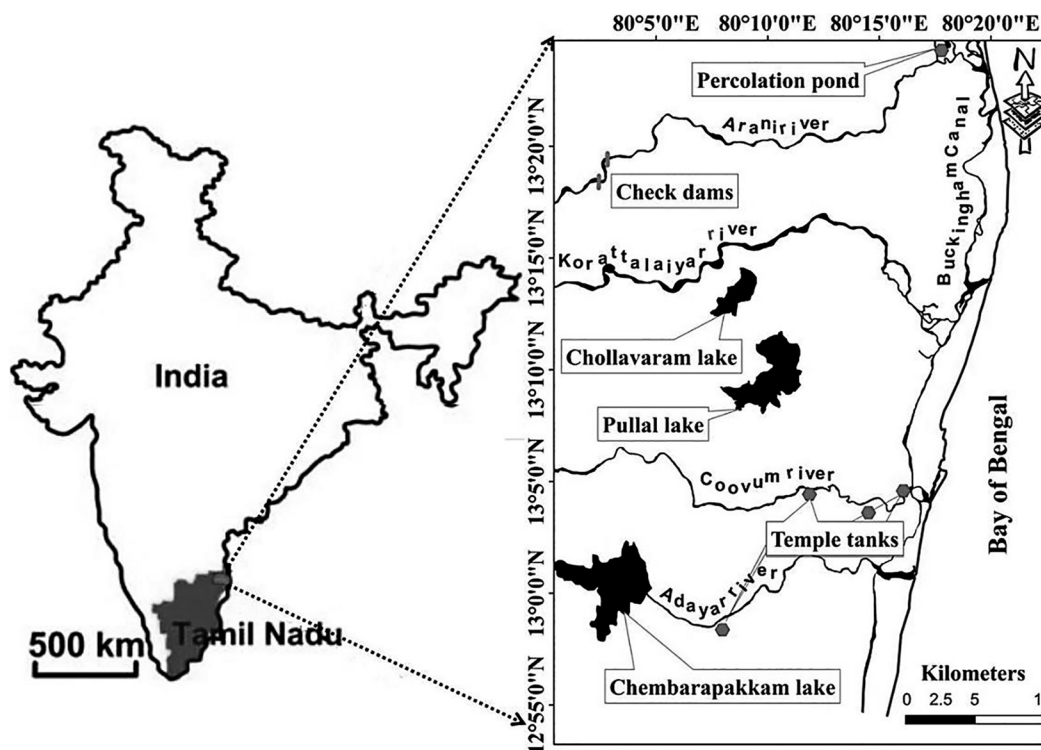
**Figure 1.5** Geological map of Maheshwaram watershed (see Figure 1.2 for location of study site within India) (Boisson *et al.* 2014c).

### 1.2.6 Chennai

Chennai is the largest city in South India located in the eastern coastal plains. Water supply to the Chennai city is met from reservoirs and by pumping groundwater. The total surface water basin area of Chennai region is 7,282 km<sup>2</sup>, divided between Andhra Pradesh and Tamil Nadu. The north east monsoon is significant as it replenishes the surface reservoirs and also recharges the groundwater. Water is stored in reservoirs and used cautiously. The reservoirs are virtually empty before the next annual rainfall and the shortfall in surface water storage systems is met from groundwater resources (Elango, 2009). More than one third of the water demand is met by groundwater from three wellfields known as Minjur, Panjetty and Tamaraiakkam situated about 40 km north of Chennai (Figure 1.6). The average rainfall on the basin is 7–9 billion m<sup>3</sup>/year, which corresponds to 950–1,250 mm/year. Even though the annual rainfall is moderate, extreme cases of very high daily rainfall were recorded in past in the Chennai basin. Severe rainfall during short periods of time combined with high percentage of impervious areas in this region is the major source of flooding (D5.2, Saph Pani). The city has two major rivers, Adyar and Cooum. Both rivers usually carry sewage and only heavy rain events can flush them. The city itself has meager groundwater resources due to very little recharge. However, a considerable amount of groundwater is pumped to the city from well fields located in the Arani and Korttalai river basins north of Chennai. Severe pumping from these regions for Chennai's water supply and for local irrigational needs has resulted in seawater intrusion (D5.2, Saph Pani). The Minjur wellfield lies

nearest to the coast (9 km) and is hydraulically connected with the sea. Since 1969 this wellfield has been intruded by seawater up to a distance of 15km inland due to extensive extraction of groundwater for agricultural, industrial and domestic uses for prolonged periods. Thus, on one hand the Chennai region is affected by floods and on the other hand by severe shortage of water. The objective of the tasks in WP2 for the Chennai case study site was to undertake a comprehensive assessment of MAR for coping with sea-water intrusion and groundwater over-exploitation and to develop recommendations and a management plan for implementing MAR systems that utilize excess monsoon water to counteract seawater intrusion by:

- Using existing data in close collaboration with WP5 (modelling).
- Conducting a water quality monitoring programme, hydro-geochemical analyses and geophysical investigations.
- Identifying a pilot area or an existing recharge structure to determine its efficiency in preventing seawater intrusion.
- Development of a decision support system for identifying suitable measures to counteract seawater intrusion by utilizing artificial recharge in cooperation with WP5.
- Assessing the impact of infiltration through temple tanks on groundwater quality development.



**Figure 1.6** Location of the Check dams and the Percolation pond north of Chennai city (Raicy *et al.* 2015).

### 1.2.7 Raipur

Raipur city is situated in the central Indian state of Chhattisgarh in the fertile plains of the Mahanadi River basin. According to a projection, the present population of the city is nearly 1,200,000 (Agrawal, 2013). Currently about 65% of the city's water supply is covered by pipeline distribution of surface water from Kharun River, a tributary of Mahanadi that has been dammed to create a reservoir. About 35% is supplied by local hand pumps which tap the aquifers that are sparsely distributed throughout the city and consist mainly of deeply weathered baseline rocks. Growth of population led to excessive withdrawal and depletion of the old dug wells and hand pumps. At present any private individual interested in having a bore well has to seek a series of permits and 'No Objection Certificates' from the Government.

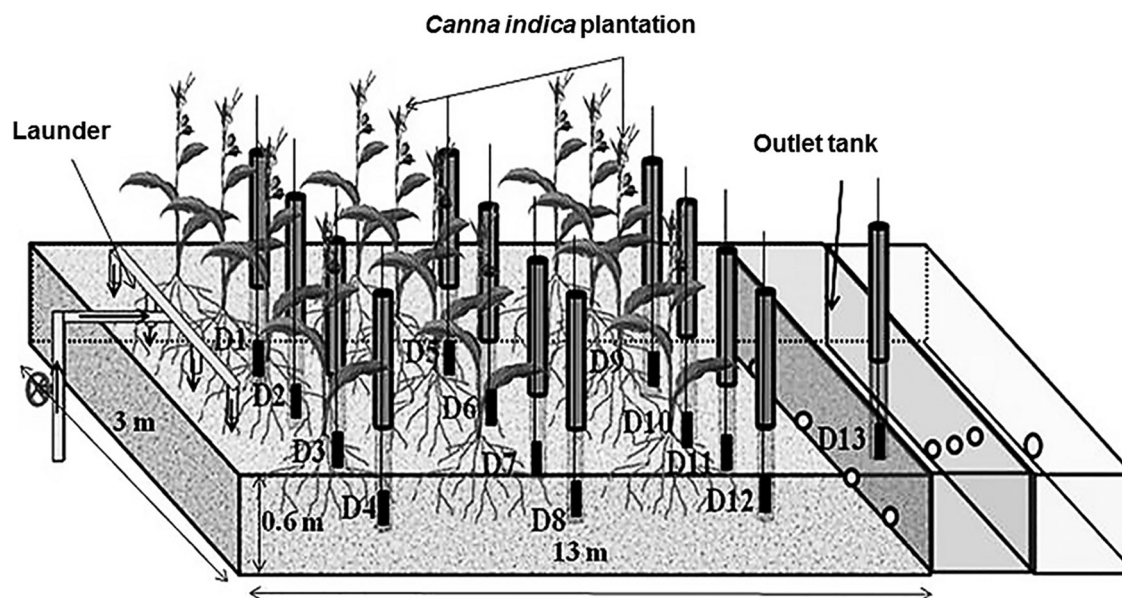
Initially Raipur had 154 natural and man-made water bodies, locally called talabs. These water bodies were usually connected by storm water channels. Therefore, despite a history of heavy rainfall of more than 1,200 mm during the monsoon period of 4–5 months per year, the city never had any problems with water logging and flooding. Because of the unplanned city development only 85 talabs have survived to the present. As a result the excess storm water leads to water logging even

during short but intensive rainfall events. The excess of water during monsoon time is in strong contrast to the periods of water scarcity throughout the rest of the year. Furthermore, the large scale deterioration of lake water quality throughout the city due to the discharge and dumping of municipal wastes, both liquid and solid, is a big problem. Some highly contaminated lakes have become so malodorous and intense breeding sites for mosquitos that nearby residents are considering the option of converting these talabs into landfilling or drying them up. This would, however, further complicate storm water management and increase the problem of water logging.

In lieu of population growth and the resulting pressure to the already inadequate infrastructure, there is a need for reintegration of lakes in the overall water management in order to address the problems of ground water depletion, buffering of flood waters, and prevention of water logging. The objective of the tasks in WP2 for Raipur was to make an assessment of the potential of storm water infiltration from existing talabs by selecting test sites for infiltration studies, hydrogeological investigations and groundwater quality investigations on the basis of an existing storm water management model, and to derive recommendations for measures to enhance lake water quality and improve infiltration capacity if possible.

### 1.2.8 Mumbai

The Mumbai case study in WP3 focused on the setup and evaluation of a CW. The study site is located in Mumbai on the campus of IIT Bombay which is set in the northern suburb of the city. Currently, about 15,000 people reside on the campus including students, staff and family of faculties. The campus area is about 200 hectares and a wide range of biodiversity can be found. A pilot scale horizontal subsurface flow CW was commissioned for demonstration and research purposes. Local available wastewater from the campus was used as a feed for the wetland. Tracer tests were performed to investigate the flow pattern in the wetland and biochar was produced from the plant material. The objectives of the case study were to determine suitable plant species to be applied in the wetland, the assessment of performance of the system and to explore innovative ways to utilise the harvested plant material. The schematic setup of the pilot-scale CW-facility is displayed in Figure 1.7.



**Figure 1.7** Scheme of the constructed wetland, (D1, D2, D3, . . . , D13 are the detectors).

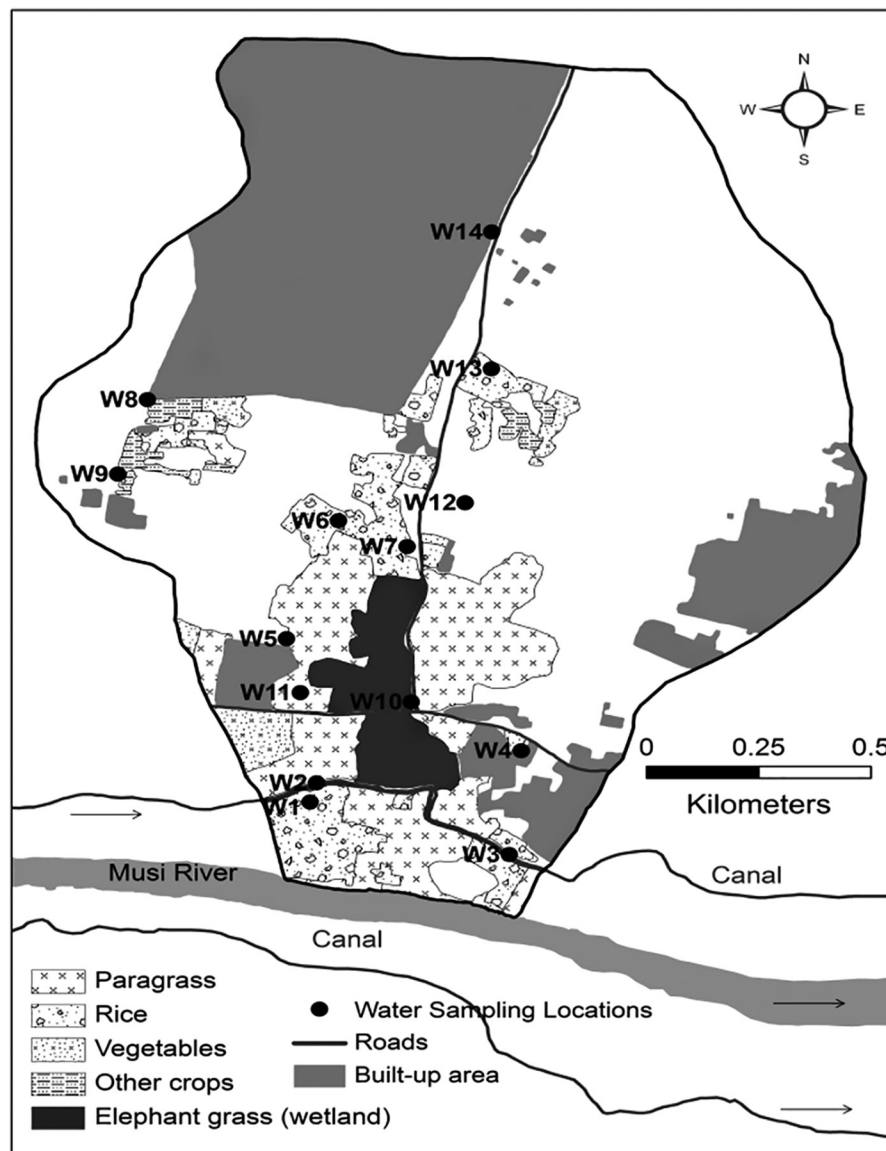
### 1.2.9 Hyderabad, Musi River watershed

The Musi River flows through the city of Hyderabad which is located in the state of Telangana and is associated with an ancient irrigation system comprising a series of natural and engineered wetlands (Figure 1.8). Over 1.2 million m<sup>3</sup>/day of partially treated domestic and industrial wastewater is discharged into the river from the city.

The river water is used for irrigation, either directly via a system of irrigation canals or after storage in sedimentation ponds/tanks (Ensink *et al.* 2010). The wastewater is a significant resource in this semi-arid periurban environment where the cultivation of fodder grass, paddy and vegetables provides economic benefits to many inhabitants of the area.



Year round cultivation, which generates large return flows from irrigated fields contributes to a large share of the hard rock aquifer recharge. Shallow groundwater is also pumped locally for irrigation on terrains where canal water is not accessible, or where it is too polluted for certain crops, especially paddy rice. A micro-watershed in the Musi River catchment, near Hyderabad was hydrodynamically characterised (WP3) and modelled (WP5) and the natural cycles of water, salt, nutrients and selected pollutants were described. This model was used to optimise the performance of a combination of passive and engineered forms of treatment.



**Figure 1.8** Musi River micro-watershed downstream of Hyderabad city. *Source:* IWMI (see chapter 11).

### 1.2.10 MAR and SAT Case study summary

Some basic features pertaining to study sites investigating MAR or wetland approaches are presented in Table 1.3. Three of the sites investigated MAR and are intended to augment the groundwater resources for drinking water (two cases) and irrigation water (one case) supply. In the Musi River Watershed wetlands could make a contribution to improve water resources quality for irrigation water.



**Table 1.3** Features of case studies on MAR and wetlands in Maheshwaram Chennai, Hyderabad and Raipur.

Urban Case Study Site	Maheshwaram	Chennai	Raipur	Hyderabad (Musli River Watershed)
Natural water systems & treatment technologies considered	MAR	MAR	MAR	Wetland
Permanent population (Census of India, 2011)	4,000	6,560,250	1,200,000 (2010)	5,742,000
Rainfall [mm/a]	700–1,000	950–1,250	1,400	300–500
Current major raw water source	Groundwater	Groundwater (supplied from well fields of Arani and Korttalai river basins north of city) & surface water	Surface & Groundwater	Surface water & shallow groundwater
Uses of raw water	Irrigation	Drinking water	Drinking water	Irrigation, ground water recharge, nutrient recycling, pathogen removal
Water quality	Poor (high concentration of salts & nutrients)	Varying degrees (salt water intrusion due to over abstraction of groundwater)	Poor, due to eutrophication of local talabs of varying sizes (disposal of partially treated to untreated domestic sewage)	Poor due to domestic sewage, industrial pollutants and agriculture run-off
Issues relevant to natural water systems	<ul style="list-style-type: none"> <li>Overexploitation of groundwater</li> <li>Deterioration of groundwater quality</li> <li>Fluoride exceeds maximum permissible limit (1.5 mg/L)</li> <li>Salinisation</li> </ul>	<ul style="list-style-type: none"> <li>Low exploitable groundwater resources due to low recharge</li> <li>Floods due to inadequate storm water run-off in monsoon</li> <li>Salt water intrusion</li> <li>Hydro-geochemical evolution – cation exchange</li> </ul>	<ul style="list-style-type: none"> <li>Contamination of surface water</li> <li>Eutrophication</li> <li>Waterlogging</li> <li>Flooding from storm water discharge</li> <li>Risk for future contamination of groundwater with nitrate</li> </ul>	<ul style="list-style-type: none"> <li>Contaminants from sewers and industries; treatment potential not quantified</li> <li>Minimal institutional support</li> </ul>
Treatment technologies to be addressed in the project	<ul style="list-style-type: none"> <li>Groundwater aug-mentation by MAR</li> <li>Enhanced ground-water quality by infiltrating water into the aquifer through percolation tanks and defunct dugwells</li> </ul>	<ul style="list-style-type: none"> <li>Check-dams</li> <li>Pre-treatment i.e. settling ponds</li> <li>treatment: sand filtration, infiltration ponds</li> </ul>	Using city's numerous existing lakes and talabs as: <ul style="list-style-type: none"> <li>Infiltration ponds</li> <li>For sand filtration</li> <li>Integrating storm water drainage into an integrated MAR approach</li> </ul>	Based on the status of existing surface water quality, enhancement of natural treatment technologies to reach water quality standards for drinking and/or agriculture purposes
Relevant references	Boisson <i>et al.</i> (2014a, 2014b); Pettenati <i>et al.</i> (2014); Picot-Colbeaux <i>et al.</i> (2014); Dewandel <i>et al.</i> (2006); Maréchal <i>et al.</i> (2004, 2006); Wyns <i>et al.</i> (2004); Perrin <i>et al.</i> (2011)	Parimalarenganayaki and Elango (2014), Elango (2009)	CGWB (2007), Mukherjee <i>et al.</i> (2011)	Amerasinghe <i>et al.</i> (2009); Schmitt <i>et al.</i> (2010)

### 1.3 STRUCTURE OF THE BOOK

The book follows the project structure and depicts the various case studies and the accomplished investigations in detail in the different chapters. The first sections cover the BF studies, first giving an overview on the relevance of that technology for India and then reporting on case study specific work. Similarly, the book section on MAR will start with a review chapter on the current MAR practice in India. Maheshwaram and Chennai will then be detailed as case studies and the methodologies and results will be depicted.

Natural and CW systems are in the focus of the third book section, which is opened by a status on natural water treatment including wetlands for wastewater treatment in India. The experiences gained with the experimental studies utilizing the CW system on the IIT Bombay campus including complementary small scale studies are described subsequently. The Musi river basin is the second case study on wetland systems which is illustrated.

The book goes further to analyse the role of pre- and post-treatment systems in combination with natural treatment components, particularly wetlands and MAR. A methodology to present adequate pre- and post-treatment systems to comply with water quality requirements is presented. Dedicated chapters detail the role of hydrological and hydro-geochemical modelling approaches to facilitate analysis, design and operation of natural water treatment systems. Examples are provided related to the Saph Pani case studies which show how the fundamental understanding of the conditions can help in system development. A section on integrated assessment of natural water treatment systems concludes the book. The basic methodology followed is outlined and application cases are described. Specific attention is paid to health risk assessment and the basic structure of MAR recharge risk assessment guidelines is outlined.

### 1.4 REFERENCES

- Agrawal V. (2013). Raipur as a new capital: Impact on population. *International Journal of Engineering Research Science & Technology*, 2(1), 41–46. ISSN: 2319–5991
- Amerasinghe P., Weckenbrock P., Simmons R., Acharya S. and Blummel M. (2009). An atlas of water quality, health and agronomic risks and benefits associated with “wastewater” irrigated agriculture an atlas of water quality and agronomic risk and benefits associated with “wastewater” irrigated agriculture. A study from the banks of the Musi River, India. <http://www.freidok.uni-freiburg.de/volltexte/6963> (accessed 15 January 2014).
- Asano T. (1985). Artificial Recharge of Groundwater. Butterworth Publishers, Boston, United States.
- Athavale R. N., Rangarajan R. and Muralidharan D. (1992). Measurement of natural recharge in India. *Journal of Geological Society of India*, 39(3), 235–244.
- Aquastat (2010). FAO’s global water information system. <http://www.fao.org/nr/aquastat/> (accessed 8 September 2014).
- Bartak R., Page D., Sandhu C., Grischek T., Saini B., Mehrotra I., Jain C. K. and Ghosh N. C. (2015). Application of risk-based assessment and management to riverbank filtration sites in India. *Journal of Water and Health*, 13(1), 174–189.
- Boisson A., Baisset M., Alazard M., Perrin J., Villesseche D., Kloppmann W., Chandra S., Dewandel B., Picot-Colbeaux G., Ahmed S. and Maréchal J. C. (2014a). Comparison of surface and groundwater balance approaches in the evaluation of managed aquifer recharge structure: Case of a percolation tank in hard rocks aquifer in India. *Journal of Hydrology*, 519, 1620–1633. doi:10.1016/j.jhydrol.2014.09.022.
- Boisson A., Villesseche D., Baisset M., Perrin J., Viossanges M., Kloppmann W., Chandra S., Dewandel B., Picot-Colbeaux G., Rangarajan R., Maréchal J. C. and Ahmed S. (2014b). Questioning the impact and sustainability of percolation tanks as aquifer recharge structures in semi-arid crystalline context. *Environmental Earth Sciences*, doi 10.1007/s12665-014-3229-2.
- Boisson A., Guihéneuf N., Perrin J., Maréchal J. C., Bour O., Dewandel B., Dausse A., Viossanges M. and Chandra S. (2014c). Estimation of the vertical evolution of hydrodynamic parameters in weathered and fractured crystalline rock aquifers: Insights from a detailed study on an instrumented site. *Submitted to Hydrogeology Journal*.
- Brown L. R. (2005). Outgrowing the Earth: The Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures. W. W. Norton & Co, New York, United States.
- Census of India (2011). Cities having population 1 lakh and above. Provisional Population Totals. Office of The Registrar General and Census Commissioner, Ministry of Home Affairs, Government of India, India. In: Saph Pani D1.2 (2013). Guidelines for flood-risk management of bank filtration schemes during monsoon in India. Saph Pani Project Deliverable. <http://www.saphpani.eu/downloads> (accessed 29 September 2014).
- CGWB (Central Ground Water Board) (2000). Manual on Artificial Recharge of groundwater, Ministry of Water Resources, Government of India, India. [http://www.cgwb.gov.in/documents/Guide\\_on\\_ArtificialRecharge.pdf](http://www.cgwb.gov.in/documents/Guide_on_ArtificialRecharge.pdf) (accessed 30 September 2014).
- CGWB (2007). Central Ground Water Board North Central Chhattisgarh Region. [www.cgwb.gov.in/NCCR/index.html](http://www.cgwb.gov.in/NCCR/index.html) (accessed 8 September 2014).
- CWC (2014). River stage gauge and flood forecasting station Haridwar. Central Water Commission (CWC), Ministry of Water Resources, Government of India, India. <http://www.india-water.gov.in/ffs/data-flow-list-based/flood-forecasted-site> (accessed 28 August 2014).

- Campana M. E. (2007). Sustainable Management of Groundwater in Mexico. In: Proceedings of a workshop, Series: Strengthening Science-Based Making in Developing Countries, pp. 26–35.
- CPCB (Central Pollution Control Board) (2009). Status of water supply, wastewater generation and treatment in class-I cities and class-II towns of India. Control of Urban Pollution series: CUPS/70/2009–10, CPCB, Ministry of Environment and Forests, Government of India, New Delhi, India.
- Dash R. R., Mehrotra I., Kumar P. and Grischek T. (2008). Lake bank filtration at Nainital, India: Water-quality evaluation. *Hydrogeol. J.*, **16**(6), 1089–1099.
- Dash R. R., Bhanu Prakash E. V. P., Kumar P., Mehrotra I., Sandhu C. and Grischek T. (2010). River bank filtration in Haridwar, India: Removal of turbidity, organics and bacteria. *Hydrogeology Journal*, **18**(4), 973–983.
- Dewandel B., Lachassagne P., Wyns R., Maréchal J. C. and Krishnamurthy N. S. (2006). A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering. *J. Hydrol.*, **330**, 260–284.
- Elango L. (2009). Groundwater modeling to assess the feasibility of pumping seawater from a beach well for Chennai desalinization plant. *Journal of Applied hydrology*, **22**(1), 84–92.
- Elango L. and Senthilkumar M. (2006). Modelling the effect of subsurface barrier on groundwater flow regime. In: MODFLOW and More, Managing groundwater systems, Colorado School of Mines, pp. 806–810.
- Ensink J. H., Scott C. A., Brooker S. and Cairncross S. (2010). Sewage disposal in the Musi-River, India: Water quality remediation through irrigation infrastructure. *Irrigation and Drainage Systems*, **24**(1–2), 65–77.
- Essl L., Starkl M., Kimothi P. C., Sandhu C. and Grischek T. (2014). Riverbank filtration and managed aquifer recharge as alternative water supply technologies for India: Strengths–weaknesses–opportunities–threats analysis. *Water Science and Technology: Water Supply*, **14**(4), 690–697.
- FAO (2007). The state of the world's land and water resources and for food and agriculture, managing systems at risk, Food and Agriculture Organization of the United States and Earthscan, <http://www.fao.org/docrep/017/i1688e/i1688e.pdf> (accessed 21 January 2015).
- Gale I. and Dillon P. (2005). Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas. UNESCO-IHP, Paris, France.
- Gangwar K. K. and Joshi B. D. (2004). A preliminary study on solid waste generation at Har Ki Pauri, Haridwar, around the Ardh-Kumbh period of sacred bathing in the river Ganga in 2004. *Environmentalist*, **28**(3), 297–300.
- Groeschke M. (2013). Challenges to riverbank filtration in Delhi (India): Elevated ammonium concentrations in the groundwater of an alluvial aquifer. *Zentralblatt für Geologie und Paläontologie*, **1**(1), 1–9.
- Gupta A., Ronghang M., Kumar P., Mehrotra I., Kumar S., Grischek T., Sandhu C. and Knoeller K. (2015a). Nitrate Contamination of Riverbank Filtrate at Srinagar, Uttarakhand, India: A Case of Geogenic Mineralization. *Submitted to Journal of Hydrology*.
- Gupta A., Singh H., Ahmed F., Mehrotra I., Kumar P., Kumar S., Grischek T. and Sandhu C. (2015b). Lake bank filtration in landslide debris: Irregular hydrology with effective filtration. *Sustain. Water Resour. Manag.* doi:10.1007/s40899-015-0001-z
- HTW Dresden and IIT Roorkee (2014). Case study of nitrate pollution in groundwater of Srinagar and investigations about the water quality in Haridwar. Report prepared by R. Mink and S. Paufler, Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany in cooperation with Environmental Engineering Section, Department of Civil Engineering, Indian Institute of Technology Roorkee (IIT Roorkee), Roorkee, India.
- India Vision 2020 (2002). Planning Commission Report, Government of India, New Delhi, India. [http://www.google.ch/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCoQFjAB&url=http%3A%2F%2Fwww.teindia.nic.in%2FFiles%2FReports%2FCCR%2Fpl\\_vsn2020.pdf&ei=GrwNVMKaDsay7AafhYHoCg&usq=AFQjCNEJF3UivByv5IjPIrXbZPG-NQWj8Q&bvm=bv.74649129,d.ZGU](http://www.google.ch/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CCoQFjAB&url=http%3A%2F%2Fwww.teindia.nic.in%2FFiles%2FReports%2FCCR%2Fpl_vsn2020.pdf&ei=GrwNVMKaDsay7AafhYHoCg&usq=AFQjCNEJF3UivByv5IjPIrXbZPG-NQWj8Q&bvm=bv.74649129,d.ZGU) (accessed 8 September 2014).
- Journal of Indian Water Works Association (JIWWA) (2012). Special Issue on River Bank Filtration. Journal of Indian Water Works Association, Mumbai, India. ISSN 0970–275X.
- Karanth K. R. and Prasad P. S. (1979). Some studies on hydrologic parameters of groundwater recharge in Andhra Pradesh, *Journal of Geological Society of India*, **20**, 404–414.
- Kimothi P. C., Dimri D. D., Adlakha L. K., Kumar S., Rawat O. P., Patwal P. S., Grischek T., Sandhu C., Ebermann J., Ruppert M., Dobhal R., Ronghang M., Kumar P., Mehrotra I. and Uniyal H. P. (2012). Development of Riverbank Filtration in Uttarakhand. *Journal of Indian Water Works Association*, Special Issue on River Bank Filtration (December, 2012), 13–18.
- Lal M. (2001). Climatic Change—Implications for India's Water Resources. *Journal of Social and Economic Development*, **3**, 58–87.
- Lorenzen G., Sprenger C., Taute T., Pekdeger A., Mittal A. 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.
- Maréchal J. C., Dewandel B. and Subrahmanyam K. (2004). Use of hydraulic tests at different scales to characterize fracture network properties in the weathered-fractured layer of a hard rock aquifer. *Water Resour. Res.*, **40**(11), W11508. doi:10.1029/2004WR003137.
- Maréchal J. C., Dewandel B., Ahmed S., Galeazzi L. and Zaidi F. K. (2006). Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. *J. Hydrol.*, **329**, 281–293.
- McIntosh A. C. (2003). Asian Water Supplies: Reaching the Urban Poor. IWA Publ., London, United Kingdom.
- Mishra B. K., Takara K., Asce M. and Tachikawa Y. (2009). Integrating the NRCS Runoff Curve Number in Delineation of Hydrologic Homogeneous regions. *Journal of hydrologic engineering*, 10.1061/ASCEHE.1943–5584.0000101.
- Mukherjee R., Sahoo M. and Naik K. C. (2011). Raipur city, Chhattisgarh. In: Groundwater scenario in major cities of India. Report of Central Ground Water Board, Government of India, pp. 188–195.

- Muralidharan D., Andrade R. and Rangarajan R. (2007). Evaluation of check-dam recharge through water-table response in ponding area, *Current Science*, **92**(10), 1350–1352.
- Nagaraj N. (1999). Institutional management regimes for pricing of irrigation water: The French model—lessons for India, *Agricultural Systems*, **61**(3), 191–205. doi:10.1016/S0308–521X(99)00052–9.
- NWP (National Water Policy) (2002). Ministry of Water Resources, Government of India, New Delhi, India.
- Pant M. C., Gupta P. K., Pande J., Sharma P. C. and Sharma A. P. (1981). Aspects of water pollution in Lake Nainital, U.P., India. *Environmental Conservation*, **8**(2), 113–117.
- Parimalarenganayaki S. and Elango L. (2014). Impact of recharge from a check dam on groundwater quality and assessment of suitability for drinking and irrigation purposes. *Arabian Journal of Geosciences*, **7**(8), 3119–3129.
- Parthasarathi G. S. and Patel A. S. (1997). Groundwater recharge through people's participation in Jamnagar region. *Journal of Indian Water Works Association*, 51–56.
- Pekdeger A., Lorenzen G. and 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 3 (+1) field sites. TECHNEAU integrated project deliverable D5.2.2. <http://www.techneau.org> (accessed 30 September 2014).
- Pettenati M., Picot-Colbeaux G., Thiéry D., Boisson A., Alazard M., Perrin J., Dewandel B., Maréchal J. C., Ahmed S. and Kloppmann W. (2014). Water quality evolution during managed aquifer recharge (MAR) in India crystalline basement aquifers: Reactive transport modeling in critical zone. *GES - Procedia: Earth and Planetary Science*, **10**, 82–87. doi:10.1016/j.proeps.2014.08.016.
- Perrin J., Mascré C., Pauwels H. and Ahmed S. (2011). Solute recycling: An emerging threat to groundwater quality in southern India? *J. Hydrol.*, **398**(1–2), 144–154.
- Picot-Colbeaux G., Thiéry D., Pettenati M., Boisson A., Perrin J., Sarah S., Dewandel B., Maréchal J. C., Ahmed S. and Kloppmann, W. (2014). Modeling managed aquifer recharge capacity of crystalline aquifers in semi-arid context (South India): Implementing natural percolation tank dynamics into MARTHE code. *Submitted to Hydrogeology Journal*.
- Ragunath H. M. (1987). Groundwater, 2nd edn, New Age, International (p) Limited Publisher, New Delhi, India.
- Raicy M. C., Renganayaki S. P., Thirunavukkarasu M. and Elango L. (2015). Understanding the surface water-ground water inter-actions by geochemical measurements in three different groundwater re-charge structures. *Submitted to Journal of Environmental Science and Management*.
- Raju K. C. B. (1998). Importance of recharging depleted aquifers: State of the art of artificial recharge in India. *Journal of Geological Society of India*, **51**, 429–454.
- Sandhu C. and Grischek T. (2012). Riverbank filtration in India – using ecosystem services to safeguard human health. *Water Science and Technology: Water Supply*, **12**(6), 783–790.
- Sandhu C., Grischek T., Kumar P. and Ray C. (2011). Potential for riverbank filtration in India. *Clean Technologies and Environmental Policy*, **13**(2), 295–316.
- Schmitt R. (2010). Wastewater reuse in Indian peri-urban agriculture: Assessment of irrigation practices in a small, peri-urban catchment in Hyderabad, Andhra Pradesh, India. MSc report, Swiss Federal Institute of Technology, Zurich, Switzerland.
- Saph Pani D1.1 (2012). Database of relevant pollutants in urban areas and their attenuation at RBF sites. Saph Pani Project Deliverable. <http://www.saphpani.eu/downloads> (accessed 19 August 2014).
- Saph Pani D1.2 (2013). Guidelines for flood-risk management of bank filtration schemes during monsoon in India. Saph Pani Project Deliverable. <http://www.saphpani.eu/downloads> (accessed 19 August 2014).
- Saph Pani D5.2 (2012). Preliminary models and system design. Saph Pani Project Deliverable. <http://www.saphpani.eu/downloads> (accessed 19 August 2014).
- Shivanna K., Kulkarni U. P., Joseph T. B. and Navada S. V. (2004). Contribution of storms to groundwater recharge in the semi-arid region of Karnataka, India. *Hydrological Processes*, **18**, 473–485.
- Singh P., Kumar P., Mehrotra I. and Grischek T. (2010). Impact of riverbank filtration on treatment of polluted river water. *J. Environ. Manage.*, **91**(5), 1055–1062.
- Sprenger C., Lorenzen G. and Pekdeger A. (2008). Occurrence and fate of microbial pathogens and organic trace compounds at riverbank filtration sites in Delhi, India. TECHNEAU integrated project: Deliverable D5.2.6. <http://www.techneau.org> (accessed 30 November 2014).
- The Economic Times (2007). <http://economictimes.indiatimes.com/articleshow/msid-2234576,prtpage-1.cms> (accessed 24 October 2010).
- UNICEF, FAO and SaciWATERS (2013). Water in India: Situation and Prospects, Report UNICEF; FAO and SaciWATERS, New Delhi, India.
- UN Water (2006). Coping with water scarcity: A strategic issue and priority for system-wide action. UN Water thematic initiatives Report, New York, United States.
- World Bank (2005). India's Water Economy: Bracing for a Turbulent Future. World Bank Report, Washington DC, United States.
- Wyns R., Baltassat J. M., Lachassagne P., Legtchenko A. and Vairon J. (2004). Application of proton magnetic resonance soundings to groundwater reserves mapping in weathered basement rocks (Brittany, France). *Bull SocGéol France*, **175**, 21–34.
- WHO (2011). Guidelines for drinking-water quality. 4th edn, World Health Organization, Geneva, Switzerland, ISBN 978–9241541851.