Saph Pani

Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India

Project supported by the European Commission within the Seventh Framework Programme Grant agreement No. 282911

Deliverable D 6.2

Report on case study assessments and feasibility studies

Work package	WP6 Integrated sustainability assessment
Deliverable number	D 6.2
Deliverable title	Report on case study assessments and feasibility studies
Due date	Month 24
Actual submission date	07.07.2014
Start date of project	01.10.2011
Participants (Partner short names)	CEMDS (Editor) Anna Univ. (Case study Chennai) BRGM (Social assessment) CSIRO (Risk assessments) IWMI (Case study Hyderabad) SPT (Case study Chennai) UJS (Case study Haridwar)
Authors in alphabetic order	P. Amerasinghe (case study Hyderabad), M. Bouzit (social assessment), N. Brunner (stakeholder surveys Chennai, Hyderabad), L. Essl (all sections apart from risk assessments), M. Jampani (case study Hyderabad), C. Kimothi (case study Haridwar), E. Lakshmanan (case study Chennai), J. Sidhu (risk assessments), D. Page (risk assessments), C. Sandhu (case study Haridwar), M. Starkl (all sections apart from risk assessments), Thirunavukkarasu (case study Chennai)
Reviewed by:	C. Sprenger
Contact for queries	Markus Starkl CEMDS Gregor – Mendel – Strasse 33 A-1180 Wien +43-1-47654-5057 markus.starkl@boku.ac.at
Dissemination level:	PU
(**PU**blic, Restricted to other **P**rogrammes **P**articipants, **RE**stricted to a group specified by the consortium, **CO**nfidential- only for members of the consortium)	
Deliverable Status:	Draft 1.0

Content

Contents

List of tables

List of figures

Abbreviations

CETP	-	Common Effluent Treatment Plant
EIA	-	Environment Impact Assessment
EU	-	European Union
GO	-	Government Order
GOI	-	Government Of India
HC	-	High Court
M.P	-	Miscellaneous Petition
MAR	-	Managed Aquifer Recharge
NGO	-	Non- governmental Organisation
O&M	-	Operation And Maintenance
QMRA	-	Quantitative Microbial Risk Assessment
RBF	-	River Bank Filtration
RWH	-	Rain Water Harvesting
SC	-	Supreme Court
TERI	-	The Energy And Resource Institute
TWAD	-	Tamil Nadu Water Supply and Drainage Board
UNDP	-	United Nations Development Programme
WP	-	Writ Petition
WTP	-	Willingness To Pay

1 Introduction

WP6 is aimed at complementing the technical components of work packages (WP) 1, 2 and 3 through investigations on environmental, health and safety, economic, social and institutional aspects of the Saph Pani technologies. This will enable the Saph Pani project to develop policy recommendations based on an integrated assessment of selected case studies, incorporating social, health, environmental, institutional and economic aspects which are as important as technical factors to achieve sustainable provision and access of water for communities in India.

Task 1 of WP6 conducted an initial sustainability appraisal of currently existing natural treatment systems (Deliverable D6.1, Starkl et al., 2013, Starkl et al., 2014). It has highlighted the importance of these non-technical aspects for the overall sustainability of natural treatment systems.

This deliverable D6.2 conducted a more detailed investigation on those sustainability aspects in selected Saph Pani case studies and encompasses the results of the following tasks:

Task 6.2: Assessment of risks to human health and environment

Task 6:3: Economic feasibility and financial analysis

Task 6.4: Assessment of institutional viability

Task 6.5: Social (risk) acceptance assessment

Task 6.2 has been led by Partner CSIRO (Commonwealth Scientific and Industrial Research Organisation), task 6.3 and 6.4 have been led by CEMDS (Centre for Environmental Management and Decision Support), and task 6.5 has been led by BRGM (Bureau de Recherches Geologiques et Minieres).

The results of this deliverable will feed the following task 6.6 (Integration of assessment tasks) which will assess the overall sustainability of the Saph Pani technologies in the selected case studies.

2 Methodology and approach

2.1 Selection of Saph Pani case studies

In consultation with the technical WPs 1, 2 and 3 suitable case studies were selected for the purpose of the four tasks 6.2-6.5. The selection process has been discussed during the Consortium Meetings in Chennai (December 2012) and Berlin (May 2013) and it was concluded that one case study for each studied Saph Pani technology should be selected, where as far as possible all the four tasks can be conducted. This resulted in the selection of the following three case studies which can be seen in Figure 1.

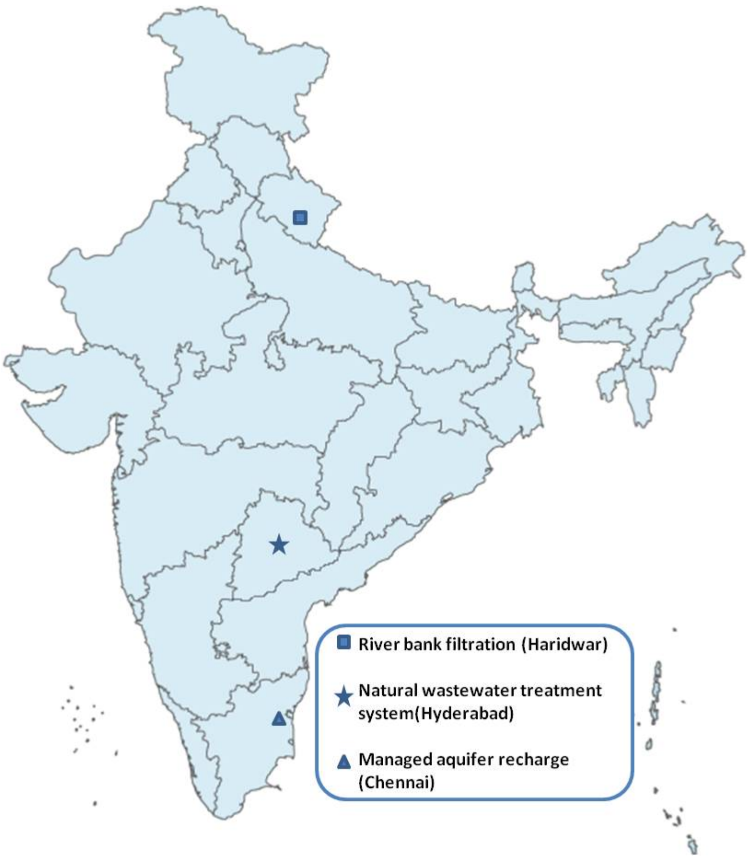


Figure 1 Location of selected Saph Pani case studies.

A main determining factor for the selection of case studies was the availability and accessibility of data and information. An overview of tasks performed at the selected case studies is given in table 1 and is further discussed in the following sections.

Table 1 Overview of tasks performed at selected case studies.

Case Study	Task 6.2 Risk assessment to health and environment	Task 6.3 Economic feasibility	Task 6.4 Institutional viability	Task 6.5 Social (risk) acceptance assessment
Haridwar	Yes (CSIRO)	Moved to WP1 (HTWD)	Summary (UJS)	no
Hyderabad	Simplified (CSIRO)	No	Yes (CEMDS, IWMI)	Simplified (BRGM)
Chennai	no	Simplified (CEMDS, SPT)	Extended (CEMDS, ANNA, SPT)	no

2.2 Assessment of risks to human health and environment

This task is in particular dependent on the availability of extensive monitoring data which were expected to be collected under technical work packages. Due to limitations in these data, this task could only be fully conducted in the Haridwar case study. In the Hyderabad case study a simplified risk assessment was conducted. No risk assessment could be conducted in Chennai.

The methodology for the risk assessment followed the approach developed by CSIRO for the Australian Government which is based on an entry level assessment, investigations and the actual risk assessment. Detailed information on this methodology can be found in NRMMC–EPHC–AHMC (2006 and 2009).

2.3 Economic feasibility and financial analysis

For the case study Haridwar it was decided during the consortium meeting in Berlin in May 2013 that this task should not be continued in WP6 as similar tasks were foreseen in WP 1 and WP 4. To avoid overlaps, it was decided that this task should only be conducted in WP 1. The cost data that were collected so far in WP6 have been provided to WP1 for this purpose. It was envisaged that a brief summary of this cost calculation will be added to this deliverable, however, it was not yet ready at the time of completion of this deliverable.

For the Hyderabad case study it was envisaged that a constructed wetland will be designed in cooperation with WP3 and costs estimated based on the experiences of partner IIT-Bombay. However, due to limited data a design and cost estimation was not possible. Nevertheless, data on the acceptance of additional treatment costs by farmers could be elicited from a previous study of the International Water Management Institute (Mahesh et al. 2014).

For the Chennai case study, the cost estimations have been based on the actual construction costs of recently finished managed aquifer recharge structures (Check-dams and infiltration ponds) which were collected from governmental sources (for Check dams) and from the actual costs of a pilot infiltration pond from Anna University. The financial feasibility has been assessed by comparing the costs for the MAR structures with the costs of alternative measures such as desalination.

2.4 Assessment of institutional viability

This task investigated the applicable laws, policies and regulations for the concerned natural treatment systems and then conducted a more detailed investigation of the institutional situation in each case study location.

In Haridwar, this task was only conducted insofar, as a brief summary of the key institutional issues was provided by the local utility partner (UJS). The reason was that local partner UJS has vast experience with institutional aspects of RBF and therefore there was no need to additionally study these aspects within Saph Pani.

In Hyderabad and Chennai stakeholder workshops were conducted to elicit the perception of the local (institutional and non-institutional) stakeholders on the proposed natural treatment systems.

2.5 Social (risk) acceptance assessment

During the consortium meeting in Berlin in May 2013 this task has been discussed with the Indian case study coordinators and it was concluded that this task shall only be conducted for the Musi case study (as no additional insights to those already found in Deliverable D6.1 were expected). For the Musi case study, social issues concerned mainly the acceptance of local farmers for the use of untreated and treated wastewater for irrigation. In terms of methodology, the social assessment combines qualitative and quantitative techniques (e.g. surveys, focus group workshops, stakeholders' interview etc). As similar studies were already carried out by the case study coordinator IWMI (International Water Management Institute), it was concluded that no additional field survey was required. Further, it was decided to review and analyse the previous studies to assess the social responses related to use of wastewater by farmers.

2.6 Structure of the report

Following the above described methodology and approach, the further sections of this report are structured as follows:

Section 3: Case study Haridwar

Section 4: Case study Hyderabad

Section 5: Case study Chennai

Each case study section is then divided in the following sub-sections:

- Sub-section 1: Overview of case study
- Sub-section 2: Role and potential of natural treatment system

  For the Haridwar case study this section is combined with section 1.
- Sub-section 3: Assessment of risks to human health and environment

  For the Haridwar and Hyderabad case studies a summary has been added to the report. The full risk assessment reports of CSIRO can be found in the Appendix. This task could not be conducted for the Chennai case study (see above).
- Sub-section 4: Economic feasibility and financial analysis

  For the Haridwar case study this task has been shifted to WP1 and can be found in deliverable D1.4 of WP1. For Hyderabad this task could not be conducted (see above). However, it was recorded from previous studies that farmers were in favour of paying for cleaner water, which has been included in sub-section 6.
- Sub-section 5: Assessment of institutional viability
- Sub-section 6: Social (risk) acceptance assessment

  This task was only conducted for the Hyderabad case study (see above).

As the results of this report feed the following task 6.6 which will conduct an integrated assessment, no discussion or conclusions are added in this report. Instead, they will be included in the next deliverable D6.3 (Report on integration of results and final recommendations).

3 Case study Haridwar (River Bank Filtration)

3.1 Overview of case study

Haridwar is situated on the bank of river Ganga, the largest perennial river of India. The town therefore enjoys water of this river as source for drinking by river bank filtration (RBF). However, the RBF wells are located close to the river. For the areas further away from the river ground water is considered the most suitable source. Both these sources are available in abundance in Haridwar.

RBF has been introduced to utilize a natural treatment process through soil infiltration. Even during monsoons, when the turbidity and coliform count of the Ganga River increases considerably, sufficiently pre-treated water is abstracted by the RBF wells such that the abstracted water is only disinfected by adding mainly sodium hypochlorite and sometimes bleaching powder. Further, RBF led to an equilibration of the seasonal variations for the river providing a constant water supply source. For details of the technology please refer to Saph Pani reports D1.1 (2012), D1.2 (2013) and D6.1 (2012), and to relevant sections in other deliverables of work packages 4 and 5.

The first RBF wells were constructed in 1965. Twenty two RBF wells abstract a mixture of bank filtrate and groundwater from the upper unconfined aquifer, which accounts for nearly 68 % (> 43,000 m3/day) of the total drinking water production of the entire population within the main city of Haridwar (Sandhu and Grischek, 2012). Groundwater abstraction through vertical production wells (colloquially called “tube” wells) from the deeper confined aquifer covers the remainder of the drinking water production in the main city. The main challenge for the water supplier are the high variations in water demand during religious festivals such as during the major Kumbh and Ardh Kumbh Melas festivities when up to around two million additional persons have to be supplied with drinking water.

3.2 Assessment of risks to human health and environment

Riverbank filtration (RBF) has been used in Haridwar since the 1980s as an alternative to surface water abstraction and to supplement groundwater abstraction. The usage of bank filtration in India offers the benefit of a significant reduction in turbidity and coliform in the source water that is directly supplied after disinfection without the needs for further extensive post-treatment. This RBF risk assessment and Water Safety Plan was developed for an existing riverbank filtration site in northern India in order to 1) assess risks and hazards to the drinking water supply of the city of Haridwar and 2) develop a water safety plan that can be used for other existing and planned bank filtration and MAR sites in India. It also serves to present a prototype of the type of water safety plan appropriate for other Saph Pani project sites and for the development of water quality guidance for the Central Pollution Control Board of India (CPCB).

The Haridwar case study is structured to address risk assessment for managed aquifer recharge following the Australian Guidelines for Managed Aquifer-Recharge (NRMMC–EPHC–NHMRC 2009). This makes use of a risk management framework which is consistent with the WHO water safety plans (WHO 2011). Although the RBF wells in Haridwar have been in existence since 1965, the health risk assessment is structured as though the Haridwar bank filtration facilities are being constructed. Data from existing operations are introduced under investigation. This approach allows a consistent risk assessment framework for the health risk assessment of new and existing bank filtration sites.

The Stage 1 (entry level) assessment has shown that the Haridwar project site is viable for the operation as riverbank filtration and aquifer treatment site. Stage 2 assessment revealed that 1) although turbidity is high during monsoon, the particular hydrology of the Upper Ganga Canal and the canal bed maintenance ensure that canal bed clogging is not an issue for the sustainable operation of the RBF wells, and 2) industrial land use pose no risk to the project site whereas fecal groundwater contamination and the social-economic use of the project site for public washing, religious bathing and housing in the absence of well head protection zones pose a high risk for pathogens. Maximal risk assessment (no RBF and chlorine treatment) identified iron, manganese, nitrate, alkalinity, TDS, total hardness and fecal indicators in groundwater and turbidity and fecal indicators in the Ganga as high risk for the human endpoint (drinking water). Pathogens and turbidity were rated as high environmental risks. Pre-commissioning operational residual risk investigations by Dash et al. (2010) assessed the feasibility of RBF as preventive measure to reduce risks identified in the maximal risk assessment. It was shown that RBF is capable of providing high quality water with no further treatment required other than disinfection.

The operational residual risk assessment monitoring assessed the residual risk associated with inorganic chemicals, salinity, nutrients and turbidity as low against the Indian (IS 10500 (2004)) and WHO (2011) guideline values. Pathogenic risks for E. coli O157:H7, Cryptosporidium and rotavirus were assessed and quantified using a deterministic quantitative microbial risk assessment (QMRA) approach (Bartak et al., in preparation). A quantitative microbial risk assessment undertaken by Bartak et al. (in preparation) on the water recovered from the aquifer indicated that the residual risks of 0.00165 DALYs posed by the reference bacteria E.coli O157:H7 were below the national diarrhoeal incidence of 0.027 DALYs and meet the health target in this study of 0.005 DALYs per person per year, which corresponds to the WHO regional diarrhoeal incidence in South-East Asia..

Additional treatment steps can be applied to the source of contamination, well operation or at the tap (boiling water). Watershed protection such as reducing sewer overflow and limiting discharge of untreated wastewater or human excreta into the Ganga River can reduce pathogen numbers by 0.5 to 1 log10 (NHMRC 2011). Another 1 to 2 log10 unit removal can be achieved by primary and secondary wastewater treatment (NRMMC–EPHC–AHMC 2006). Improvement of the current disinfection practice, well head protection zones, well sanitation and protection of well heads against direct contaminations is necessary to reduce pathogen related risks. The subsurface treatment process can be improved by operational management during monsoon and non-monsoon according to travel time, riverbank filtrate to groundwater ratio and well productivity. Generally, wells that are assumed to receive only a small portion of groundwater have evidence to deliver water with better microbial and physic-chemical water quality compared to wells that receive a significant portion of groundwater and can be operated preferentially. Wells such as IW18 that provide excellent water quality during both non-monsoon and monsoon period (Dash et al. 2010) but suffer well clogging and cannot operate continuously (Dash et al. 2010), may be rehabilitated or replaced to increase productivity. Regular and necessary well maintenance and rehabilitation may be performed during non-monsoon while operational wells are operated to meet water demand. During monsoon, inundated well must be not operated and properly disconnected from the network to avoid ingress of flood water into the drinking water distribution network. Furthermore, optimized monsoon well operation such as increasing abstraction rate of wells with longer travel distance and reduction of abstraction rates at wells with short travel times is also a potential operation philosophy to minimise risks.

3.3 Assessment of institutional viability

3.3.1 Legal framework

At the national no specific policies, laws and regulations for river bank filtration exist. However at state level, the Department of Drinking Water, Government of Uttarakhand, issued a government order on 25.03.2006 wherein specific technologies for drinking water supply such as RBF and the use of indigenous ‘Koop’ wells (Sandhu and Grischek, 2012) should be encouraged by water supply companies working in Uttarakhand (CCRBF, 2008). Furthermore, RBF is covered by existing national policies, laws and regulations related to water management and drinking water supply as shown in Table 2.

Table 2 Relevant policies and laws for RBF

Policies at national level	Relevance for RBF
National Water Policy, 2002	- RBF provides naturally (pre-) treated water for drinking
Drinking water specifications IS: 10500, 1992	- Standard for drinking water
Central Pollution Control Board (CPCB) water quality targets	- Indian water quality targets for water sources

Nevertheless, according to Sandhu and Grischek (2012) the technical and socio-economic feasibility of using RBF for urban and decentralised water supply schemes in India should be investigated for locations (covered by various programmes such as the City Development Plans or various schemes such as the ‘Jawaharlal Nehru National Urban Renewal Mission’, the Asian Development Bank’s current ‘North Eastern Region Capital Cities Development Investment Programme’ and the planned ‘Uttarakhand Urban Sector Development Investment Programme’ and the World Bank’s ‘National Ganga River Basin Project’) having suitable hydrogeological conditions. This would also serve as a first step towards meeting the goals of the Government of India’s ‘National Action Plan on Climate Change’.

3.3.2 Stakeholder survey

The main institution involved in developing and managing RBFs in Uttarakhand is the Uttarakhand State Water Supply and Sewerage Organisation - *Uttarakhand Jal Sansthan* (UJS). It is responsible for implementation, operation as well as monitoring of RBF plants. However, there are several other stakeholders at national, state and local level who have responsibilities or interests related to RBF. They are briefly described in Table 3.

Table 3 Relevant stakeholders in case study area

Haridwar	Key role concerning RBF	Interest
National		
Central Groundwater Board	- Cooperation in adopting RBF technique in Karanprayag and Srinagar	- Ground water Monitoring and exploration
Central Pollution Control Board	- Prevention and control of environmental pollution - Monitoring of river water quality	- Protection of water bodies from pollution
Ministry of Water Resources	- Formulation of policies (“National Water Policy”)	- Protection of water resources, support of sustainable use of water
Ministry of Environment and Forests	- Development of laws and regulations concerning water pollution	- Protection of water resources
Irrigation department	- Scientific analysis and exploration of irrigated water	- To maintain water quality and quantity
All water works of India	- drinking water exploration and analysis	- To maintain drinking water quality
State level		
State government of Uttarakhand	- Funding	- To maintain the rule and regulation in state
Uttarakhand Jal Sansthan (UJS)	- Provision and operation of water supply infrastructure in the state	- Use of water from RBF to supply users in Hardiwar
Cooperation Centre for Riverbank Filtration (CCRBF)	- Network of institutions involved in RBF - Collaborating scientific partners: - IIT Roorkee, - University of Applied Sciences (HTWD) - Dusselford water company Stadwerke	- Support cooperation between stakeholders - Information centre and RBF demon-stration site in Haridwar for sharing RBF experience - providing technical support to RBF projects in India - developing RBF investigation guidelines - organizing training

		courses for professionals and supervising student projects
Uttarakhand State Council for Science and Technology (UCOST)	- promotion and support of science in the area of RBF	- Generation of scientific background information related to RBF
Municipal level		
Research Institutes (e.g. Pollution Control Research Institute,	- research on RBF	- Generation of scientific background information related to RBF
Users	- Consumers of water	- Use of water from RBF systems
Media	- Awareness raising in newspapers, journals, etc.	- Awareness raising, information of public

3.3.3 Recommendations for institutional strengthening to support the implementation of RBF

The Saph Pani project partner Uttarakhand State Water Supply and Sewerage Organisation – Uttarakhand Jal Sansthan (UJS), is one of the few institutions in India with a proven track-record of persistently implementing RBF since 2005 in the predominantly hilly state of Uttarakhand (Kimothi et al., 2012). UJS has actively participated with national and international academic institutions in a number of incremental applied research and capacity building projects. Although these projects have been funded by various organisations, the successful implementation of these projects is also due to UJS's own support and in-house capacity. Consequently certain practical conclusions can be drawn. A tried and tested approach is to integrate the results of applied research projects into the decision-making process of institutions. To achieve this, research, education and project work need to be integrated through different communication, exchange and technical approaches (Sandhu et al., 2012). The decision-making of the institution has to be based on a sound scientific understanding of the technology to be implemented (in this case RBF). In this context some recommendations can be derived from Sandhu et al., (2012) as follows:

- Conducting regular workshops, training courses, project-meetings and field excursions jointly with research and academic institutions, engineers and managers from the institutions and policy and decision-making organisations in order to maintain forward momentum for all project activities.
- Exposing the institution to state of the art technology through participation / visits to industry trade fairs.
- Engaging young professionals from the institution to support practical training periods for students from academic institutions to enhance the "learning by doing" concept and create enthusiasm amongst those involved. This allows the academics/ researchers to appreciate the practical difficulties routinely faced by the institution and vice-versa.

- Creating dedicated thematic working groups within the institution. In this context UJS created the RBF cell comprising dedicated staff working on RBF.
- Improving in-house infrastructure (laboratory capacity, procurement of equipment, training of staff).

These recommendations can constitute a long-term quality improvement program for ensuring future capacity and sustainability in the field of RBF, especially among the younger generations of engineers and managers. From a policy perspective, it is encouraging that the state Government of Uttarakhand is willing to support UJS to develop more RBF sites to improve the drinking water quality and quantity supplied. Furthermore, the Water Technology Initiative of the Department of Science and Technology (DST-WTI) of the Government of India has expressed keen interest to spread the concept of BF to other parts of India. The DST-WTI is already funding RBF R&D projects of Uttarakhand Jal Sansthan in Uttarakhand (Kimothi et al. 2012).

4 Case study Hyderabad (Natural wastewater treatment system)

4.1 Overview of case study

The Musi River originates about 60 km upstream of Hyderabad in the Anantagiri hills, runs for about 20 km within city limits of Hyderabad, bifurcating the city into north and south portions and joins the Krishna River after 160 km in the Nalgonda district.

There are two big reservoirs upstream of Hyderabad which were built in the 1920s to supply the city with water and reduce the impact of floods (Ensink et al. 2010). With the growing water demand of the city, water is now lifted from places as far as 150 km away. The river as it enters the city, is reduced to a trickle and as it leaves city perimeter after 20 km, picks up the drainage from the entire municipal corporation area as well as parts of surrounding municipalities (CSE, year unknown). With increasing urban expansion, the water in the river is a mixture of partially treated and untreated wastewater, and enters irrigation channels via a series of water diversion structures, so called anicuts (Ensink et al. 2010). Downstream of Musi River is also the Musi Project which provides irrigation water for a large command area. The overall water demand for agriculture in the Musi basin during 2001/02 was calculated to be around 76% of total water use for all sectors (George et al. 2007). An overview of the water supply for different sectors can be seen in Table 4.

Table 4 Water supply for different sectors in the Musi River Basin in 2001/02 (Source: George et al. 2007)

Sector	Million m³	Percentage of total water use
Agriculture	1258	76 (77 groundwater, 23 surface water)
Domestic use	323	20
Industry	60	4
Total	**1641**	**100**

The Ministry of Environment and Forests has provided funds for the National River Conservation Directorate (NRCD) to develop a pollution abatement plan, under which four sewage treatment plants (Amberpet, Nagole, Nallacheruvu, Attapur) with a total capacity of 592 MLD (see Figure 2 and Table 5) have been proposed, of which three are currently operational. At present ~50% of the generated sewage of Hyderabad is treated as shown in Table 5.

The plan also expects to install interceptors at 16 points of the storm water drains, where the wastewater enters the river. All interceptors are in place at present.

Apart from sewage, industrial wastewater is treated at 2 CETPs (Common Effluent Treatment Plant) before being discharged to the Musi River. A study by Larsson et al (2007) showed high concentrations of pharmaceuticals in the effluent of a wastewater treatment plant in Patancheru. Since then special effort has been made to ensure that the CEPT treated water achieves the safety standards. The issue however, is the fact that, there are many industries that are not connected to the CETPs, especially the small concerns. While the pollution in the river appears to be arrested to a certain degree, with the government efforts, much more needs to be done to achieve a level of safety for direct human use.

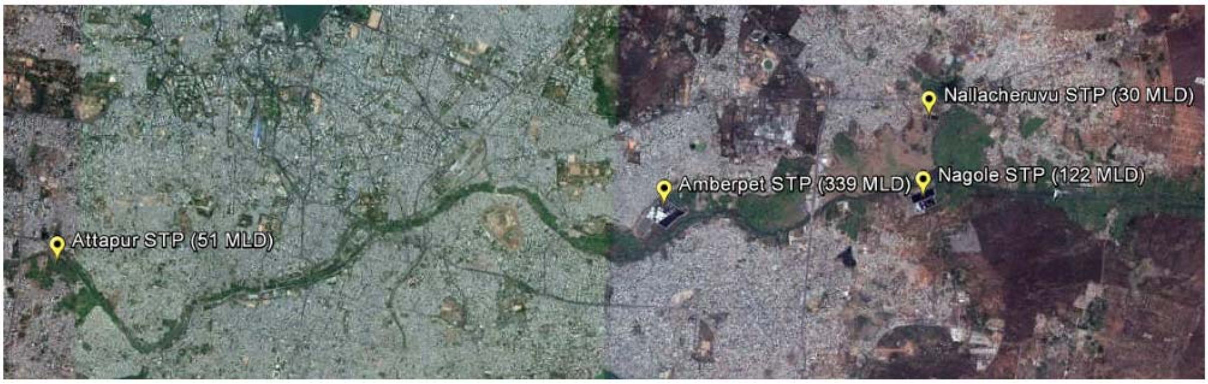


Figure 2 Location of STPs along Musi River (Source: Zimmermann 2011)

Table 5 Current practice of wastewater treatment

Current practices of wastewater management	Value (MLD)	Source of information
Sewage generated (80% of water supply to the city)	1250	HMWSSB[1]
Treatment capacity	651	HMWSSB
Amberpet	*339*	HMWSSB
Nagole	*172*	HMWSSB
Nallacheruvu	*30*	HMWSSB
Attapur	*51*	HMWSSB
Hussein Sagar	*20*	GHMC[2]
Patel Cheruvu	*2.5*	HMDA[3]
Pedda Cheruvu	*10*	HMDA
Durgam Cheruvu	*5*	HMDA
Mir Alam Cheruvu	*10*	HMDA
Saroor Nagar Lake	*2.5*	HMDA
Safil Guda Lake	*0.6*	HMDA
Langer Houz Lake	*1.2*	HMDA
Noor Mohammad Kunta	*4*	HMDA

[1] Hyderabad Water Supply and Sewerage Board

[2] Greater Hyderabad Municipal Corporation

[3] Hyderabad Metropolitan Development Authority

Ranghadhamini Lake	5	HMDA
Amount of untreated wastewater reaching the waterways	599	

Water from the Musi River is used for irrigation within the city's boundaries for growing paragrass and downstream for growing rice and vegetables. The irrigated areas are shown in Figure 3 and the current practice of irrigation in Table 6.

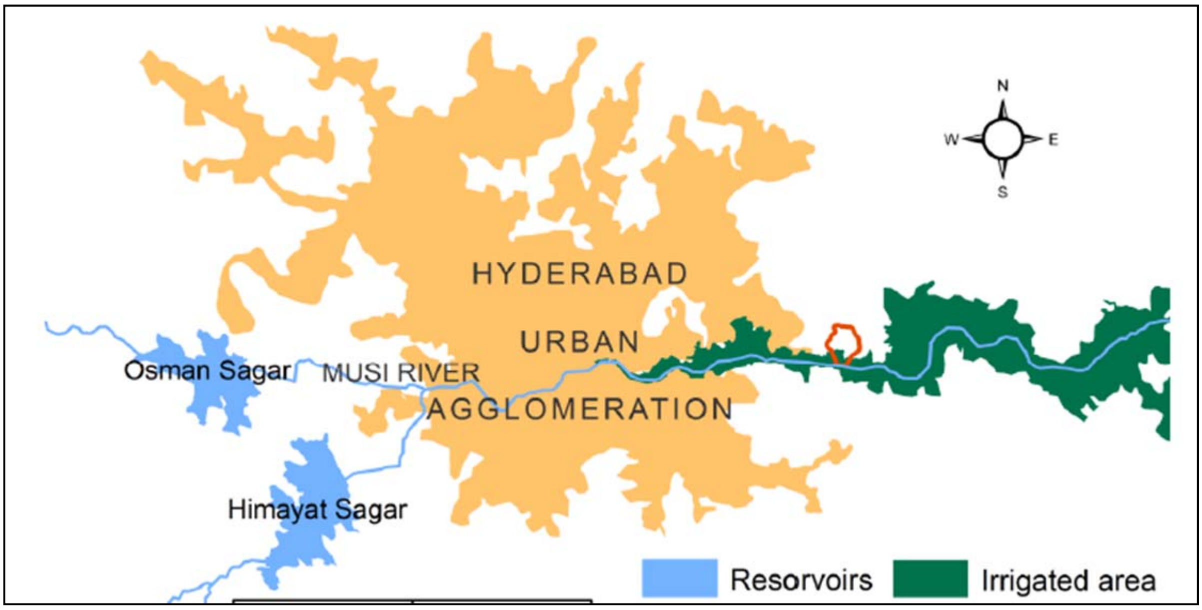


Figure 3 Irrigated areas in and downstream of Hyderabad city (from Jampani et al., 2014)

Table 6 Current practice of irrigation

Current practices for irrigation	Area irrigated (ha)	Source of information
Use of water from Musi River within Hyderabad	100	Buechler et al. 2002
Use of canal water (from Musi River) downstream of Hyderabad	15,974 – 40,600	Buechler and Mekala 2005 Buechler and Devi 2003

River water is not directly used from the Musi River, but from irrigation canals on both sides of the river (Amerasinghe et al. 2009). Where possible, the natural slope was used (gravity flow), supported by lift irrigation to irrigated land 1-2 km away from the canals. Groundwater is used by farmers without access to the canals, and is extracted from bore wells and open wells (Amerasinghe et al. 2009).

A study carried out in a small catchment within the peri-urban areas of Hyderabad, was exemplified by the village Kachiwani Singaram that uses both wastewater and ground water for irrigation of paragrass, paddy and vegetables (Amerasinghe et al., 2009; Perrin et al., 2010, Mahesh et al., 2013). Interviews with farmers revealed that an intricate network of pipes carry water to distances as far as 2 km away from the canal (Table 7, Jampani et al. 2013).

Table 7 Irrigation practices and cropping scenarios in the wastewater irrigated area of Kachiwanisingaram.

Cropping scenarios in Kachivani Singaram			
	2010		
Water Use	Khariff season (monsoon crop –July to October	Rabi season (winter crop - October to March)	Zaid season (summer crop – March to July)
GW (Groundwater)	Vegetables	Vegetables	Vegetables
GW	Paragrass	Paragrass	Paragrass
GW	Rice	Rice	-
GW	Rice	Rice	Vegetables
GW	Rice	Vegetables	Vegetables
WW (Wastewater)	Paragrass	Paragrass	Paragrass
WW	Vegetables	Vegetables	Vegetables
WW	Rice	Rice	-

4.2 Role and potential of natural treatment systems

The potential of a natural wastewater treatment system, specifically a constructed wetland, for treating the canal water that is used for irrigation has been discussed in consultation with work package 3. However, due to limited data on the microbiological loads of the canal water (a monitoring campaign is still in progress) and due to the fact that there are no established design formulas for constructed wetlands that reduce microbiological risks, a technical feasibility study has not been attempted so far. Research on these aspects is currently conducted in WP 3 (pilot plant at IIT-B). Nevertheless, previous experiences indicate that a 3-4 log reduction of *E.coli* can be achieved by a constructed wetland. More detailed information on a constructed wetland can be found in the deliverables of WP3.2.

4.3 Assessment of risks to human health and environment

4.3.1 Site description

The Musi River study site is a natural and engineered MAR/wetland system (Kachwani Singaram), and therefore complex in its surface and ground water interactions. It comprises large areas of flooded paragrass, seasonal paddy fields, vegetable plots and reed beds. Partially treated waste water from Hyderabad enters the Musi River and is diverted by weirs into irrigation canals, where the water is either lifted or directly used for crop irrigation and wetland maintenance. Seepage of this water used for irrigation contributes unintentionally to aquifer recharge in the local area. Shallow groundwater is also used for irrigation in areas where canal water is not accessible for irrigation or not suitable for crops (Amerasinghe et al. 2009).

Geography and climate

The case study site, Kachwani Singaram micro-watershed is part of the Musi sub-basin and located 10 km downstream in the eastern direction of Hyderabad along the northern bank of the Musi River between the rural villages of Parvatapuram and Kachivani Singaram in the Ranga Reddy district. The climate is semi-arid with average annual rainfall (2001 – 2005) in Ranga Reddy of 783 mm (CGWB 2007). Monthly average rainfall (1951 – 2000) in Hyderabad ranges from 5.9 mm in December to 178.7 mm in August. About 74 % of the total rainfall (828.5 mm) occurs in the wet season from June to September. Minimum and maximum mean temperatures range from 14.5 to 28 ºC in December and from 26.2 to 39 ºC in May (GoI 2013).

Aquifer description

The fractured rock aquifer is composed of orthogneissic granite as basement with granite, quartz and dolerite intrusions (Schmitt 2010, Perrin et al. 2011, Aellen 2011). The weathering profile was investigated by Perrin et al.(2011) through 4 bore hole drilling (MU 01 to 04, Figure 4) to a maximum depth of 65.5 m below surface (Figure 4) and was described as: a thin layer of red soil or black soil compromised by sandy clay with an average thickness of 0.6 m; 3 to 6 m thick layer of sandy regolith, 8 to 14 m weathered granite rock (laminated saprolite) and 25 to 35 m thick fissured rock. Fissures were detected between 7 and 23 m bgl based by flow meter measurements and significant presence of iron oxides minerals as coatings or as infill. This represents the highly productive part of the aquifer (Perrin et al. 2011). Fresh basement rock was projected at 55 to 65 m below surface (Perrin et al. 2010, Schmitt 2011).

Groundwater flow follows the general topography from North to South towards the Musi River, which is a gaining stream at all seasons (Perrin et al. 2011). The water table is locally influenced by groundwater pumping and seepage from irrigation. Maximum depth to groundwater table varies between 0.65 and 14.48 m below ground surface (bgs) in summer pre-monsoon period in May to 0.31 to 9.99 m bgs in at the end of the monsoon season in October (Perrin et al. 2011). Hydraulic conductivity and transmissivity of the hard rock aquifer was estimated by conducting pump tests to range from 2×10^{-5} to 7×10^{-5} m/s and 1×10^{-3} to 3×10^{-3} m^2/s. Storativity was estimated to 3×10^{-4} after short term pumping (Perrin et al. 2011).

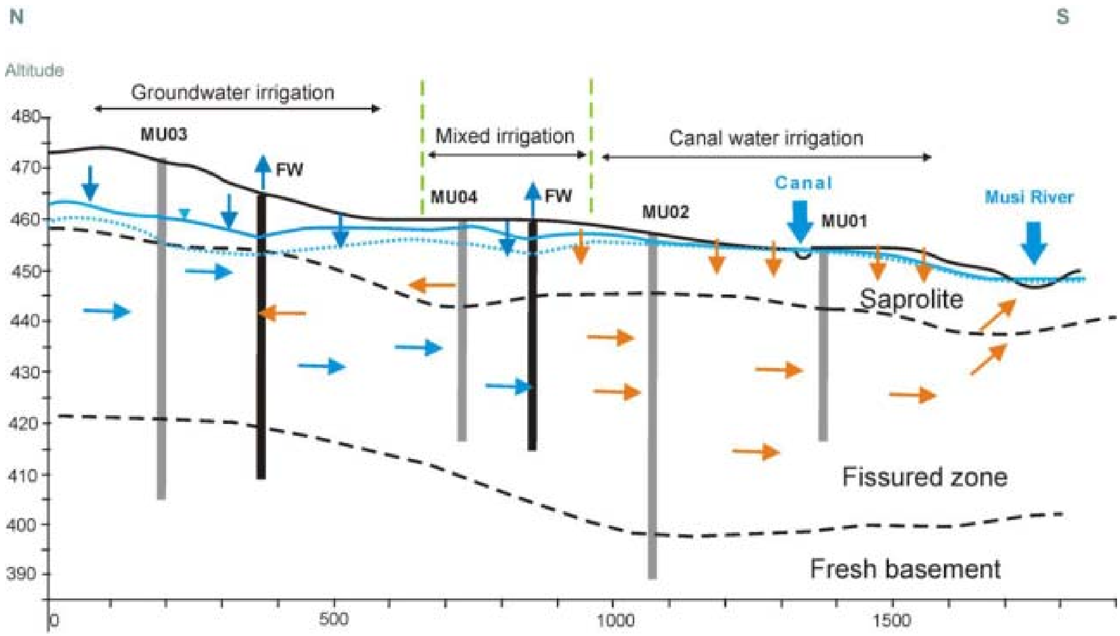


Figure 4 Geological profile of Kachwani Singaram MAR system (Perrin et al. 2011)

Source water description

The Musi River originates in the Anantha Hills localized 90 km west of Hyderabad, and flows through Hyderabad from west to east across flat topography (mean slope < 1%) (Massuel et al. 2007, Perrin et al. 2011). Downstream of the city, a series of weirs along the river, collect and divert water to a network of irrigation and drainage canals and small reservoirs. This network is used to irrigate approximately 10,000 ha of paddy rice and para grass (perennial and cultivated for buffalo fodder) along the Musi sub-basin (Perrin et al. 2011).

Over the last 10 to 15 years, the discharge of large amounts of untreated waste water from the City of Hyderabad into the Musi River turned the previously seasonal river into a perennial, highly polluted river (Amerasinghe et al. 2009). *E.coli* and nematode egg numbers reported by Amerasinghe et al. (2009) were in the order of 10^6 cfu/100mL and 2 eggs/L. Schmitt (2010) projected pathogen numbers in the Musi River based on discharge and treatment efficiency of the waste water treatment plants in the order of 10^5 cfu/100 mL and 10^1 Helminth eggs per litre. Waste water (~1.2 Mm^3/d) is discharged into the Musi River and mixes with other surface runoff and groundwater discharge. For perspective, waste water discharged daily is 13.9 m^3/s (Amerasinghe et al. 2009) and average discharge of the Musi river at Nagole bridge (a few km upstream of the study area) is 13 m^3/s for the year 2004. This indicates that the Musi River is mainly compromised of waste water (IWMI unpublished data, Perrin et al. 2011). Groundwater budgeting further confirmed that the Musi River is dominated by surface runoff and waste water discharge and groundwater input at the study site is <0.4 % of Musi River base flow. By 2011, 70 – 80 % of the waste water discharged is secondary treated sewage (Perrin et al. 2011) compared to just 5 % in before 2003 (Ensink et al. 2009). The Nallacheravu waste water treatment plant is 1 of 4 plants that are designed to treat waste water from Hyderabad via anaerobic digestion, aerobic lagoons and disinfection. Physico-chemical and biological parameters of pre-treated and treated waste water from Nallacheravu are given in Table 8.

Table 8 Performance of treatment plant in Nallacheravu, Hyderabad (taken from: Periodic Report M1-M18 IWMI/NGRI/BRGM 2013; Annual average 2011, Source: HMWSSB 2012)

Parameter	Pre-treatment	Post- treatment
pH	7.7 ± 1.0	7.9 ± 0.2
Total suspended solids (mg/L)	452 ± 56	48 ± 21
Chemical oxygen demand (COD) (mg/L)	453 ± 75	86±11
Biological Oxygen Demand (BOD_5) at 20ºC (mg/L)	178 ± 43	18± 4
Thermotolerant coliforms (MPN/100mL)	$6.4\times10^5 \pm 0.8\times10^5$	$6.3\times10^3 \pm 0.8\times10^3$

Musi ionic composition is mainly based on sodium (>250 mg/L), chloride (150 mg/L, up to 250 mg/L), and sulphate (~100 mg/L) (GOI 2008). Groundwater salinity of the study site has been investigated by Perrin et al. (2011) in 2010. It was found, that EC was highly variable, influenced by evapotranspiration and canal water irrigation return flows. Native groundwater EC of < 1000 µS/cm in the northern part increased to > 1000 µS/cm in the southern part that is irrigated with or influenced by canal water irrigation. According to the CGWB (2007), groundwater quality in Ranga Reddy is "suitable for both domestic (may include drinking water) and irrigation processes" with the exception of nitrate and fluoride values. Nitrate and fluoride concentrations are in the range of 19 to 240 mg/L and 0.4 to 11 mg/L and exceed guideline values of 45 and 1 mg/L for drinking and irrigation water (IS10500, WHO 2006).

Site configuration

The Kachwani Singaram micro-watershed is part of the Musi sub-basin irrigation network and compromises an area of 2.74 km^2 mainly used for rice and para grass cultivation. Other crops include buffalo grass and vegetables such as cabbage, cauliflower, corn, tomatoes, chilli and a variety of green leafy vegetables (mint, spinach, chilli and amaranth etc.) (Amerasinghe et al. 2009, Jacobi et al. 2009, personal communication with Amerasinghe). About 74.5 % of the area is irrigated with canal water (waste water), 24 % with groundwater and 2 % with recovered water (mixed groundwater and irrigation water) (Schmitt 2010). About 54 % of the total area is used for the cultivation of para grass, 38 % for rice and 8 % for vegetables. Vegetables are mainly but not solely grown with groundwater that has a lower salinity compared to the canal water (Schmitt 2010). In order to develop a groundwater budget, the study area was extended by Perrin et al. (2011) to its hydrogeological boundaries. The total study area covers 12 km^2 and is bounded by a dolerite dyke in the north, the Musi River in the south and no-flow boundaries along the west and east edges.

The Musi River site was identified as MAR site and can be categorized as "spreading method - incidental recharge" (Gale and Dillon 2005). Groundwater is recharged with waste water from the irrigation canal/Musi River. Irrigation return flows from paddy rice and para grass cultivation mix with native groundwater and are recovered via groundwater wells for irrigation (Figure 5). The system is fed with water from the Musi that is diverted via weirs into an irrigation canal that flows to the Musi River. At the study site, water from the canal is pumped (19.5 L/s) up to 0.5 km inland into irrigation ditches (14 L/s), onto fields or as re-fill directly into “open wells” (13 L/s). For consistency with existing reports, the term “open wells” refers to unsealed, hand dug, ground pit holes with a diameter of up to 20 m that may be under influence of groundwater and are re-filled with canal water. Water is recovered by 5 bore wells (1.1 L/s to 3.75 L/s) and 3 open wells.

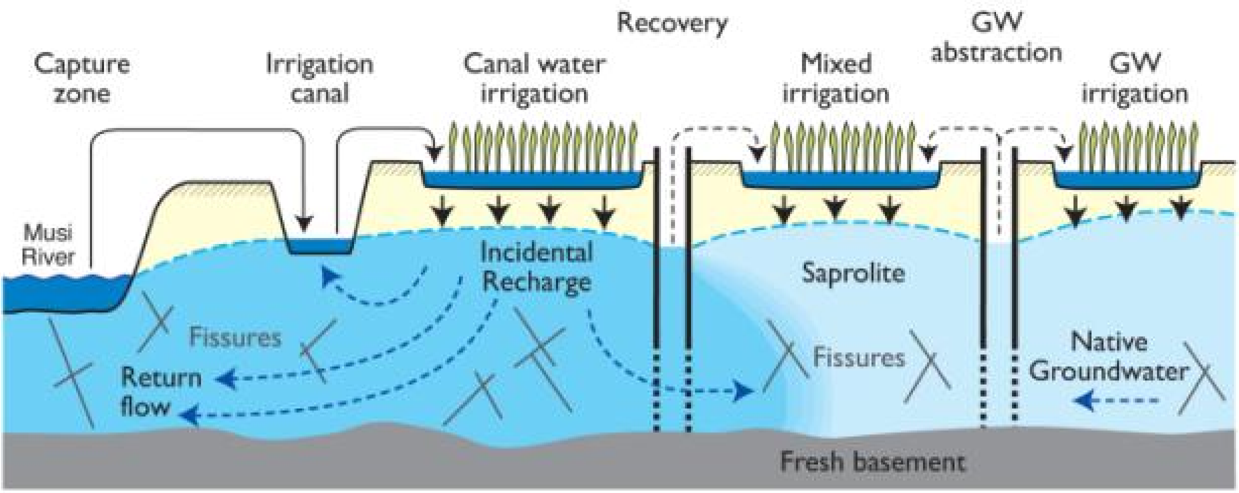


Figure 5 Kachwani Singaram MAR system configuration

A site map of the Kachwani Singaram MAR system is shown in Figure 6. Table 9 provides an overview of the system components of the MAR system.

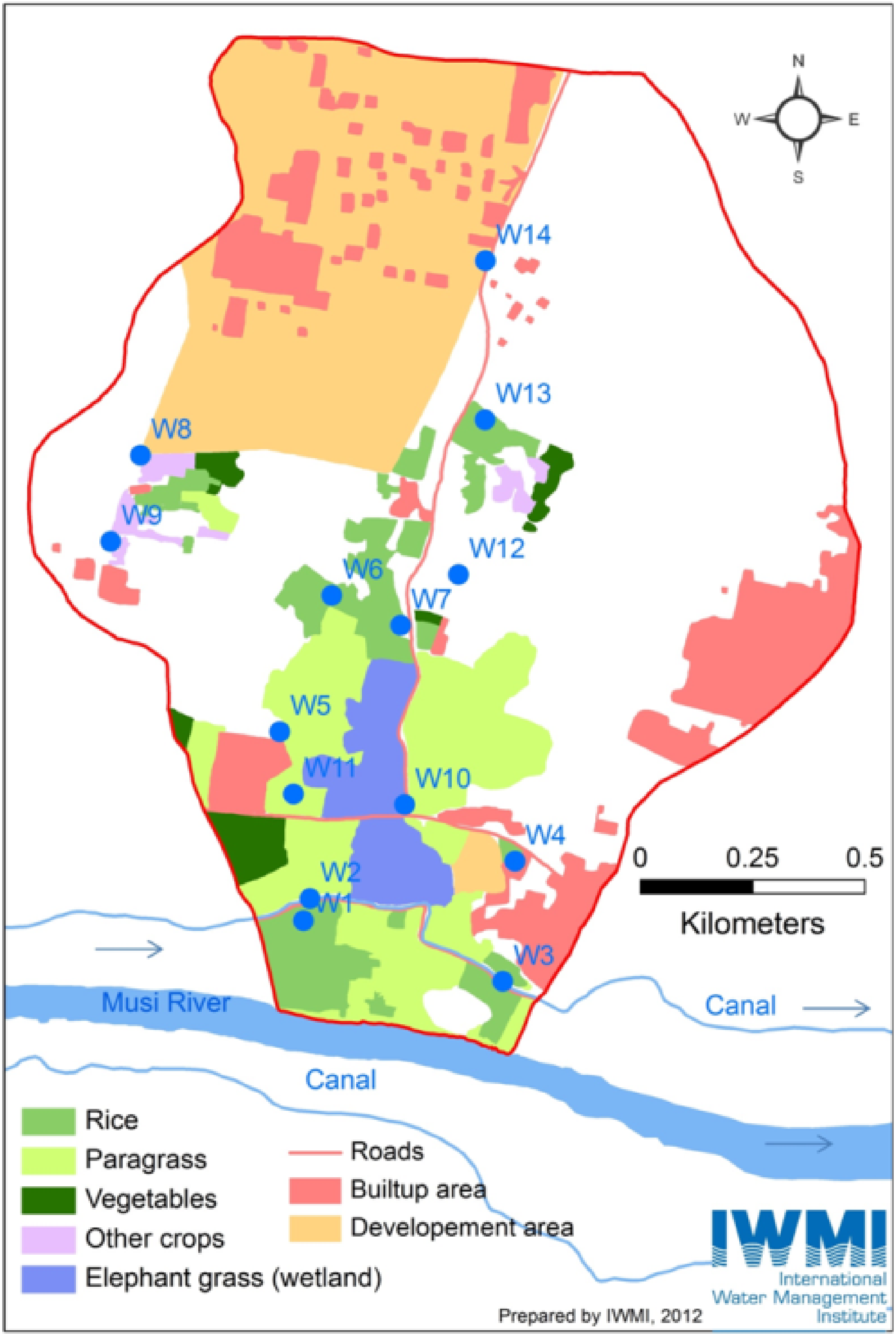


Figure 6 Site map of Kachwani Singaram MAR system

Table 9 Kachwani Singaram MAR system components

Component	Kachwani Singaram MAR system
1. Capture zone	Musi River and groundwater
2. Pre-treatment	None
3. Recharge	Flood irrigation and seepage
4. Subsurface storage	Sandy regolith and fractured hard rock
5. Recovery	Groundwater abstraction via bore and open wells
6. Post-treatment	None
7. End use	Crop irrigation: in rare cases domestic drinking water supply

4.3.2 Stage 1 Musi River Entry level assessment

Table 10 and Table 11 show the completed entry-level risk assessment for the Musi River scheme, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC, .2009).

Table 10 Kachwani Singaram MAR entry level assessment part 1—Viability

	Attribute	Kachwani Singaram MAR answer
1	Intended water use	
	Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Yes – The Musi River water is a significant resource in this semi-arid environment where the cultivation of fodder grass, paddy and vegetables has provided economic benefits to many inhabitants of the area. Recovered wetland treated water is used for irrigation when canal water is too polluted or not accessible.
2	Source water availability and right of access	
	Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Yes – Musi River water is readily available but highly contaminated. It is mainly compromised by waste water discharge from Hyderabad; ambient groundwater mixes with return flows from irrigation and is also used as source water. Kachwani Singaram requirement is < 2.5 % of irrigation canal and 1.2 % of Musi River base flow.
3	Hydrogeological assessment	
	Is there at least one aquifer at the	✓ Yes – existing wetland above a fractured rock

	proposed managed aquifer recharge site capable of storing additional water?	aquifer
	Is the project compatible with groundwater management plans?	✓ Yes – No groundwater management plan but return flows from irrigated fields contribute ~29 % of the aquifer recharge.
4	Space for water capture and treatment	
	Is there sufficient land available for capture and treatment of the water?	✓ Yes – Existing natural and engineered wetland system and supply through ancient canals along the Musi River.
5	Capability to design, construct and operate	
	Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ Yes – Farmers have experience in operation and maintenance of the irrigation channels. The IWMI has expertise to investigate water quantity and quality issues and works closely with farmers in Kachwani Singaram

Table 11 Kachwani Singaram MAR entry assessment part 2—Degree of difficulty

Question	Kachwani Singaram MAR answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	No – Salinity of the irrigation water is higher than values of the aquifer. Require Stage 2 investigations to assess risks.	Source water quality evaluation
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – Musi River water quality is strongly influenced by waste water discharge; pathogens, nutrients and TDS pose risks. Require Stage 2 investigations to evaluate hazard attenuation processes during riverbank filtration	Source water quality evaluation
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total	Yes – source water is of poor quality and may lead to a high rate of soil clogging.	Clogging studies

organic carbon or total nitrogen >10 mg/L, and is soil or aquifer free of macrospores?		
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Uncertain – Require Stage 2 investigations to evaluate groundwater quality, sources of any contaminants and protective measures required.	Groundwater quality evaluation
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	No – target aquifer is used for crop cultivation.	None
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) The salinity criterion for uses of recovered water?	Yes to (b) – EC values found in groundwater in Ranga Reddy are reported to be up to 2000. Recommend Stage 2 investigations to evaluate salinity of groundwater and recovered water and its suitability for irrigation.	Groundwater quality evaluation
7 Reactions between source water and aquifer		
Is redo status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	No – redox status, nutrient status, and ionic, strength of source water is different to that of groundwater. Require Stage 2 investigations to evaluate geochemical reactions.	Geochemical evaluation
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–	Yes – Require Stage 2 investigations to evaluate other users, assess risk to them and risks to the MAR operations.	Identify other users and assess related risks

1000 m) the MAR site?		
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	No – Water table is not deeper than 4 m in rural area. Require Stage 2 investigations to evaluate elevation of the groundwater level, flow direction and travel times.	Assessment of groundwater elevation, flow direction, travel times and water balance
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	No – unconfined aquifer with recovered water used for the purpose of crop irrigation.	None
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – aquifer is composed of orthogneissic granite as basement with granite, quartz and dolerite intrusions. Require Stage 2 investigations to assess the potential consequences of iron and manganese dissolution and to evaluate potential for release of radionuclides.	Geochemical evaluation
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes – similar SAT sites in nearby villages	None
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – proponents have history of operating SAT system and using recovered water for crop irrigation.	None

In summary of the Stage 1 assessment, the following investigations listed in Table 12 were identified as necessary in proceeding to Stage 2.

Table 12 Summary of Stage 2 investigations required in Kachwani Singaram, India

Issue		Investigations required at stage 2
1	Does source water quality meet the requirements for the environmental values of ambient groundwater?	Source water quality investigation
2	Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Source water quality investigation
3	Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, and is soil or aquifer free of macrospores?	Clogging studies
4	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Groundwater quality evaluation
6	Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) The salinity criterion for uses of recovered water?	Groundwater quality evaluation
7	Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Geochemical evaluation
8	Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Assessment of other users in the vicinity and likely interference effects
9	Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Assessment of groundwater flow direction, and ground water budget

4.3.3 Stage 2 Musi River Investigations

Within the micro-watershed, four major water types were identified: irrigation canal water (CW), groundwater (GW), recovered groundwater water (RW) and mixed ground and canal water in open wells (MW). Water quality sampling was performed in pre-monsoon season (June 2012) as single grab sample at 14 monitoring points (IWMI/NGRI/BRGM 2013). Groundwater flow direction was found to be towards the irrigation canal and water quality of the canal water used for irrigation was investigated at 2 sampling points approximately 500 m apart from each other in the inflow (W2) and outflow (W3) of the micro-watershed. Groundwater/mixed water samples were taken across the water shed from 3 open wells and 8 bore wells or piezometers. Water samples were tested for physical characteristics, major ions, pesticides (organochlorines, organophosphates and carbamates) and microbial parameters such as total plate count, total coliforms, thermotolerant coliforms, *E. coli* O157:H7, *Salmonella, Shigella and Campylobacter.*

4.3.3.1 Water quality assessment

Sample evaluation

Water samples were excluded for salinity/sodicity risk assessment when the calculated error in the ion balance was >20 %. Other samples such as W11 were excluded as the calcium concentration of 0.03 mg/L was assumed to be an error. This will be addressed in the period of activity. Results from the microbial analysis by IWMI/NGRI/BRGM (2013) were also uncertain as thermotolerant coliform numbers in the Musi River source water were 5 $\log_{10}$ units below the previously reported *E.coli* numbers (Amerasinghe et al. 2009), Ensink et al. (2009), and Schmitt (2010) (see *source water quality assessment*), and thus not included as part of this risk assessment. Water quality data were analysed against the guideline values for drinking water (IS 10500) and for good irrigation practice (WHO 2006, ANZECC–ARMCANZ 2000).

Water quality tests show that faecal coliform counts and *E. coli* can be highly variable at the Musi River source and the W2 irrigation canal point. There could be multiple reasons, and a time series sampling will better illustrate the variability and the intensity of these contaminants. The city has better wastewater treatment capacity now and a fairly thorough solid waste collection programme, that it is possible the illegal dumping of sewage from tankers and solid waste has reduced considerably. As such, there will be a re-assessment during the next period of activity with another round of water quality sampling for health risk assessment.

Source water quality assessment

A source water quality evaluation was performed to assess 1) if the Musi River water meets the quality requirements for the purpose of drinking water and 2) its impact on groundwater quality.

Musi River is mainly composed of waste water and expected to have a high number of pathogens. However, microbial analysis for *E. coli O157:H7, Salmonella, Shigella and Campylobacter* in the canal water samples, close the KS MAR site were negative. Total plate count and coliform numbers were in the order of 10^4 to 10^6 cfu/mL. Thermotolerant coliform numbers were low for waste water and decreased in flow direction from 21 (W2) to >1 cfu/100mL (W3) (IWMI/NGRI/BRGM 2013). In comparison, Ensink et al. (2009) measured helminth eggs and *E. coli* at 8 sampling points along the main Musi river from 2003 to 2005, when untreated waste water accounted for 95 % of the total waste water discharge into the Musi, and reported helminth eggs and *E. coli* numbers in the range from 3.7 to 7.2 eggs/L and from 7.5×10^5 to 3.7×10^6 *cfu/*100mL. In a separate study carried out a few years later, Amerasinghe et al.(2009) measured 1.5×10^6 *E.coli*/100mL and 2 nematode eggs/L and Schmitt (2010) estimated numbers for *E.coli* and helminth eggs in the Musi based on the performance of the water treatment plant, current treatment capacity and water demand projections for 2021 to 77 eggs/L and 2×10^5 cfu/100mL. Diarrhoeal incidence at the Musi site was assessed in a separate cross-sectional study (n=298) in 2007 (Amerasinghe et al. 2009). The study showed that ~57% of the rural and 48 % of the non-farming population engaging in Musi River related activities (n=196) complained of having suffered from an episode of diarrhoea during a two week to three month period prior to the date of interview. Similarly, ~33% of the rural and 81 % of the non-farming population perceived that it was associated with water. Only a few (7.1% rural, 4.1 % non-farming) stated that the episode was related to food (Amerasinghe et al. 2009). Risk from drinking water exposure was assessed similar to the approach in Haridwar using a QMRA analysis. It was conservatively conducted with *E.coli* numbers in Musi River water based on the reported data by Amerasinghe et al. (2009) and Ensink et al. (2009) of 10^6 cfu/100ml, WHO (2011) estimate numbers for *Cryptosporidium* in raw sewage of 10^4 /L, and adjusted numbers for rotavirus in Indian-derived sewage of 10^5 /L. Highest pathogenic risk is associated with *E.coli* O157:H7 (0.11 DALY's/person/year) and exceeds the national diarrhoeal incidence (0.027 DALY's) (Table 13). Lowest risk is associated with *Cryptosporidium* (0.0014 DALY's) and was below the regional incidence of 0.005 DALY's for South-East Asia (WHO 2012). Risk from a daily aerosol/spray inhalation of 1 ml irrigation water (Gabella et al. 2010) ranged from 0.0014 DALY's for *Cryptosporidium* to 0.061 DALY's for *E.coli* O157:H7 (Table 13) when it was assumed that growers/irrigators work every day in the field and are irrigating different crops every day. Average *E.coli* numbers in canal water irrigated (flood type) amaranth, spinach, mint and coriander ranged from approx. 3 to 63 cfu/g (Amerasinghe et al. 2009). Numbers were highest in spinach with mean and maximum values of approx. 63 and 75 cfu/g. The human endpoint "crop ingestion" was assessed based on a daily consumption of 100 g (Bhushan et al. 2013) spinach (substitute for leafy vegetables) contaminated with 75 *E.coli* /g (Amerasinghe et al. 2009). A withholding period of 7 days between last irrigation event and harvest/consumption was used to account for microbial decay in the transport to market. Temperature and humidity have the highest impact on pathogen decay on crops with decay increasing with temperature and decreasing with humidity (WHO 2006). The study site is characterized by dry and hot climate and therefore, the pathogen one $\log_{10}$ reduction times *E. coli* = 15 d^{-1}, *Cryptosporidium* = 2 d^{-1}, rotavirus = 15 d^{-1} on crops were adopted (WHO 2006). The risk from the ingestion of 100 g Spinach contaminated with 75 *E.coli*/g equals a risk of 0.02 DALY's (Table 13) associated with *E.coli* O157:H7 and is equal to the national diarrhoeal incidence.

Table 13 Musi river maximum risk QMRA-results for human endpoints (in DALYs / person / year)

Bacteria	Crop ingestion	Spray ingestion	Drinking water
E. coli O157:H7	1.8E-02	5.6E-02	1.1E-01
Cryptosporidium	1.4E-03	1.4E-03	1.4E-03
Rotavirus	5.4E-02	5.4E-02	5.4E-02

Mean pH was 7.3 and increased in downstream flow direction from 7.0 to 7.6. Musi ionic composition is mainly based on chloride (182 mg/L), sodium (152 mg/L) and sulphate (58.3 mg/L) (Figure 7). Chloride and sodium equivalents pose a toxicity risk to plants and require a moderate degree of restriction on use (WHO 2006). Chloride concentration in the canal water is higher than in groundwater and is below the guideline value of 350 mg/l for increasing crop cadmium concentrations (McLaughlin et al. 1999 in ANZECC–ARMCANZ 2000). No data on heavy metals concentration in canal water was available but concentration in soil and crops was assessed and evaluated by Amerasinghe et al. (2009). In rural areas, soil zinc and led concentrations were below European Union maximum permissible (EU MP) guideline values of <300 mg Zn/kg (WHO 2006:

no guideline value) and <300 mg Pb/kg (WHO 2006: 84 mg Pb/kg). 47 % of the soil samples investigated for cadmium exceeded the guideline value of <3.0 mg Cd/kg (WHO 2006: 4mg Cd/kg) for pH >7. Those samples that exceeded guideline value were strongly correlated with soil organic carbon concentrations. Vegetables sampled for Cd were orders of magnitude below the EU MP levels for Pb and Cd in feed materials of <1.0 and <10 mg/kg, the maximum permissible levels established by Codex Commission on Food Additives and Contaminants (CCFAC) and the weekly intake of Cd and Pb derived from the consumption of Amaranthus or Spinach was for both men and women less than 0.5% of the Joint FAO/WHO Expert Committee on Food Additives (JECFA) provisional tolerable weekly intake (Amerasinghe et al. 2009).

Salinity increases downstream due to the combined effects of additional wastewater discharge and irrigation return flows (Perrin et al. 2011). Perrin et al. (2010) reported an average canal water EC value of 1320 µS/cm for post- and pre-monsoon. Hyderabad wastewater was estimated adding 200 – 500 mg/L of TDS compared to the source water supplied to the city (Perrin et al. 2010). 94% of salinity comes from the city and the EC of soil irrigated by wastewater sampled within 8 km of the city is 6.0 to 8.4 times more than soil EC irrigated by groundwater. Fields irrigated with wastewater from the Musi River have elevated soil sodicity (>3.3 ms/cm (Amerasinghe et al. 2009) above the recommended salinity threshold for rice (0.7 mS/cm) (Biggs and Jiang, 2009; McCartney et al, 2008, Perrin et al. 2010). However, the salinity of waste water effluent was lower to the Musi River water and general values for waste water of 1100-1600 mg/L in India reported by Buechler and Mekala (2005). Risk from Salinity was assessed by comparing soil extract and canal water salinity to irrigation guideline values for 4 reference crops: Rhodes grass (perennial grass similar to para grass), paddy rice, spinach (a green leafy vegetable crop), and tomatoes (Table 14). Soil salinity at the study site was estimated by Amerasinghe et al. (2009) to 3.3 mS/cm for recently (<5 yrs irrigation) and 3.81 mS/cm for long term canal water irrigation (> 25yrs) land. Based on EC, canal water is suitable for irrigation of all 4 reference crops. However, soil EC extract from canal irrigated area land exceeded guideline values for paddy rice, spinach and tomatoes by 0.3 to >1.0 mS/cm and indicated strong salination due to evapotranspiration and mineralization (Perrin et al. 2011). Canal water SAR values derived from Perrin et al. (2011) ranged from 2.7 to 4.5. According to Ayers and Westcott (1994), SAR does not pose a risk when EC of irrigation water is >1.2 mS/cm.

Nitrate concentration varied between 0.3 and 163.9 mg/L and average concentration (84 mg/L) exceeds guideline value for drinking water. Average total nitrate nitrogen (19 mg/L) requires restrictions in use for irrigation purpose in order to prevent overstimulation of crops, delayed maturity and poor produce quality (WHO 2006). Ammonia and nitrite concentrations of 28.81 mg/L and 67.6 mg/L are above levels of concern for drinking water and likely caused by the application of nitrate-based fertilizer. Phosphate phosphorus in canal water was 1.2 mg/L. Soil accumulation was assessed by comparing soil-N, soil-P and crop yield for soils irrigated with canal water for <5 yrs and >25 yrs (Amerasinghe et al. 2009). It was found that soil-N and soil-P were up to 2.1 and 12.9 times higher in soil irrigated for >25 yrs compared to recently irrigated soils (<5yrs). Excess level of nitrogen was found to reduce rice crop yield in soil irrigated >25 yrs compared to recently cultivated soils in combination with a soil-P caused zinc deficiency in rice (Amerasinghe et al. 2008). A biological oxygen demand (BOD) of 70 mg/L was measured in 2008 (Amerasinghe et al. 2008) and improves microbial activity, binds heavy metals and increases productivity (WHO 2006).

Organic chemical analysis screening was positive for 4,4-DDE and 4,4-DDD - breakdown products of DDT, atrazine, malathion and metalaxyl but are below guideline levels for drinking water.

No data was available for turbidity and radionuclide assessment and risk associated with clogging and radionuclides are yet to be investigated.

Ground water quality assessment

Ground water quality was investigated in order to assess if the groundwater meets the quality requirements for the purpose of drinking water supply and irrigation.

Groundwater total coliforms ranged from 10^1 to 9.7×10^4 cfu/mL and were 1 $\log_{10}$ unit less than in the input surface water (W2). Thermotolerant coliform numbers were between <0.3 and 24 cfu/100m L (IWMI/NGRI/BRGM 2013). *E. coli* O157:H7, *Salmonella, Shigella and Campylobacter* detections were negative in all samples.

Average groundwater ionic composition is mainly based on Bicarbonate (515 mg/L), sodium (72 mg/L), chloride (45.2 mg/L), and sulphate (42.2 mg/L) (Perrin et al. (2011) (Figure 7). According to WHO (2006), bicarbonate concentration may damage crops (severe restrictions required). The pH was 6.9 and fluoride (1.3 mg/L) was above the guideline value of 1 mg/L for drinking water and irrigation (IS 10500, WHO 2006, Perrin et al. 2011). Native groundwater SAR was calculated to 2.1 and leaching does not pose a risk to infiltration rate (Ayers and Westcott 1994).

EC was 820 µS/cm corresponds to a TDS of approximately 549 mg/L. Groundwater sodium concentration is above the guideline value of 3meq/L for non-restricted use for irrigation. However, although groundwater salinity is lower than canal water salinity, the soil salinity of groundwater irrigated land was estimated to 4.0 mS/cm and is 0.7 to 0.2 mS/cm higher canal water irrigated soil. Soil extract of groundwater irrigated soil exceeds guideline values for paddy rice, spinach and tomatoes by 1 to >1.7 mS/cm and indicates strong salination due to evapotranspiration and mineralization (Perrin et al. 2011).

Total nitrogen as nitrate concentration of 11.8 mg/L (nitrate = 52.4 mg/L) is above drinking water guideline value and characterized by slight to moderate risk for poor quality produce (IS 10500, WHO 2006). Ammonia concentration varies between 0.4 – 0.5 mg/L and risk was rated low. Phosphate was below detection limit.

Water samples were positive for 4,4-DDE, 4,4-DDD and 4,4-DDT (all breakdown products of DDT), atrazine, malathion, metalaxyl, parathion methyl, and hexochlorohexane isomers (IWMI/NGRI/BRGM 2013). The domestic well W14 exceeded drinking water guidelines values for hexochlorohexane isomers alpha (0.02 µg/L) and beta HCH (0.07 µg/L) that were twice as high as the drinking water guideline values. Tanaka et al. (1998) assumed that through consuming vegetables irrigated with reclaimed water, people would be exposed to an daily equivalent of 10 mL of irrigation water compared to 4 L of drinking water per day. HCH isomers in the native groundwater were above drinking water guideline value and risk associated with crop ingestion was assessed for women (50 kg, aged 20-50yrs, Amerasinghe et al. (2009) by comparing the theoretical maximum daily intake (TMDI) based on a daily equivalent water intake of 10 mL (Tanaka et al. (1998) against the Joint FAO/WHO Meeting on Pesticide Residues (JMPR) acceptable daily intakes (ADI) guideline values. Although alpha and beta HCH exceed guideline values for drinking water, the estimated TMDI for both pesticides was less than 1 % (<0.0004%) of the ADI guideline values and of low risk for human endpoints

No data was available for turbidity and radionuclide assessment and risk associated with clogging and radionuclides are yet to be investigated.

Table 14 Relative soil and irrigation salinity tolerance thresholds of reference crops in Kachwani Singaram, India (Ayers and Westcot 1985 in NRMMC–EPHC–AHMC 2006)

Crops	EC_i µS/cm	EC_e mS/cm	Irrigation water	EC_{IW} µS/cm	EC_{Soil} mS/cm	Salinity risk
Buffalo grass	5,200	4 – 8	Canal water	1,320	3.3 – 3.8	Low
Paddy rice	2,600	3	Canal water	1,320	3.3 – 3.8	High
Spinach	1,700	2	Canal water	1,320	3.3 – 3.8	High
tomato	2,100	2.3	Canal water	1,320	3.3 – 3.8	High
Spinach	1,700	2	Groundwater	820	4.01	High
tomato	2,100	2.3	Groundwater	820	4.01	High

Source: Perrin et al. 2011, IWMI/NGRI/BRGM 2013

EC_i, irrigation; EC_e, soil extract; EC_{IW}, irrigation water; EC_{Soi}, soil extract canal water irrigation

4.3.3.2 Groundwater hydrology assessment

Groundwater flow direction and groundwater budget was assessed in order to 1) understand and assess environmental risks and 2) link water quality data to soil-aquifer treatment.

Groundwater flow direction

Groundwater flow direction is from North to South towards the Musi River, which is a gaining stream in all seasons. The hydraulic gradient was estimated to 0.018 (typical gradient between the canal and the river within the study area, Perrin et al. 2011). However, travel times, well catchment area, system in- and outflow and mixing ratios are yet to be investigated.

Groundwater budgeting

A groundwater budget was constructed by Perrin et al. (2011). The outflow of from the study site system and its contribution to the Musi River base flow was evaluated considering natural recharge (rainfall), recharge from irrigation (groundwater, canal, mixed), recharge from domestic use, canal loss or gain, groundwater pumping and evaporation. Natural recharge on non-irrigated area was estimated to be ~70 mm/yr. Groundwater pumping (7 h/day, 300 days/yr, domestic and irrigation) was also estimated to be ~70 mm/yr. Recharge back from irrigated agriculture to the canal (return flow) was estimated by crop budgeting. Total average return flow was estimated to 144 mm/yr and is compromised by 129 mm canal water, 29 mm groundwater and 0.9 mm domestic water (wash water, cooking, drinking). Hydraulic head of the irrigation canal equals the groundwater level and hydraulic gradient north and south of the canal are equal. It was assumed that the canal gains groundwater from the up gradient part of the aquifer (north) and looses the same amount of water to the aquifer towards the down gradient part of the aquifer (south). Canal water uptake is ~2 – 2.5

% of the canal flow and insignificant. Thus, canal gain and losses are assumed to be 0 mm/yr (Perrin et al. (2010). The steady-state groundwater budget showed that currently the groundwater pumping was balanced by natural recharge and that return flows constituted "surplus" recharge that is only partly lost as evaporation and mostly contributed to Musi River base flow. Musi River groundwater discharge was calculated to 134 – 138 mm/yr. This correspondence to 50 l/s or less than 0.4 % of Musi River base flow (13 m^3/s).

4.3.3.3 Assessment of other groundwater users

Other groundwater users were assessed in order to identify and assess risk to any possible human and environmental endpoints that can be linked to the MAR system.

Domestic well W14 is reported to be used as source for drinking water supply (IWMI/NGRI/BRGM 2013). Other wells located in canal water irrigated land (dw 27) may also be used for drinking water supply.

4.3.3.4 Assessment of urban land uses and risks to groundwater quality

Urban land uses and risk to groundwater were investigated to assess environmental risk from the MAR system and to identify risk from urban land uses to the MAR system.

The study area is used for farming, dairy production and sheep rearing. The application of pesticides and herbicides as confirmed by the 2012 pre-monsoon sampling (IWMI/NGRI/BRGM 2013) indicated risk to human health from organics by ingestion (drinking, food chain).

A survey in 2008 revealed that only 60% of the households had latrine facilities and a large percentage (40%) was defecating in the areas surrounding the settlements (Amerasinghe et al. 2009). Groundwater pollution from human faecal pathogens poses an extreme risk to groundwater.

4.3.3.5 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the Australian MAR Guidelines (NRMMC–EPHC–NHMRC 2009). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low, uncertain and high risks respectively (Table 15). A detailed summary of the risk assessment for hazards 1 to 12 is given in the following section. The maximal risk assessments for the human health end points "spray ingestion" and "drinking water" were conducted by comparing the water quality data from domestic well W14 for hazards 1 to 7 to the Indian Standards for Drinking Water (IS 10500). For the environmental end point 'irrigation", groundwater and irrigation canal water quality data for hazards 1 to 7 were compared to WHO (2006) and ANZECC–ARMCANZ (2000) irrigation guidelines values. There are no guideline values for the aquifer endpoint; however, there should be a commitment to protect the aquifer. For the environmental endpoint, the quality of untreated canal water canal was compared to native groundwater values. For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere.

This risk assessment will be re-evaluated with the post monsoon data during the next activity period.

Table 15 Maximal risk assessment for Kachwani Singaram, India

	MAR Hazards	Human endpoint – crop ingestion	Human endpoint – spray ingestion	Human endpoint – drinking water	Environ. endpoint – irrigation fodder crops	Environ. endpoint – irrigation veg. crops	Environ. endpoint – irrigation fodder soil	Environ. endpoint – irrigation veg. soil	Environ. endpoint – aquifer
1.	Pathogens – present in high numbers	H	H	H	L	L	L	L	U
2.	Inorganic chemicals – nitrate and fluoride concentration in groundwater exceed drinking guideline values, reactive iron oxides are present in the aquifer	L	L	H	H	H	H	H	L
3.	Salinity and sodicity – canal salinity is above native aquifer salinity; native groundwater TDS is below guideline values for drinking water; irrigation water EC is suitable for crops, however, evapotranspiration and mineralization increase soil extract EC, which is unsuitable for vegetables and rice, Musi sodium and chloride concentrations pose a toxicity risk to plants	L	L	L	U	H	U	H	H
4.	Nutrients – soil-N and soil-P in excess and above irrigation guidelines, nitrate and nitrite in groundwater can cause infant methaemoglobinaemia	L	L	H	H	H	H	H	H
5.	Organic chemicals – positive detection for pesticides at above drinking water guideline values, low risk from ingestion, pesticides are very persistent in soil and aquifer	L	L	H	L	L	U	U	U
6.	Turbidity and particulates – source water turbidity unknown, clogging evaluation yet to be done	U	U	U	U	U	U	U	U
7.	Radionuclides – uncertain, aquifer is compromised by granite and a potential source of radionuclides	L	L	U	L	L	L	L	L
8.	Pressure, flow rates, volumes and groundwater levels – enhanced gravitational recharge into an unconfined aquifer								L

9.	Contaminant migration in fractured rock and karstic aquifers – highly productive fissures present								H
10.	Aquifer dissolution and stability of well and aquitard – pumping wells observed to be stable after >20 years								L
11.	Aquifer and groundwater-dependent ecosystems – yet to be investigated								U
12.	Energy and greenhouse gas considerations – incidental recharge.								L

Risk assessment for human endpoint – drinking water was performed for native groundwater

(1) Pathogens:

Faecal contamination was evident in the source water with indicator levels up to 10^6 *E. coli* /100 mL. Pathogenic risks for three reference pathogens (*E.coli O157:H7*, *Cryptosporidium* and rotavirus) were calculated to 0.0014 to 0.11 DALY's/person/year. Risks associated with pathogens are above national diarrhoeal incidence (0.027 DALY's) for *E.coli* O157:H7 and rotavirus. Native groundwater pollution was evident but risk to aquifer was rated uncertain due to insufficient data.

(2) Inorganic chemicals:

Cadmium, Zinc and led were found in concentrations below EU maximum permissible level in soil and plants and were rated as low risk to human endpoints. Fluoride concentration of 1.3 mg/L in groundwater is above guideline values for both drinking water and irrigation. Reactive metals are present but risk was rated uncertain due to limitations in data.

(3) Salinity and sodicity:

Salinity risks to water quality for the canal water were high (EC measured as 1320 µS/cm) and above the native groundwater value (EC of 820 µS/cm). Continuous canal water irrigation has been implicated in increasing soil sodicity. Soil EC extract is 3.3 to 4.1 ms/cm and above guideline values for vegetables (spinach = 1.7 mS/cm, tomatoes=2.1 mS/cm and rice = 2.6 mS/cm). Groundwater TDS (calculated as 0.67 × EC) was 550 mg/l and exceeds national guideline value (500 mg/l) for drinking water. However, it is below WHO (2011) guideline value of 600 mg/l and as such rated low risk for drinking water. Sodium and chloride in canal water pose a toxicity risk to plants (WHO 2006)

(4) Nutrients:

Plants have a high nitrogen demand during initial growth stages, but this demand decreases during flowering and maturation. Nitrate-N was up to 39 mg/L (average 19 mg/L) and 1) promotes soil and aquifer clogging during recharge and 2) exceeds guideline values of 5 mg/L (WHO 2006) in ground and canal water and may cause delayed maturity and poor produce quality (WHO 2006). Phosphorus short term irrigation values (0.8-12 mg/L) are site specific values, with the need to consider the fertiliser value of phosphorus in water, other fertiliser inputs, the retention capacity of the soil as well as plant growth and associated reactions with trace elements. According to Amerasinghe et al. (2009), phosphorus was found to cause zinc deficit in rice and decrease rice yield. No guideline values or data exist for organic carbon in irrigation water, but it plays an important role in redox reactions (iron and manganese dissolution) and can induce biological clogging.

(5) Organic chemicals:

Six water samples (two piezometers, 2 canal water samples, reed pond and one domestic well) were positive for pesticides. Organochlorines were alpha-HCH (0.02 µg/L), beta-HCH (0.07 µg/L), gamma-HCH (0.01 µg/L), delta-HCH (0.02 µg/L), 4, 4 DDE - breakdown products of DDT (0.02 µg/L); organophosphates – malathion (0.05 µg/L), atrazine (0.01 µg/L); carbamates – parathion (0.02 µg/L) were detected (IWMI/NGRI/BRGM 2013).

Values for organochlorines in domestic well W14 are above drinking water guideline for α- (0.01 µg/L) and β- HCH (0.04 µg/L). Environmental risk for aquifer and soil were rated uncertain as organochlorines are very persistent. However, the amount that can persist on top of leaves after irrigation or that can be ingested through aerosol inhalation will be very low, thus not posing a risk to any of the ingestion end points (crop and spray). Water from the domestic well was positive for a high number of pesticides (α-, β-, γ- and δ HCH, butachlor, 4, 4 DDT, malathion and parathion) and 2 organochlorines (α- and β- HCH) were twice as high as the guideline value for drinking water, and thus rated a high risk.

(6) Turbidity and particulates:

Turbidity and particulates do not pose a direct health risk to human or crops, but in high amounts can reduce the permeability of the soil and cause clogging of irrigation infrastructure. High turbidity is also an aesthetic risk to drinking water quality. Currently there is no available data for turbidity and a clogging evaluation is yet to be done. Therefore, the risks of turbidity and particulates to water quality were rated as uncertain.

(7) Radionuclides:

Radionuclides pose a risk to human health; natural radionuclides can be transferred to crops through irrigation, although they do not concentrate in plants and crops (ANZECC and ARMCANZ, 2000). Gross alpha and gross beta values for irrigation water are given considering an annual committed effective dose of 1 mSv (NHMRC–NRMMC 2004, Section 7.5). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 in NHMRC–NRMMC (2004). No radionuclide data is available for the canal water. The aquifer is composed of orthogneissic granite as basement with granite (Schmitt 2010, Perrin et al. 2011, Aellen 2011) and may contain radionuclide concentrations in excess of guideline values (Herczeg and Dighton 1998, NRMMC–EPHC–NHMRC 2009). However, in the absence of data the risk was rated uncertain.

(8) Pressure, flow rates, volumes and groundwater levels:

Hydraulic hazards are assessed to present a low risk, because fractured rock aquifer is unconfined, recharge is only induced and limited not by pressure. The risks from pressure, flow rates and groundwater levels are considered to be low.

(9) Contaminant migration in fractured rock or karstic aquifers:

Highly productive fissures were detected in the fractured rock aquifer between 7 and 23 m below ground level. The risk for contaminant migration such as pesticides via fractures is high (Perrin et al. 2010).

(10) Aquifer dissolution and stability of well and aquitard:

Calcium carbonate (calcrete) was found in the laminated layer between 3 and 14 m. However, the fractured rock aquifer is composed of orthogneissic granite (Schmitt 2010, Perrin et al. 2011, Aellen 2011) and the risks to aquifer dissolution/well stability is assumed to pose low risk.

(11) Aquifer and groundwater-dependent ecosystem:

No data is available on aquifer dependent ecosystems and the risk is uncertain.

(12) Energy and greenhouse gas considerations:

Recharge is gravity fed and thus requires no additional energy and produces no additional green house gases. The risks for this system of excess energy use are considered low.

4.3.4 Stage 3 Musi River Risk assessment

4.3.4.1 Return flow and recovered water quality assessment

Water quality data from IWMI/NGRI/BRGM (2013) and Perrin et al. (2011) was used to perform the residual risk assessment for the Musi River site. Based on the conceptual layout of the Musi River system (Figure 7), sampling points from Perrin et al. (2011) were categorized based on location and EC values into native groundwater, canal water, mixed groundwater water (recovered groundwater) and return flow (recovered canal irrigation water) and corresponding data was used for evaluation of MAR guideline hazards 2 to 7.

Thermotolerant coliform numbers detected in recovered water and return flow were between <0.3 and 3.5 cfu/100mL and up to 1 $\log_{10}$ unit below numbers in canal water (IWMI/NGRI/BRGM 2013). However, it is conservatively assumed that numbers are higher because source water thermotolerant counts by (IWMI/NGRI/BRGM 2013) were below numbers for wastewater and up to 5 $\log_{10}$ units lower than previously reported by Amerasinghe et al. (2008), Ensink et al. (2009) and Schmitt (2010). *E. coli* O157:H7, *Salmonella, Shigella and Campylobacter* detections were negative in all samples.

Return flow magnesium concentration increased after irrigation and subsequent aquifer storage 1.5 times to 43.9 mg/L. Magnesium concentration in canal water was similar to groundwater and the increase in magnesium has been linked to other sources of contamination (Perrin et al. 2010) such as fertilizer (Mg $(NO_3)_2$). Potassium and calcium decreased about 2 to 1.1 times to 5.5 and 56.8 mg/l. Sulphate concentration increased from 58 to 89 mg/L in return flow (SO_4^{2-}in GW = 42 mg/L) and thus may be geogenic (e.g. from pyrite oxidation). Recovered groundwater quality was significantly affected by mixing with canal irrigation return flows. Major ions except potassium and hydrogen carbonate increased 1.1 (calcium) to 2.9 (chloride) times (Perrin et al. 2010). Groundwater was particularly enriched with sodium and chloride and the calcium-hydrogencarbonate type water was transformed into mixed water (Figure 7). Chloride concentration was relatively stable compared to sodium and may increase through cation exchange with calcium. Dissolved oxygen in groundwater and recovered water was determined to 2.1 and 28 % oxygen saturation (Perrin et al. 2010). Fluoride is geogenic (Perrin et al. 2010) and concentration increased from 0.8 mg/L up to 2.3 mg/L (mean 1.4 mg/L). Average fluoride concentration was similar return flow water and recovered mixed water and above guideline values for drinking water supply and irrigation.

Average return flow EC and sodium increased after irrigation and subsequent aquifer storage 1.1, and 1.3 times to 1477 µS/cm and 192.2 mg/L due to evaporation and mineralization. Thus, return flows from canal irrigation have a higher salinity as the source water and cause a general increase in concentrations of many parameters in the Musi River in downstream direction (Perrin et al. 2010). EC in recovered mixed water increased from 820 to 1226 µS/cm (Perrin et al. 2010) due to an increase in calcium and magnesium concentration. Similar to return flow water, sulphate concentration increased significantly (2.2 times). Both, return flow and recovered mixed groundwater meet the salinity requirements for the Musi reference crops (1.7 – 5.2 mS/cm). However, as identified in the maximal risk assessment, soil salinity in both groundwater and canal water irrigated area is above guideline values for rice and vegetables. Sodium and chloride concentrations of 109 and 131 mg/L in recovered groundwater and 192 and 194 mg/L in return flow are clearly above guideline values (Na = 69 mg/L (3 meq/L), Cl = 142 mg/L (4 meq/L)) and pose a high toxicity risk for plants.

In comparison with canal water, phosphorus and nitrogen were lower in return flow and thus fixed in soil and plants after irrigation and soil-aquifer treatment. Concentrations of nitrate, ammonia and phosphorus in canal water decreased 2.5, 6.1, and 4.9 times after irrigation. Average nitrate concentration decreased from 84 mg/L (canal water) to 34.5 mg/L (return flow). Phosphate was found in return flow water in concentrations up to 3.44 mg/L but mean concentration deceased from 1.2 mg/L to 0.77 mg/L. Contrary to canal irrigation water, nitrate concentration increased slightly from 52.4 (groundwater) to 57.2 mg/L (Perrin et al. 2010) in recovered mixed groundwater. This may be attributed to fertilizer application if farmers are aware of waste water being a source for nitrogen. Phosphate was below detection limit in all samples. This indicates canal irrigation water as primary source for phosphorus besides from fertilizer. Total nitrate nitrogen is above guideline values (5 mg/L) but phosphate phosphorus (0.4 mg/L) decreased below STV-values of 0.8 – 1.2 mg/L.

For organic detections, one out of 5 water samples (W5) from sampling points that are not re-filled with canal water (W5, W6, W8, W9, W12, W13) was positive for only atrazine (0.03 µg/L) and metalaxyl (0.03 µg/L) and located in canal water irrigated land (IWMI/NGRI/BRGM 2013.

No data was available for turbidity and radionuclide assessment and risk associated with clogging and radionuclides are yet to be investigated.

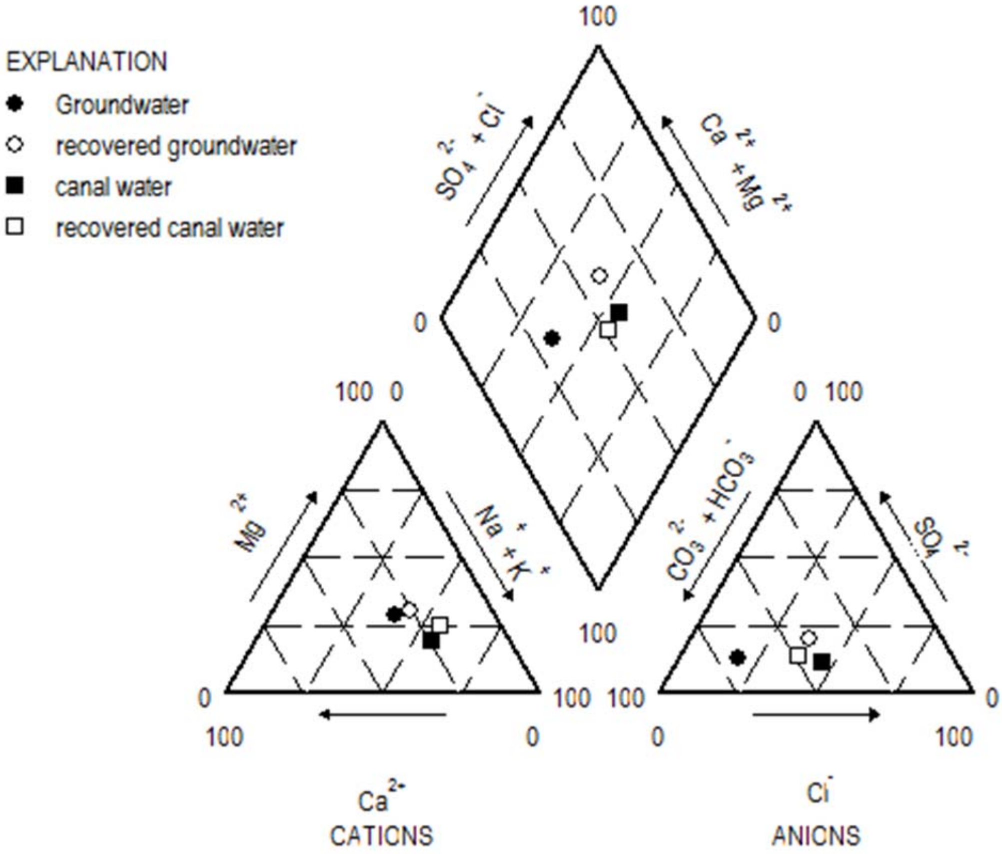


Figure 7 Piper diagram showing average groundwater, canal water, recovered groundwater and recovered canal water chemistry

4.3.4.2 Residual risk assessment

The Stage 2 semi-quantitative residual risk assessment for the Kachwani Singaram recharge system was performed using the same approach as for the maximal risk assessment is summarized in the following section.

1) Pathogens:

Risks from pathogens are conservatively assumed to be equal or less compared to the maximal risk and rated as highly uncertain because 1) system including in and outflow, travel times and flow distances is not fully understood yet and 2) microbial analysis of recovered water samples is questionable.

(2) Inorganic chemicals:

Cadmium, zinc and lead were found in concentrations below EU maximum permissible level in soil and plants and were rated as low risk to human health endpoints. Mean fluoride concentration in both return flow and mixed water was equal or above drinking water guideline value (1.0 mg/l) and is likely of geogenic origin (Perrin et al. 2010). The amount of fluoride ingestion through aerosol inhalation and vegetables will be very low, thus not posing a risk to any of the ingestion end points. Presence of iron is yet to be determined and rated uncertain.

(3) Salinity and sodicity:

Average EC of recovered water was 1226 µS/cm in mixed groundwater and 1477 µS/cm in return flow and suitable for reference vegetables, rice and fodder. However, soil EC (3.3 to 4.1 ms/cm) exceeded guideline values for vegetables (spinach, tomatoes) and rice due to evapotranspiration and mineralization. Recovered water TDS (0.67*EC) was 821 and 989 mg/l is below WHO (2011) guideline value for potable water supply (1,200 mg/L).

(4) Nutrients:

Average nitrogen and phosphorus values in recovered water are 12.9 mg NO_3^--N/l and 0.4 mg PO_4^--P/l in recovered mixed water and 7.7 mg NO_3^--N/l and 0.2 mg PO_4^--P/l in return flow and above guideline values for nitrogen (WHO 2006). Nitrate concentration of 57.2 mg/L in recovered groundwater exceeds guideline value for drinking water.

(5) Organic chemicals:

Atrazine (0.03 µg/l) and metalaxyl (0.03 µg/l) were found in return flow water in concentrations below drinking water guideline values. However, detections represent a grab sample and risk associated with organic chemicals was conservatively rated uncertain.

(6) Turbidity and particulates:

Clogging evaluation is yet to be done and was rated uncertain

(7) Radionuclides:

Radionuclides pose a risk to human health; radiologically significant natural radionuclides can be transferred to crops through irrigation, although they do not concentrate in plants and crops (ANZECC and ARMCANZ, 2000). Gross alpha and gross beta values for irrigation water are given considering an annual committed effective dose of 1 mSv (NHMRC–NRMMC 2004, Section 7.5). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 in NHMRC–NRMMC (2004). No radionuclide data is available for the canal water. The aquifer is composed of orthogneissic granite as basement with granite (Schmitt 2010, Perrin et al. 2011, Aellen 2011) and may contain high radionuclide concentrations (Herczeg and Dighton 1998, NRMMC–EPHC–NHMRC 2009). Therefore, for the purposes of the maximal risk assessment it has been considered that radionuclides may be present in groundwater and canal water, and risk was rated uncertain.

(7) Radionuclides:

Radionuclides pose a risk to human health; natural radionuclides can be transferred to crops through irrigation, although they do not concentrate in plants and crops (ANZECC and ARMCANZ, 2000). Gross alpha and gross beta values for irrigation water are given considering an annual committed effective dose of 1 mSv (NHMRC–NRMMC 2004, Section 7.5). Dose estimates based on the dosage per unit intake of individual radionuclides can be calculated using Table 7.1 and Section 7.6 in NHMRC–NRMMC (2004). No radionuclide data is available for the canal water. The aquifer is composed of orthogneissic granite as basement with granite (Schmitt 2010, Perrin et al. 2011, Aellen 2011) and may contain radionuclide concentrations in excess of guideline values

(Herczeg and Dighton 1998, NRMMC–EPHC–NHMRC 2009). However, in the absence of data the risk was rated uncertain.

(8) Pressure, flow rates, volumes and groundwater levels:

Hydraulic hazards are assessed to present a low risk, because fractured rock aquifer is unconfined, recharge is only induced and limited not by pressure. The risks from pressure, flow rates and groundwater levels are considered to be low.

(9) Contaminant migration in fractured rock or karstic aquifers:

Highly productive fissures were detected in the fractured rock aquifer between 7 and 23 m below ground level. The risk for contaminant migration such as pesticides via fractures is high (Perrin et al. 2010).

(10) Aquifer dissolution and stability of well and aquitard:

Calcium carbonate (calcrete) was found in the laminated layer between 3 and 14 m. However, the fractured rock aquifer is composed of orthogneissic granite (Schmitt 2010, Perrin et al. 2011, Aellen 2011) and the risks to aquifer dissolution/well stability is assumed to pose low risk.

(11) Aquifer and groundwater-dependent ecosystem:

No data is available on aquifer dependent ecosystems and the risk is uncertain.

(12) Energy and greenhouse gas considerations:

Recharge is gravity fed and thus requires no additional energy and produces no additional green house gases. The risks for this system of excess energy use are considered low.

4.3.5 Conclusion

Several investigations have improved the understanding of the hazards (e.g. salination, heavy metals) related to waste water usage for irrigation and aquifer recharge at the Musi River site. However, some specific questions remain concerning pathogen capabilities; capture zones for monitoring wells (travel times, groundwater mixing ratio, flow distances) and redox geochemistry. The residual operational risk from recovered water after SAT treatment cannot be assessed properly yet due to uncertainty of data and risks for hazards 1 to 12 are equal to the maximal risk assessment. According to the maximum risk assessment, Musi River water and groundwater are not suitable for its purpose as source for irrigation and potable supply. In order to improve reduce uncertainty of existing data and/or identify treatment requirements to make risks acceptable, a second water quality monitoring with improved quality control is necessary. Risks that were identified as high are:

- Pathogens are evident in high numbers in source water (10^6 cfu/100 mL). Risks from *E.coli* O157:H7 and rotavirus in source water are above national diarrhoeal incidence (0.027 DALY’s) for any human endpoints and pose a high risk. Risk from pathogens in recovered water is uncertain and yet to be investigated.
- Fluoride concentration of 1.3 mg/L is above guideline values for drinking water and irrigation in both source and recovered water,

- High source water salinity, flood irrigation practise and arid climate conditions have caused severe soil salination. Soil extract salinity exceeds guideline values for rice and vegetables.
- Nitrogen and phosphorus concentration in both source and recovered water are above recommended guideline values for human (nitrate) and environmental endpoints (plant growth and associate reactions with trace elements such as zinc),
- Organic chemicals are evident in source and recovered water. Alpha-HCH (0.02 µg/L) and beta-HCH (0.07 µg/L) in native groundwater exceed drinking water guidelines.

Additional pathogen treatment such as limiting discharge of untreated wastewater or human excreta into the Musi River can be applied to the source of contamination and reduce pathogen numbers by 0.5 to 1 $\log_{10}$ (NHMRC 2011). Groundwater and does not meet the requirements for fluoride, nitrate, pathogens and pesticides. However, in the absence of any alternative following pre-cautions are strongly recommended: 1) do not feed infants with groundwater and 2) boil water for the purpose of food ingestion and potable water supply. Soil salinity and soluble nutrients accumulate in soil but can be reduced by monsoon rainwater harvesting and applying excess rainwater to leach soil and adequate fertilizer management according to plant grow stages and season. Evapotranspiration and soil salination in future cultivated soils for vegetable cultivation may be reduced by drip-irrigation, high vegetation and blending with harvested rainwater.

4.4 Assessment of institutional viability

4.4.1 Legal framework

A summary of the relevant policies and laws for wastewater treatment and irrigation in the case study at national, state and municipal level can be seen in Table 16.

Table 16 Relevant policies and laws for case study

Musi River	Key statement concerning wastewater treatment, surface water and irrigation
National	
Draft National Water Policy, 2012	- Recycling and reuse of water should be the general norm - Water bodies should not be polluted - Concerning alternatives: Rain Water Harvesting and desalination encouraged
Planning Commission Model Bill for the Conservation, Protection and Regulation of Groundwater, 2011	- Recognizing interaction between groundwater and surface water - Encourage recycling and reuse of water
(National Urban Sanitation Policy 2008)	- Recycling and reuse of water should be

	encouraged
National Water Policy, 2002	- Effluents shall be treated before discharged to streams - Recycling and reuse of water should be encouraged
Environment (Protection) Second Amendment Rules, 1993	- Standards for discharge of treated WW to streams / sea / sewers or for use in agriculture
Environment (Protection) Act, 1986	- All discharged wastewaters shall comply with the existing standards
Prevention and Control of Pollution Act, 1974	- Pollution of rivers and streams is prohibited
State level	
Andhra Pradesh State Water Policy, 2008	- Conservation of water bodies and wetlands by enforcement of standards - Promotion of sustainable use of groundwater - Enforcing recycling of wastewater - Regulation of land use around water bodies - Consideration of environmental aspects (mitigation of negative impacts, surface and groundwater sustainability) - Maintain ecological services and water quality of surface waters
(Water, Land and Trees Act, 2002)	- Constitution of the Andhra Pradesh State Water, Land and Trees Authority - water bodies can be especially protected (“heritage body”)
Andhra Pradesh Water Resources Development Corporation Act, 1997	- Constitution of the Andhra Pradesh Water Resources Development Corporation
Andhra Pradesh Farmers' Management of Irrigation Systems Act, 1997	- Water User Association are responsible for operating irrigation infrastructure
The Andhra Pradesh Irrigation Utilisation and Command Area Development Act, 1984	- Constitution of Development Authority
Municipal level	
The Hyderabad Metropolitan Water Supply and Sewerage Act, 1989	- Constitution of the Hyderabad Metropolitan Water Supply and Sewerage Board

4.4.2 Stakeholder survey

An overview of the relevant stakeholders for wastewater treatment and irrigation in the case study at national, state and municipal level can be seen in Table 17.

Table 17 Relevant stakeholders in case study area

Musi River (NWWTS)	Key role concerning NWWTS	Interest
National		
Central Pollution Control Board	- Preparation of manuals, codes and guidelines relating to treatment and disposal of sewage - Definition of standards - Prevention and control of environmental pollution.	- Water and Air pollution control towards protection of water bodies and air
Ministry of Water Resources	- Formulation of policies ("National Water Policy" 2002 and Draft 2012)	- Development and management of water resources
Ministry of Environment and Forests	- Implementation and funding of "National River Conservation Plan" (3148.5 million INR investment in Musi River area[4]) to improve river water quality	- implementation of policies and programmes relating to conservation of the country's natural resources including lakes and rivers, its biodiversity, forests and wildlife, ensuring the welfare of animals and prevention and abatement of pollution.
Ministry of Urban Development	- Formulation of policies ("National Urban Sanitation Policy" 2002)	- Manage urban wastewater among a large number of other mandates
State level		
State Government of Andhra Pradesh	- Funding (30% of river conservation plan)	- Protection of water bodies - Provision of services to users (interest: satisfied citizens)
Andhra Pradesh Pollution Control Board	- Analysis of river water quality - Control of discharge (of industries) to river - -development of technology	- Protection of water bodies from pollution at state level
Andhra Pradesh Water Resources Development Corporation	- Prevent pollution of river water which is used for irrigation purposes - Implementation of irrigation and drinking water supply projects	- Protection of water bodies from pollution - Provision of water supply infrastructure

[4] Download Presentation by Ministry of Environment and Forests (15.3.2010) on National River Conservation Plan

Andhra Pradesh Water, Land and Trees Authority	- Promotion of water conservation, regulation of water exploitation	- Protection of water resources
Municipal level		
Greater Hyderabad Municipal Corporation (GHMC)	- Responsible for all types of urban development activities and services through its multiple wings.	- Protection of water resources
Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB)	- Responsible for water supply and wastewater treatment and operation of systems	- Provision of services (water supply and wastewater collection and treatment) to consumers
Hyderabad Metropolitan Development Authority (HMDA)	- Preparation of Master Plans for Hyderabad[5]	- Future development areas and planning
CSOs (e.g.Forum For a Better Hyderabad)	- Interest in improving environmental situation in Hyderabad	- Protection of water resources
Research Centres (IWMI, Osmania University, Hyderabad Central University, Ronald Ross Institute of Tropical Diseases, Centre for Economic and Social Studies, University of Hyderabad)	- Studies on river water quality, urban agriculture, water pollution, etc.	- Provision of scientific background information - Awareness raising
Farmers within Hyderabad (~250 farmers)	- Users of river water for irrigation of paragrass	- Use of river water
Farmers outside Hyderabad (downstream Musi River)	- Users of river water for irrigation of paragrass, rice and vegetables	- Use of river water
Water User Associations	- Operation of irrigation schemes	- Protection and representation of farmers interests concerning irrigation
Bhagya Nagar Kisan Sangh (BNKS) – Farmer's Association	- Platform for urban farmers,	- Defending and representation of rights of urban farmers
Industry	- Discharging wastewater to Musi River - Consumers of river water	- Users of river water - Low costs for wastewater treatment (discharge to river)

5 http://220.227.252.236/ehmr/

City residents	- Beneficiaries of cleaner Musi River - Less Payment for sewerage treatment	- Reduce environmental pollution and "yuk factor" leading to cleaner environment
Health institutions	- Impact of treatment on improved health of farmers (and consumers?)	- Improve health of population

4.4.3 Analysis of stakeholder interests

Following a workshop with representatives of institutional stakeholders, where the above findings were presented, 25 of them filled in questionnaires to inform about their perception of the future development of the Musi river catchment. The Table 18 below summarizes the results. In order to protect the anonymity of respondents, names and age were deleted and institutions were grouped together. Respondents were aged 27 to 60, a third of them women; 14 came from academia, 7 from government and 4 from other institutions (NGOs, water user associations).

Table 18 Results of a Stakeholder Survey

No	Institution	Gender	Urbanization expected	Preserve catchment	Pollution solvable	End irrigation	WWTP beneficial	CW suitable	Rank pollution	Rank costs	Rank acceptance	Rank efforts	Rank health	Cluster
1	O	F	Y	Y	Y	Y	Y	Y	1	5	2	3	4	O
2	A	M	Y	Y	Y	Y	Y	Y	1	5	4	2	3	O
3	G	M	Y	Y	Y	Y	Y	Y	1	4	3	5	2	H
4	O	M	N	Y	Y	N	Y	Y	1	5	3	4	2	H
5	O	M	Y	Y	Y	N	Y	Y	2	3	NA	NA	1	H
6	A	M	Y	Y	Y	Y	Y	Y	4	1	5	2	3	C
7	A	M	Y	Y	Y	Y	Y	Y	5	3	4	1	2	H
8	G	M	N	Y	NA	NA	NA	NA	NA	NA	NA	NA	NA	O
9	A	F	Y	Y	Y	Y	Y	Y	1	4	5	3	2	H
10	A	F	Y	Y	N	Y	Y	Y	1	2	4	3	5	C
11	A	F	Y	Y	Y	Y	Y	Y	2	1	3	5	4	C
12	A	F	N	Y	Y	Y	Y	Y	1	5	3	4	2	H
13	A	F	Y	Y	N	Y	Y	Y	1	3	4	5	2	H
14	G	F	Y	Y	Y	Y	Y	Y	2	5	3	4	2	H
15	A	M	Y	Y	Y	Y	Y	Y	2	4	1	5	3	O
16	A	F	Y	Y	Y	Y	Y	Y	1	5	4	3	2	H
17	G	M	Y	Y	Y	Y	Y	Y	5	4	3	1	2	H

18	G	M	N	Y	Y	Y	Y	Y	5	4	1	2	3	O
19	G	M	N	Y	Y	Y	Y	N	1	5	4	3	2	H
20	G	M	Y	Y	Y	Y	Y	Y	2	5	4	3	1	H
21	A	M	Y	Y	Y	Y	Y	Y	NA	NA	NA	NA	NA	O
22	A	M	Y	Y	Y	Y	Y	Y	1	2	5	3	4	C
23	A	M	Y	Y	Y	Y	Y	Y	2	4	3	5	1	H
24	A	M	Y	Y	N	Y	Y	Y	1	5	3	4	2	H
25	O	M	Y	Y	Y	N	Y	Y	2	3	NA	NA	1	H

Explanations: Institutions: A Academia, G Government, O Other; CW constructed wetland; WWTP wastewater treatment plant; F female, M male; Y yes, N no, NA no answer; cluster: C costs, H health, O other

Musi river now … and in 2025?

Figure 8 Present state and possible development scenario for Musi river catchment

Urbanization was perceived as a key issue: 80% of the respondents expected the catchment to become urbanized within the next decade (c.f. Figure 8 above), whereas all respondents stated their wish to preserve this as a natural habitat for future generations. 84% were optimistic about solutions to water pollution and asked that actions should be taken. In particular, to resolve health issues related to irrigation with water from a channel fed by Musi river, 84% stated preference to end that praxis and 96% agreed that it would be beneficial, if instead treated water from a new wastewater treatment plant would be used. 92% considered constructed wetlands (CW) or similar solutions as suitable. Overall, 92% considered the preparation of a water management plan as beneficial. However, with regard to the questions about who should be responsible for the planning of e.g. a wastewater treatment plant, who should be in charge of its operation, and who should pay for it, there was no clear preference: For planning and operation respondents mentioned Hyderabad Metro Water Supply & Sewerage Board, the Irrigation & Command Area Development Department, but also diverse other government departments, water user associations, or private agencies. As to the financing, respondents considered that the government should pay (e.g. one of the above mentioned departments), the polluters (e.g. high fines), public-private partnerships, or the citizens.

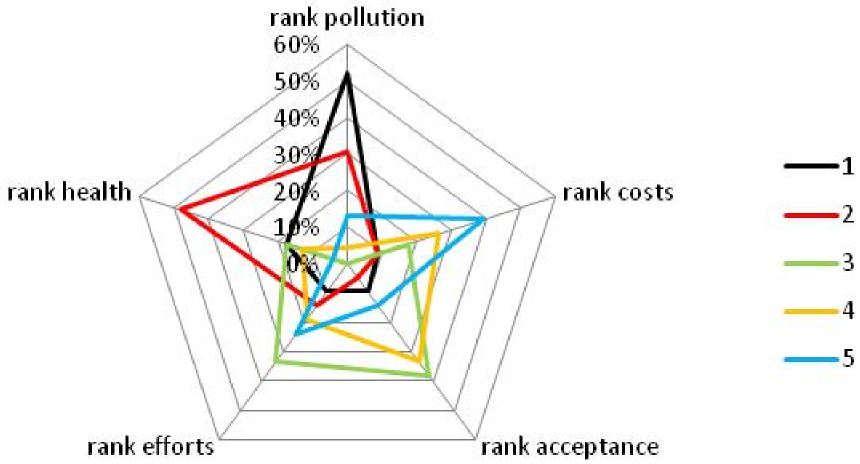


Figure 9 Ranking of criteria (NA not counted)

Stakeholder representatives were also interviewed about their motivation, both specifically for each question, and generally, about the importance of key criteria for technology selection to them, asking about the relative importance of pollution control, costs, acceptance by users, ease of operation (low efforts), and safety for health; see Figure 9. This resulted in two clusters, cost-conscious and health-conscious respondents: The first cluster refers to a smaller group of four respondents (all in academia), to whom costs mattered (criterion ranked as first or second most important), whereas health was not so important (ranked third to fourth). The second cluster refers to a larger group of 15 respondents (from all types of institutions), for whom health mattered (criterion ranked as first or second most important), whereas costs were not so important (ranked third to fourth). Two respondents stated no preferences and four others put pollution or ease of use (2 respondents each) in number-one position.

It follows that the interviewed representatives of institutional stakeholders displayed strong preferences for environmental issues (pollution control and health), which resulted in a high level of agreement about the possible approaches to solve the environmental problems of Musi river catchment. Minor discrepancies occurred about the importance of costs. However, respondents had no clear preferences for the implementation (i.e. who should plan, operate or finance infrastructure).

4.5 Social (risk) acceptance assessment

The social acceptance issues of concern are the acceptance of the farmers to use the treated wastewater for irrigation and the acceptance of the consumers to buy agricultural products that have been irrigated with treated wastewater. As the current practice, to use polluted canal water for irrigation, seems well accepted, the major issue seems to be to convince farmers to use treated canal water for irrigation and to bear the costs for it, as well as to explore acceptance of consumers to pay possibly higher prices for the resulting, safer, goods. As these topics have already been partially studied by local partner IWMI, it was not required to conduct a social survey to investigate these questions in more detail. Instead, two recent studies conducted by IWMI are briefly summarized below:

4.5.1 Farmers' perception of wastewater (re)use

In a recent study of IWMI, Jampani et al. (2013) conducted a survey to investigate the dynamics of wastewater irrigation practices in face of rapid urbanization of Hyderabad city. The study specifically focused on land-use patterns, crop choices, farmers perceptions on wastewater use, awareness of nutrient availability in irrigation waters, perception on water quality, health problems, socioeconomic status, costs and benefits associated with wastewater irrigation, institutional support and the interest to pay for cleaner water for agriculture. 47 farmers were interviewed in the neighbourhood of Hyderabad (Kachivani Singaram micro-watershed) using a structured and direct questionnaire. 39 of the 47 farmers were using wastewater from the canal, 8 were only groundwater users and 1 farmer was using both sources of water for irrigation.

Regarding the farmers perception on wastewater uses, the main results of the survey can be presented as follows:

- The eight farmers using groundwater for irrigation were of the opinion that the quality of wastewater was not appropriate for crop production;
- Farmers using wastewater are satisfied with the nutrient quality (benefit), they accept it as a trade-off and were willing to continue to use wastewater for crops irrigation;
- All farmers complained of the "yuck factor- a reaction of repugnance or distaste" associated with the Musi River water
- Other common complaint was the indirect effect associated with the nuisance of mosquitoes in the para-grass growing areas. Farmers were of the opinion that the frequent fevers that families suffered were due to the high number of mosquitoes in the villages. Health risks were considered as being one of the key disadvantages working with wastewater.
- Farmers whose perception on water quality was poor felt that irrigation with wastewater changed the soil quality with the increase of salinity level. They mentioned salinity as an explanation for paddy yield reductions;
- Farmers whose perception on water quality was good were referring to the nutrients already available in the wastewater, and they were confident that the water has good potential for irrigation;
- Most farmers felt that the water quality appears to have improved over time, with the installation of three new sewage plants;

- Paradoxically, most of the farmers think that further treatment of wastewater is required before using it for irrigation purposes.
- Farmers mentioned that they are willing to accept and pay small amounts, which is around INR 100 to INR 200 per year (per household), if cleaner water is supplied for irrigation.

From the survey, it appears that farmers are more or less familiar with the risks and benefits of wastewater use. Nutrient benefits seen to be the primary reason of using wastewater and its acceptance for irrigation. The disgust (or "yuck") factor and the mosquitoes problems are the most cited determinants of social rejection of wastewaters. These two determinants seem to be the principal indicators influencing the farmers' willingness to pay for treatment of wastewater before reuse in irrigation.

Like all surveys dealing with perception, this one is subject to some cautionary notes. The survey conclusions were based on responses from low sample that were too small to permit reliable analysis. For instance, the survey does not inform about others factors that influence farmers' acceptance/rejection of wastewater use. Inclusion of questions that are relevant to farmers' acceptance needs to be taken into account as part of an extended social survey. One of the most important cautionary is the elicitation of willingness to pay of farmers for cleaner wastewater for irrigation. The direct and general question included in this survey suffers from a number of response biases. One way that economists use to assess the willingness to pay (WTP) for non-market resources, is the contingent valuation method (CVM). The method simulates a hypothetical market through a specific survey and was already implemented in another study which is presented below.

4.5.2 Hyderabad residents' willingness to pay for wastewater treatment

To find out how much people might be willing to pay for cleaner water in Musi River in Hyderabad city, Devi et al. (2009) conducted a CVM experimental survey as part of research project, supported by the IWMI.

A total of 275 residents of Hyderabad city were surveyed with an open-ended questionnaire. After a set of questions on respondents' profile, water pollution sources and issues and water quality, the respondents were asked a series of questions regarding their willingness to accept and to pay to achieve three different water quality levels in Musi River in Hyderabad. River water quality levels were described to respondents as "swimmable" (level A), "fishable" (level B) and "boatable" (level C). The explanation was supported by cartoon picture to raise respondents' comprehension and concerns about current water quality of Musi River (level D).

Payment card was employed as eliciting tools of WTP values. It shows the "cess" (i.e. a tax on a tax) on sewage tax that people might pay to the HMWSSB. The starting point is chosen as the current rate of sewage cess (35% of water supply charges on the basis of monthly water bill which is INR 90 per household) and then incremented by 5% increase. Thus, respondents were asked to choose an annual amount between INR 432 (currently paid) and INR 2785 that they would pay to improve wastewater treatment for different quality levels.

The preliminary findings of the survey are summarised as follow:

- More than 90% of the respondents were in favour of controlling pollution in the Musi River.
- About 46% ranked the industrial pollution as the first source of river pollution, followed by sewage from commercial complexes (e.g. hotels, shops, hospitals …) and sewage from domestic water users (25%).
- Among reasons and motivation of respondents to clean water in the river, 47% cited the avoidance of bad odour, mosquitos' problems and pollution of groundwater. A further 31% were motivated by their responsibility to improve the environment (general sensitivity to environmental issues).
- Cleaner wastewater was associated with irrigation and better food for only 10% of individuals surveyed.

While the large percentage of the 275 respondents have significant concerns over the quality of water in the Musi River, almost half (155 persons) of them refused to pay any additional sewerage cess. Only 29% of them were willing to pay for treatment level C (boatable), 10% for treatment level B (fishable) and 4% for treatment level A (swimmable). The authors explain this low acceptance by the following main reasons:

- Poor potable water services: Hyderabad residents are very dissatisfied by the potable water supply services (few hours a day) provided by HMWSSB and they refuse to pay more for wastewater services;
- Lack of trust: confidence in the water authorities responsible for the management of wastewater. Some people reject the idea of paying additional taxes as they did not any efficient improvement in water governance ,
- Respondents were only willing to contribute at a certain level on the condition that, first water authorities invest in wastewater treatment plants and improvement of the river water quality became visible for them.

An econometrics analysis of the survey results found that the WTP of respondents is mainly determined by their perception on the importance of controlling water pollution and their household incomes. Whereas the number of year the respondents lived in Hyderabad and the proximity of the river have an insignificant influence on the WTP values. On annual average respondents were willing to pay respectively INR 1250 for level C, INR 2217 for level B and INR 2445 for level A as per household per year. Considering the current cess rate of 35%, the increase is comprised between 81% and 191% (Table 19).

Table 19 Willingness to pay for wastewater treatment by water quality levels (from Devi et al., 2009)

Level of river water quality	Level C "boatable"	Level B "fishable"	Level A "swimmable"
Number of respondents WTP	81 (29%)	28 (10%)	11 (4%)
Average value of WTP (INR per household per year)	1250	2217	2445
Associated increase in cess rate (% of charge on water bill tax)	81%	170%	191%

By comparing WTP values with the current estimated cost of treatment (1.4 to 9 INR/m^3) it was concluded from the survey results that the cost recovery of sewerage services and wastewater treatment would not be fully achieved in Hyderabad.

4.5.3 Discussion

Besides the cautionary to be taken for the results of both studies, the CVM survey showed a greater WTP values then value obtained from the first survey where a direct question have been asked to determine farmers WTP. It can be explained by the fact that farmers are poorer (and less educated) and are willing to pay less for the improvement in the water quality of the Musi River.

Other studies where questions have been asked in order to determine people preferences for wastewater treatment showed a lesser WTP values. For instance, Birol and Das (2010) have implemented the choice experiment method (alternative economic method to CVM) to assess the WTP in the Chandernagore municipality (River Ganga) and found an average annual WTP INR 100 per year per household as additional municipal taxes.

Regarding the issue of consumers' acceptance to accept and to buy agricultural products has received scant attention in India and no studies have been carried out in Hyderabad. Further studies are needed to address both social acceptance and willingness to pay for the improvement of wastewater treatment and reuse for irrigation.

5 Case study Chennai (Managed Aquifer Recharge)

5.1 Overview of case study

Chennai is the capital of Tamil Nadu State and one of the metropolitan cities of India. In 2011, the area covered by Chennai City was extended to about 426 km^2 (from previously about 172 km^2) and as per 2011 census about 6,727 million inhabitants live in Chennai City. Chennai City is a part of the Chennai Metropolitan Area (CMA) which covers an area of 1,189 km^2. Around 9 Million people live in the Chennai Metropolitan Area. The Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB), a statutory body established in 1978, is responsible for water supply and sewerage functions within CMA. Presently, the operations of CMWSSB are restricted to Chennai city. However, CMWSSB is expected to gradually extend its services to the entire CMA.

The water supply for Chennai City is mainly covered by surface sources. To a smaller extent groundwater sources are used and recently also two desalination plants have been installed. In addition, treated wastewater is provided to industry. An overview of the present water supply sources can be seen in Table 20.

Table 20 Water supply sources of Chennai

Currently used water supply sources	Installed Capacity (MLD)	Supply as on 13 .03.2013 (MLD)	% of total installed capacity / % of total water supply on 13.03.2013	Source of information
	Piped water supply			
Surface Water (Kilpauk WTP)	270	230	17 / 26	Data from Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB), unpublished
Surface Water (Red Hills WTP)	300	140	18 / 16	
Surface Water (Veeranam WTP)	180	105	11 / 12	
Surface Water (Chembarambakkam WTP)	530	210	33 / 24	
Surface Water (Surapet WTP)	14	9	1 / 1	
Groundwater from Araniyar-Kortalaiyar basin (AK basin)	100	7.	6 / 1	

Groundwater from South Chennai	1.25	1	0 / 0	
Local sources in added areas of Chennai	30	30	2 / 3	
Desalination plant –Minjur -Nemmeli	100 100	100 48	6 / 11 6 / 5	
Treated wastewater (to industry)	41	36		

Figure 10 below shows the location of the surface and groundwater sources.

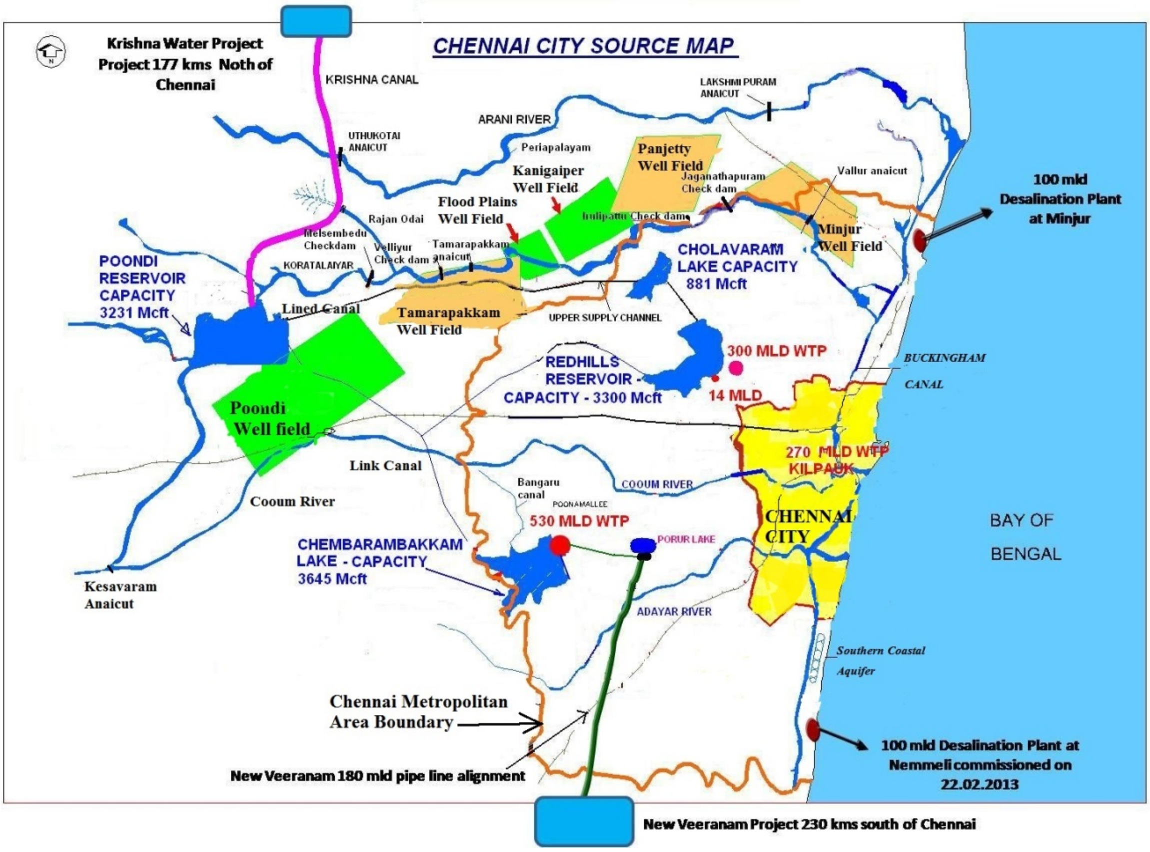


Figure 10 Source Map for Chennai Water supply (based on unpublished CMWSSB data)

5.1.1 Surface water sources

Surface water sources remain the mainstay of water supply to Chennai city. The four main interlinked surface storage reservoirs at Poondi, Cholavaram, Redhills and Chembarambakkam located within the CMA and Veeranam lake situated about 228 km south of Chennai, in Cuddalore district (added as a source to Chennai in 2003-04) are important sources of drinking water to Chennai city. The first four reservoirs referred to above are dependent on monsoons for their annual storages. The Veeranam lake is supplied by the Cauvery River in addition to its own catchment. Simultaneously ground water sources around Veeranam lake (Neyveli aquifer) were also developed (60 MLD) and integrated with the Veeranam lake conveyance system to the City. This ground water source was planned as a contingency to meet any deficit in Veeranam lake supply.

The Telugu Ganga Project, an inter- state project commissioned in 1996, conveys Krishna River water from the Kandaleru reservoir situated about 450 km from Chennai, in the adjoining Andhra Pradesh to Poondi reservoir near Chennai city.

The total storage capacity available in the five surface reservoirs is 442 ML .The present installed water treatment capacity in Chennai is 1294 MLD. The storage capacity of these reservoirs and available treatment capacities can be seen in Table 21.

Table 21 Surface storage reservoirs and treatment capacities

Reservoir	Storage capacity	Treatment capacity	
	(ML.)	existing	(MLD)
Poondi	114		
Cholavaram	31		
Redhills	116	Kilpauk	270
		Redhills	300
		Surapet	14
		Total	584
Chembarambakkam(1996)	129		530
Veeranam (2004)	52	Vadakkuthu	180
Total treatment capacity available for surface water			1294

5.1.2 Ground water sources

Based on the detailed investigations of UNDP (United Nations Development Program) funded ground water studies during 1966-69 (unpublished, figures obtained as personal information from CMWSSB), ground water sources in three well fields (Minjur, Panjetty and Tamaraipakkam) in the north of Chennai falling in Araniyar-Koratalaiyar river basin (A-K Basin) were identified with an estimated ground water potential of 125 MLD. These well fields are initially used for the industries located north of Chennai and later it was utilised for augmenting water supply to Chennai city.

A second such study during 1987-88 identified further three more well fields at Poondi, Kannigaiper and Flood Plains with an estimated potential of 55 MLD. A small quantity of ground water was also extracted from the coastal aquifers in the south of City.

Ground water from Palar basin is not used for Chennai city except in extreme drought situation when transportation of some quantity of ground water through tankers is resorted.

Chennai experiences substantial water shortages almost once in four years as monsoon flows fails to add adequate storage to the reservoirs. Some years such as 1983, 1987, 1993, 2000 and 2004 bore historic records of all the main reservoirs going totally dry and the Chennai water supply had to be managed with ground water.

Though the average abstraction of ground water from A-K basin for municipal purpose has been estimated to be about 7% of the total abstraction (about 93% is for irrigation) in poor monsoon years this goes up to about 11% (Renganayaki 2014).

Large scale extraction, particularly in the Minjur well field which is nearer to the coast resulted in sea water intrusion at alarming rate leading to deterioration in water quality and forcing CMWSSB to restrict extraction in this well field.

According to CMWSSB estimates, the saline water interface which was 3 to 3.5 km from the sea coast in 1969, moved to 7 to 8.5 km in 1983 and by 1987 extended 8.5 to 9.0 km. The extraction in Minjur well field which was about 28.42 MLD in 1978 is brought down to about 2.0 MLD in 2013.

5.2 Role and potential of managed aquifer recharge (check dams and infiltration ponds)

As can be seen from the previous section, the water supply of Chennai has mainly to be met by transporting water from varying distances with various water supply schemes (as close to Chennai there are only four non-perennial rivers). Due to exploitation of the groundwater resources (pumping of groundwater for domestic and agricultural water supply), the contribution of groundwater to the water supply of Chennai has substantially reduced, from a maximum of 25% to a currently installed capacity of around 6%. The decline of the groundwater level has further led to the intrusion of seawater in the coastal area. During the summer season on 13 April 2013 the share of groundwater was even not more than 1%. This shows the vulnerability of the Chennai water supply: Over 90% of the water supply is covered by water stemming from reservoirs, which are depending on the monsoon rains. If the reservoirs are empty then groundwater should be available to cover the gap in water supply. One measure that the State Government of Tamil Nadu took to overcome the water shortages during summer was to provision of desalination plants. Another measure was to make rainwater harvesting mandatory in all buildings, however, the effect of this measure has not been evaluated.

Therefore, managed aquifer recharge (MAR) has been introduced as a measure to increase the groundwater level and to mitigate the seawater intrusion. Two technologies for MAR have been implemented: Check-dams and infiltration ponds.

The rivers flowing north and south of the Chennai city were considered for harvesting the excess runoff by constructing a series of check dams. The rivers flowing north of the city are Arani, Koratallai and south of the city is Palar river. The proposed and expected number of check dams constructed across these rivers with their dimensions with the assumed storage is given in Table 22, 23 and 24. It can be seen that for the Arani and Koratallai rivers check dams have already been constructed or are in planning/construction phase. Though some check dams were planned across Palar river the implementation has not been given priority, as the Chennai City water supply is presently not dependent on ground water from Palar basin.

Table 22 Locations of check dams across Arani River

SI.No	Location of check dam	Height up to crest (m)	Length of crest (m)	Status of construction
1	Surutapalli	1.5	155	Existing
2	Uttukottai	1.5	345	Existing
3	Panapakkam	1.2	100	Existing
4	Kalpatu	1.2	170	Existing
5	Sengothkalam	3	225	Existing
6	Paleshwaram	3.5	260	Existing
7	A.N. Kuppam	2	135	Existing
8	LaksmipuramAnicut	2	155	Existing
9	A.Reddipalayam	3	95	Existing

Table 23 Locations of check dams across Koratallai River

Sr. no	Location of check dam	Height up to crest (m)	Length (m)	Status of construction
1	Attrampakkam	1	135	Construction planned
2	Melsembedu	1.5	245	Existing
3	Valliyur check dam	1.5	300	Existing
4	Thamaraipakkam anicut	3	200	Existing
5	Thirukandalam	6.5	175	Construction planned
6	Bandikavanur	6.3	300	Construction planned
7	Irulipattu (Jagannathapuram)	1.2	360	Existing
8	Vannipakkam	1.5	315	Existing
9	Jagannathapuram	1.5	150	Existing
10	Vallur anicut	3.5	172	Existing

Table 24 Locations of check dams across Palar River

SI.No	Location of check dam	Height up to crest (m)	Length (m)	Status of construction
1	Vayalur	2	900	Proposed
2	Kilapakkam	3	450	Proposed
3	Esoor	3	645	Proposed
4	Alapakkm	2	720	Proposed
5	Palur	3	860	Proposed
6	Vengudi	2	725	Proposed

7	Vadailuppai	2	600	Existing
8	Ariyur	3	490	Proposed
9	Palar anicut	3.5	770	Existing
10	Vallimalai Anicut	2.5	250	Existing

The contribution of check dams in recharging the aquifers was estimated to be about 50 to 60% of the annual storage (Parimalarenganyaki and Elango 2013). Other studies suggest that groundwater recharge may be enhanced by releasing the stored check dam water during times of low infiltration (Sprenger et al. 2014).

With respect to infiltration ponds currently only one pilot study is known. This has been implemented by Anna University. The results indicate that approximately 40% of water stored in the pond is recharged. The role of percolation ponds as a feasible solution will be assessed by numerical modelling in WP 5. Preliminary results indicate that about 10000 percolation ponds can be planned in this area.

5.3 Economic feasibility and financial analysis

The costs of MAR structures have been taken from actual costs. However, due to limitations in data availability only costs of the Check dam at Irulipattu, which was completed in 2013, could be researched. The costs amounted to INR 62 million (approximately 800,000 Euro, conversion rate 1 € = 77.5 INR). A picture of this check dam is shown in Figure 12 and the layout is shown in Figure 11.

Figure 11 Photograph of Check dam at Irulipattu-view from up stream

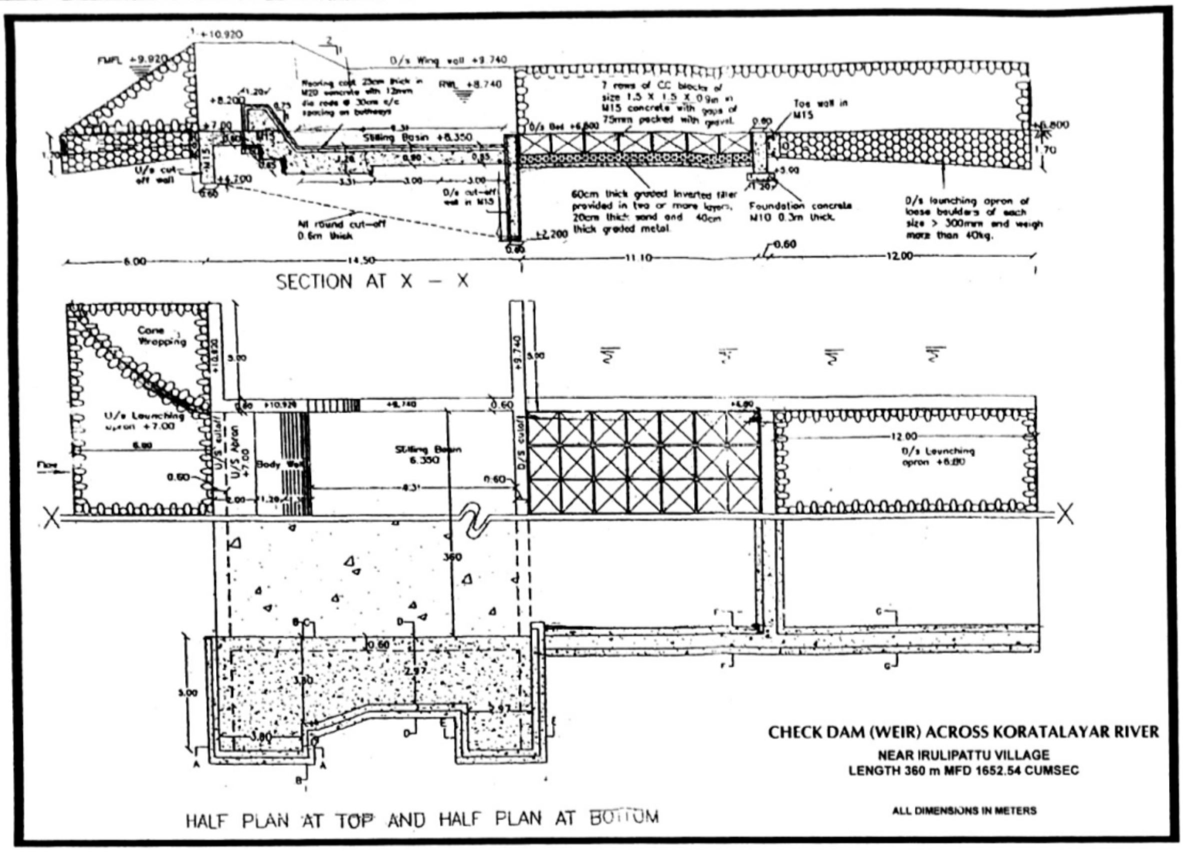


Figure 12 Check dam at Irulipattu – Detailed drawing (from Public Works Department, GoTN).

The infiltration pond that was piloted by Anna University has a size of 8x8x1.75m and the anticipated annual recharge is 100-250m^3 (average 175 m^3). The construction costs amounted to INR 15.000 (approx. 200 Euro).

To analyse the economic and financial feasibility of MAR structures their cost shall be compared with the costs of alternative water supply options. As shown in section 5.1 the main water supply source is currently surface water. This provides two alternative options for augmenting the existing water supply: Either the capacity of existing reservoirs is increased or new reservoirs are constructed. Both options have already been pursued by the Government of Tamil Nadu:

As further shown in section 5.1, desalination has also recently be identified as an option to provide additional water, and since 2010 two desalination plants with a capacity of 100 MLD each were provided. The costs of the desalination plant at Nemmeli, which was commissioned in 2013, have been reported with INR 8,712 Million (approx. 112 Million Euro).

Table 25 below summarizes the cost per unit supplied water of alternative options and MAR measures (based on the installation costs, not considering operational costs for which no data could be found).

Table 25 Cost of various water supply sources

S.No	Source category	Capacity/ Quantity		Investment cost INR million	Cost of water INR/M3
1	New surface storage reservoirs. Costs taken from actual Thervoikandigai-Kannankottai Reservoir (cost approved by Govt.in 2012)	1.00 TMC	28.31 MCM Per annum	3300	117
2	Increasing storage capacity of existing reservoirs. Costs taken from Cholavaram tank, Porur tank Ayanambakkam tank and Nemam tank (cost approved by Govt. in 2011)	568 Mcft	16.08 MCM Per annum	1300	81
3	Desalination plant. Costs taken from Nemmeli plant. (costs approved by Govt. in 2013)	100 MLD	36.50 MCM	8712	239
4	MAR – Check dam Costs taken from existing check Dam at Irulipattu constructed by Public Works Department in 2013.		0.30 MCM Per annum	62	207
5	MAR- Infiltration pond Costs taken from pilot project of Anna University		0.000175 MCM per annum	0.015	86

Note: The figures on capacity and quantity have been calculated in Deliverable D2.3 “Report on field investigations on the performance of MAR techniques under the conditions in India”.

As can be seen from Table 25 increasing the capacity of existing surface sources is the most economical option for source augmentation, followed by the creation of new reservoirs. Desalination is the most expensive option. Infiltration ponds seem also a cheap option, however, to achieve impact a large number of such ponds would need to be constructed and this requires the consent of the farmers to implement and maintain such ponds. Check-dams, based on the cost data of the Irulipattu check dam are almost as expensive as desalination with respect to installation costs (not considering operational costs such as energy costs). Actual quantity of water recharged by check dams and field infiltration ponds was scientifically studied as a part of WP 2.

With respect to financing, Table 26 below shows the current expenditures for the water supply system in Chennai and Table 27 shows the source of financing. It can be seen that the costs cannot be covered by the financing sources.

Table 26 Expenditures for water supply system in the year 2010/11, Source: CMWSSB Homepage

Cost component	Amount per year (million INR)
Power	638.5
Chemicals	59.1
Operation and maintenance	621.7
Purchase of desalinated water	957.9
Hiring of water lorries	154.5
Office and administration	63.6
Personnel costs	1’319.7
Dept. Service charge	931.1
Depreciation	1’202.27
Other costs	505.3
Total	**6’454.1**

Table 27 Financing of water supply system in the year 2010/11, Source: CMWSSB Homepage

Source of financing	Amount per year (million INR)
Sale of water	2,412.7

Water & Sewerage Tax	987.9
Grants from government	1,003.6
Other Income	795.5
Total	**5,199.7**

As can be calculated from Tables 26 and 27, the deficit in the year 2011/12 was 1,254 million INR (approx. 16 Million Euro). In Chennai, water consumption of less than 30m³ per month is subsidized. With the existing tariff (average: 10.87 INR/m³) it would possible to cover the O&M costs (average: 6.09 INR/m³) of the CMWSSB (TERI 2010). However, only 3.5 - 5% of the consumers have installed meters which would be a prerequisite to charge the users for their actual water consumption (Brocklehurst et al. 2002, TERI 2010).

5.4 Assessment of institutional viability

5.4.1 Legal framework

5.4.1.1 Introduction

This report provides an elaborate treatment on the law, policy and institutional structure relating to groundwater, and more particularly on artificial groundwater recharge in Tamil Nadu and Chennai. This report has also taken note of the recent scientific and technological developments relating to groundwater, and prefers to use the term 'Managed Aquifer Recharge' (MAR) to denote most of the groundwater recharge programmes. Presently, MAR is widely used in national and state water polices (Jain 2012). Managed aquifer recharge schemes have the potential to increase water availability by generating water supplies from sources that may otherwise be wasted. It can provide environmental, social and economic benefits. Managed aquifer recharge will not be feasible everywhere, due to hydro geological, environmental, social or cost constraints. This justifies an elaborate treatment in law to regulate the water resources with enhanced measures to protect and recharge the groundwater.

5.4.1.2 Methods and approach for investigation of legal framework

The report analyses the existing laws and policies in India and laws applicable to Tamil Nadu and Chennai. The decisions of the Indian higher judiciary form an important component of analysis as they reflect the problems at the enforcement level. The report undertakes a study on the institutional mechanism to govern MAR in Chennai. It compares the law in theory with the practices from state agencies, executives and other stake holders.

The Union laws assume importance in the context of pollution laws which are made by Parliament and Union sponsored schemes and guidelines. The laws made by Tamil Nadu legislature are the most appropriate norm creating documents for the purpose of MAR. All the State and Union laws are tabled (Table 28). The decisions of Judiciary are relevant to understand the disputes which arose while enforcing these laws. The study has taken note of various government orders and circulars as they reflect state's approach to groundwater and MAR. The policies and schemes of the government are also part of the analysis as they reflect the philosophy of the government in spite of its soft character (ie they are not legally binding). The opinions of the public, corporate, local bodies, government officials and other stakeholders are personally gathered to study the realities with the laws proclaimed. The institutions and their role in MAR governance is an integral component of this report.

5.4.1.3 Documentation and Analysis of existing Legal and Policy Framework for Groundwater and MAR

Table 28 provides an overview of all the laws, policies and guidelines applicable to groundwater and MAR at the national, state (Tamil Nadu) and municipal (Chennai) level. This exhaustive table analysis the laws, polices and guidelines which are relevant for groundwater management. Some of the instruments tabled may not have any provision relating to groundwater and MAR. However, this documentation makes an attempt to find out the relevance of 'groundwater and MAR' in every instrument discussed below. The analysis suggests and finds out the legal, institutional and policy opportunities to strengthen sustainable MAR practices.

Table 28 Legal and Policy Framework on Groundwater at national level

Legislation/ Guidelines/ Policy	Provisions relating to Groundwater and MAR	Analysis of law and policy - impact on MAR (*relevance for MAR in italics*)
	A. National	
Constitution of India, 1950.	Citizen's right to water, state's obligation to provide water and duty of citizen's to protect natural resources. '(Ground) water' as State subject, 'environment' as concurrent subject and regulation of inter-state waters.	Groundwater and MAR to be regulated by State governments. But the past three decades have witnessed the Union regulation through environmental regulations. Union's plan expenditure includes funding various water development projects.
(a)Environment	These laws establish and	The umbrella legislation relating to

(Protection) Act, 1986. (b)Water Act, 1974 (c)Rules and Ciruculars made under these laws.	provide scope for establishing institutions to govern groundwater pollution. The Pollution Control Boards established under this law provide environmental consent for operating various industrial establishments. The Central Groundwater Board is established under the powers given to government by this law. The rules made under this law establish water standards. They impose penalty for violating orders made under this law. The erring polluting units may be closed if they breach conditions.	environment is effective primarily on abatement of pollution. The institutions and rules made under this law are envisaged with greater responsibility. However these institutions face difficulties such as lack of staff members and cooperation from other stakeholders. Various stakeholders' interest complicates the enforcement (Koonan, 2010). The enforcement of environmental standards would enhance the groundwater quality and reliability. *There is a scope to establish MAR quality standards under these laws.*
Easement Act, 1882	The uncontrolled ownership of groundwater by landholders is assumed. (Cullet, Groundwater Regulation in Uttar Pradesh: Beyond 2010 Bill, 2012)	The law is insensitive about the rights of neighbors and overall improvement of groundwater resources. But the philosophy of this provision often gets the approval of the courts. *The provision has lost its relevance to MAR because of the developments in science and technology.*
National Green Tribunal Act, 2010.	Functions as an original and appellate dispute settlement mechanism.	The tribunal is active; it has taken note of sand mining and groundwater extraction, and passed prohibitory orders.
Criminal Procedure Code, 1973.	Unlawful obstructions or nuisance should be removed from any public or from any way, river or channel which is lawfully used by the public.	This provision shall remain in the statute book and applicable to pollution aspects irrespective of specific laws as said by courts. This provision indirectly helps groundwater quality by providing a remedy against pollution.
Coastal Aquaculture Authority Act ,2005	Coastal aquaculture farms are regulated. The polluting farms may be removed or demolished by the authority after hearing the occupier of the farm.	Groundwater pollution caused by aquaculture units is regulated. *MAR measures may be recommended by the authority for preventing seawater intrusion which reduces the groundwater quality.*
Guidelines for	These guidelines provide a	*The experiences from*

Implementation of Artificial Recharge Projects under the Central Sector Scheme	mechanism to receive union grants.	*implementation of schemes may be used to frame policy for future designs, funding and monitoring.*
National Environment Policy, 2006	The policy supports the practices of rain water harvesting and artificial recharge and revival of traditional methods for enhancing groundwater recharge.	*The policy supports MAR to improve environment.*
Planning Commission Model Bill for the Conservation, Protection and Regulation of Groundwater, 2011	The bill encourages rainwater harvesting, increases the role of local bodies and recognises the rights of vulnerable to use groundwater. It relies on certain progressive principles such as water as common pool resource and state holding of water in public trust. It relates electricity and groundwater nexus.	*The draft encourages MAR.* But the experience with the groundwater laws in India is discouraging as it lacks willingness on the part of the governments to implement.

Table 29 Legal and Policy Framework on Groundwater at state level (Tamil Nadu)

Legislation/ Guidelines/ Policy	**Provisions relating to Groundwater and MAR**	**Analysis of law and policy - impact on MAR (*relevance for MAR in italics*)**
a)Tamil Nadu Groundwater (Development & Management) Act, 2003 b) The Tamil Nadu Groundwater (Development and Management) Repeal Ordinance,	The legislation was not notified for the past ten years, finally repealed by the State during September 2013. The Act was intended to deal with most of the issues relevant for groundwater protection and recharge. An authority was supposed to be constituted, groundwater licensing mechanism was supposed to be initiated and registration of wells was also envisaged.	The Act had better scope for groundwater protection. But the enforcement of this law was expected to be detrimental to some stakeholders and infrastructural issues relating to implementation of this law was also a concern. The High court order to implement this law confirms the legal basis for the principles embodied in this law. This law was never notified. Selective aspects were converted as Government Orders.

2013.		The promise of the government to bring a new law to regulate groundwater may also be taken positively to adopt the recent model provided by Union Planning Commission.
a) The Tamil Nadu District Municipalities Act, 1920, the Tamil Nadu District Municipalities Building Rules, 1972. b) Tamil Nadu Panchayats Act, 1994 c) Other Laws establishing Municipal Corporations in Tami Nadu	All these laws and rules have identical provisions relating to RWH. They mandate the structures to be established within the stipulated time. These laws are applicable for both buildings already constructed and new constructions. Failing to implement this provision may lead to severance of water connections.	*These laws mandate MAR.* But, the provisions are questionable on the grounds of science and technical feasibility. Tamil Nadu has different geological patterns, varying rainfall and complex groundwater usage. A uniform model is not suitable (specifically, the hilly and rural areas). But the most accepted model of watershed methods did not have any legislative mandate or encouragement. (Kulkarni & Shankar, February 7, 2009)
a) The Tamil Nadu Protection of Tanks and Eviction of Encroachment Act, 2007. b) The Tamil Nadu Land Encroachment Act, 1905.	These laws protect the tanks area including water spread area and supply channels. Encroachments are prohibited and eviction procedure is laid down. But the State is empowered to alienate the land without affecting the quality and quantity of lake.	These laws were brought to court on number of occasions. The High court has ordered for removal of encroachments based on this law. But there is no mechanism to cross verify State's claim (on 2007 law) to alienate the lake property without affecting quality and quantity of groundwater. *Protects traditional MAR structures.*
TN Water Supply & Drainage Board Act, 1970	The Act provides mechanism to extract groundwater after feasibility studies.	The Act is less relevant for groundwater protection and MAR. *But the TWAD and CMDA are potential users of recharged water.*
Tamil Nadu Town and Country Planning Act, 1971	Establishes a planning authority, drafts master plans and infrastructure development.	Building approvals – *There is a scope to link building development and groundwater use.*
The Tamil Nadu Farmers	Establishes irrigation system management at command	There is a future scope for planning relating to groundwater. Presently,

Management of Irrigation Systems Act, 2000	area/water body level.	farmer's associations need not take note of groundwater recharge. *Water allocations and crop patterns may be decided on availability and recharge potentials.*
Tamil Nadu Aquaculture Regulation Act, 1995	Groundwater extraction for polluting units is regulated.	Groundwater extraction and pollution are regulated in relation to aquaculture units.
Tamil Nadu Industrial Township Area Development Authority Act 1997	The Act mandates for proper facilities to discharge effluents.	There is no mandate for MAR under this law.
Tamil Nadu Public Health Act 1939	The Act specifies the responsibility of the local bodies to provide water and maintain water bodies. Pollution of water courses are prohibited under this law.	Broader scope of this law was underutilised. There is very less scope for future enforcement, as there are other laws to deal with pollution and groundwater extraction.
River Conservancy Act,1884	The Act prohibits cultivating and polluting activities to protect river banks.	The Act last its relevance.
State Water Policy, 1994	Protection and improvement of all resources	*Development of groundwater*

Table 30 Legal and Policy Framework on Groundwater at local level (Chennai)

Legislation/ Guidelines/ Policy	Provisions relating to Groundwater and MAR	Analysis of law and policy - impact on MAR (*relevance for MAR in italics*)
Chennai City Municipal Corporation Act, 1919 (RWH)	Rain water harvesting is mandatory under this law.	This law is considered to be success as some reports suggests groundwater augmentation after implementing these schemes. But it lacks recent evidences to verify the maintenance of the structure. *Mandates RWH*
(a)Chennai Metropolitan water Supply	The 1978 law envisages a board to manage the water connection and sewerage	The institution faces a lot of practical difficulties such as lack of staff, cooperation from public and support

and sewerage Act ,1978 (b)Chennai Metropolitan Ground water Regulation Act ,1987 (The administration of this law to be carried out by the board created under 1978 Act)	disposal in the Chennai. Incidentally the board is empowered to take action against pollution and other illegal activities in water bodies. But those provisions were not popular in the administration. The 1987 Act recognises certain basic principles relating to groundwater management such as optimal utilisation, land-water interface and artificial recharge. It supports licensing the extraction with some exception.	from stakeholders. Lorries engaged during summer are prohibited during winter. Registration of wells largely failed. The board could play a very effective role relating to MAR by strictly adhering to sewage out let standards, registration of wells and implementing RWH.

Selected groundwater laws in other States than Tamil Nadu can be found in the Appendix 3.

5.4.1.4 Institutional Mechanisms and Interest of Stakeholders on Groundwater and MAR

The role of institutions connected with groundwater and MAR are tabled below. Table 31 analyses the institutional interest and potential conflict amongst the stake holders to protect, manage and recharge groundwater. The landholders' liberty to extract unlimited and uncontrolled groundwater restricts the scope for larger discussions under this part. The interests of the stakeholders have not been converted as their legal entitlement or obligation. The interdependence of stakeholder's interest is not recognised (Koonan, 2010).

Table 31 Relevant stakeholders in case study area

Stakeholder	Key role concerning water supply (italic: specific for MAR)	Main interest in groundwater
National		
Government of India (Ministry of Water Resources) (Planning Commission)	*Formulation of policies* ("National Water Policy") and drafting model laws. Enacting laws relating to interstate waters and pollution. *Planning, funding, monitoring and overseeing the implementation of various projects relating to groundwater protection and recharge. (ex. watershed programmes)*	Protection of groundwater – Creating entitilements and obligations

	Issuing guidelines for sanctioning schemes	
Central Groundwater Board	Regulation and control of groundwater development and management Assessment of groundwater quality Power to notify areas for groundwater recharge *Recommendations and drafting guidelines for MAR structures*	Protection of groundwater
Central Pollution Control Board	Prevention and control of environmental pollution *Issuing guidelines, circulars and framing rules*	Protection of groundwater quality
State and Local level (Tamil Nadu)		
State Government of Tamil Nadu	*Funding for water supply systems* *Law making as requested by stakeholders* *Creating institutions and adding responsibilities to the existing institutions*	Protection of groundwater – Augmentation of water sources
Tamil Nadu Pollution Control Board	Control *quality of sewage/treated wastewater* (which can affect groundwater quality)	Protection of groundwater quality
Tamil Nadu Public Works Department (Water Resources Organisation)	Construction and operation of water supply infrastructure	Use and control of groundwater - Maintenance of Water Bodies
Tamil Nadu Water Supply and Drainage (TWAD) Board	Responsible for water supply in Tamil Nadu (except Chennai) *Abstraction of groundwater in villages*	Use of groundwater
Water Resources Regulatory Authority (planed)	An authority is planned to be established. This authority will determine the entitlements of various stakeholders. Groundwater may also be brought under this category.	(Ground)water allocation (yet to be established)
Chennai Metropolitan Development Authority	Preparation of Chennai Development Plan (including environmental issues, protection of water bodies, etc.) (permission for new buildings – ensuring RWH structures)	Protection of water bodies within the city (including groundwater)
Chennai City Municipal Corporation	*Enforcing Laws which mandate RWH*	Protection of water bodies in the city (including groundwater)
Chennai Metro Water supply and sewerage board (CMWSSB)	*Responsible for water supply in CMA: groundwater abstraction in peri-urban parts of Chennai*	Use of groundwater – Protection of Groundwater

Research Centres (eg. Anna University)	*Research on MAR in Chennai area*	Generation of scientific background information related to MAR
Peri-urban villages	*Location of groundwater resources - Potential users of recharged water*	Use of groundwater for own purposes and sale
Industry	Heavy water users (e.g. sugar factory, mining) *Potential users of recharged water*	Use of groundwater – Dealing with groundwater pollution
Tanker truck operators	Suppliers of groundwater from peri-urban villages to metropolitan area	Selling groundwater
Private water companies	Companies abstract groundwater and sell bottled water *Potential users of recharged water*	Selling (ground)water
Farmers (with land) / well owners	*MAR systems may be located on their land* *Profit with selling water to water suppliers* *Potential water users of recharged water*	Use of groundwater Selling groundwater
Farm labourer (without land)	*Higher employment rate if more water is available for agriculture*	Only indirect interest (ex. own consumption)
City residents	*Potential consumers of recharged water*	Use of groundwater
CSOs, NGOs, Media and Social Scientists (Local groups against sale of groundwater in villages around Chennai) (Butterworth.J, Ducrot, Faysse, & Janakarajan, 2007),	*Awareness raising for problems related to groundwater exploitation and sea water intrusion*	Awareness raising - Protection of groundwater

5.4.1.5 Experiences and Analysis of Legal and Policy Framework in Tamil Nadu and Chennai

The groundwater regulation in Tamil Nadu necessarily involves multiple state agencies which do not have connection except on official hierarchy. For instance, the different departments of Tamil Nadu government are not aware of the happenings or developments that occur in the other wing. This absence of cooperation is not a designed one; instead this is because the agencies forgot to take note of legal-institutional developments that occurred within their organization and elsewhere. The following paragraphs explain the practical issues with the present management of groundwater and discuss the way forward for the legal and institutional feasibility of MAR in Tamil Nadu with a special reference to Chennai. The role of various stakeholders and institutions are also discussed:

- The State groundwater law which was meant to be a comprehensive legislation on groundwater did not see its commencement. The law was never notified as there were oppositions from many sides to implement this law. In the absence of an authority to regulate water in general and groundwater in particular, the State Ground and Surface Water Resource center plays a crucial role in licensing the extraction. They possibly do not have a role to play in case of any groundwater recharge. The 'Water Utilization Committee' of the Public Works Department determines the allocations and permissions for large scale projects including government projects. In fact, this is the only body which is practically competent and actually decides both the surface water and groundwater utilization for a conjunctive use.
- The Court has given a mandate to the Government for the implementation of the Groundwater Act, 2003, and it also said not to issue licenses for extraction till the law is implemented. But the extraction licenses were accorded to all industries except mineral water industries. A municipality tried to take advantage of the provisions of this Act to remove a groundwater extraction device and later changed its position understanding that the law is not notified. However, the government has decided to withdraw this law stating the practical difficulties and inadequacies in the law. Further, the government has declared that it would come with a new law to regulate groundwater. The repeal has nullified the High Court orders relating to implementation and execution of this Act. However, several provisions of this law have become governmental orders.

- The Chennai Metropolitan Water Supply and Sewerage Board is one of the first autonomous institutional mechanisms in India to regulate the use of groundwater within a municipal corporation. The board created under this law was the first agency to mandate groundwater recharge (with Chennai Corporation). The agency provides water and sewerage connections after ensuring that rainwater harvesting structures are made for all buildings. But there is an absence of effective monitoring of the structures already created under this law, as there is no need to visit the premises except in case of failure to pay water charges which is of rare occurrence. The authority denies groundwater extraction license for commercial purpose, but unauthorized extraction of groundwater is prevailing throughout the city without any punishment for the offenders. There is a problem with reference to tanker lorries which carry water to the public, they are denied entry during monsoon season but welcomed as well as engaged by the authority during summer. The temple tanks which are significant in number as recharge structures are governed by a different agency. The water bodies and channels are under the control of the Public Works Department or local bodies which are less influential in the day to day management of Metro Water. The Metro Water is believed to underestimate the use of groundwater for household purpose, as the figures of Metro Water do not include private and public wells.

- There are two State laws to deal with encroachment of water bodies. The 1907 law dealt with all encroachments. The latest law deals with encroachment against water bodies. The eviction orders are passed under both laws. At times the courts have upheld the order of eviction against peasants and households. (The encroachers constructed houses in a part of a water body and possessed them for more than 20 years. The Court upheld the order of eviction passed by executive. Uppliyanthittu Kamarajar Nagar Vs. The District Collector, AIR 2001 SC 3215) But the court has adopted a different approach when the encroachment is done by a state agency. There are number of bus stands and police stations constructed on water bodies and these state encroachments were reluctantly accepted by the courts. (In, S.Venkatesan Vs. Government of Tamil Nadu, the Court permitted the construction of a bus stand with a condition to maintain quality and quantity of encroached water body). The 2007 law seeks to survey the water bodies to curb the eviction and this Act was passed after a Court direction to provide a mechanism to survey water bodies for effective protection against encroachment. (The court has directed the State Government to identify all such natural water resources in different parts of the State and wherever illegal encroachments are found, initiate appropriate steps in accordance with the relevant provisions of law for restoring such natural water storage resources which have been classified as such in the revenue records to its original position so that the suffering of the people of the State due to water shortage is ameliorated. See Annexure 1 L.Krishnan Vs. State of Tamil Nadu. (Important Court decisions relevant for groundwater and MAR are listed in Appendix 1).

- The rural local bodies such as gram panchayats and town panchayats were also given a mandate to implement RWH structures. All other municipal corporations and municipalities have identical provisions with reference to rainwater harvesting.

Any failure to implement this law will result in severance of water connections. This is rather not an inappropriate action to implement this law as some buildings may not have a water connection at all. It is difficult to appreciate a mandate to implement the rainwater harvesting in every building without taking note of geophysical features of that locality (more specifically the nature of aquifer). The law has not taken note of water requirements, rainfall data and the capacity of the ground to hold water. The traditional water harvesting structures were not benefited by RWH laws. But the awareness and euphoria created by this law and environmental activism has lead to revival of water bodies and temple tanks.

- The lack of scientific knowledge not only affected political decision making and enactment of laws. For instance, the court has relied on a report from revenue department to deny the existence of a Kuttai. The report said that there was no inflow source to the disputed kuttai. But the fact remains that a water body need not have inflow in all cases. A kuttai is a natural or manmade structure to hold the water with short boundaries and it need not have an outlet also. We argue that the revenue records must be supplemented by scientific evidence to find out the nature of a disputed water body. Some of the disputes appear in courts confine themselves to revenue records. So, courts do not even discuss the nature and purpose of that water body in many cases. Thereby avoiding the pertinent questions relating to 'public trust', 'eminent domain' and 'state ownership' in their decisions. (S.Kulanthaivel Vs. The District Revenue Officer in Appendix 2).

- The groundwater extraction permissions granted under various government orders and circulars are significant. These orders discuss the actual practice which is to be followed in testing the eligibility for extraction such as number of hours of testing, months of extraction, maintenance of water samples during intervals such as post monsoon and pre monsoon or monthly levels, water quality tests, misuse of electricity supply by licensed, groundwater withdrawal at coastal areas and categorization of blocks as safe to overexploited. The extraction licenses are either accepted or denied, and they are not accompanied by any mandate to recharge the aquifer by the licensees. (See Appendix 2 for a summary of government orders relating groundwater)

- They are two kinds of water recharge programmes at rural level, the first one relates to rainwater harvesting for buildings which is mandated by legislation, secondly the watershed programmes under various schemes. The watershed programmes and other recharge programmes are implemented under various schemes which usually subsidize the cost of the recharge structure. These schemes emanate from various projects initiated by Union or State government. At times, these schemes are attached with the conditionality of funding agencies. There is one Union sponsored scheme in Tamil Nadu to utilize existing dug wells for rainwater harvesting. Some NGO's and educational institutions have created experimental or educative models for protecting existing water bodies or by creating new recharge structures. These models could help to frame a consistent policy or funding options for government.

- As a consequence of lack of coordination, the information pertaining to groundwater level, quality of groundwater and results of various schemes at a longer duration is difficult to determine. The State has initiated a process to monitor the groundwater data at the village level which is indeed a step in the right direction. The level of sampling must also be increased to a larger level with higher frequency of sampling including the quality components. If any scheme is introduced in a particular locality, the agencies responsible must inform the data collection centre to get an enhanced sampling. The level of information sharing amongst the organization also very minimal which ought to be improved.

- The environmental agencies such as Central Groundwater Board and Pollution Control Boards are supposed to have a larger role to play in terms of quality related issues. In practice, they clear the projects which receives a 'no objection certificate' from state agencies. They also set the emission standards of various water outlets. There is one aspect which is very relevant for our consideration; these standards are uniform throughout the country. It could be argued that different standards may be established for States having groundwater deficiency and extensive pollution such as Tamil Nadu. Lack of differential treatment is evidenced from the Orathupalayam Dam in Noyyal River which was supposed to augment the water levels in that locality and enhance the irrigation potential of Noyyal River. It yielded negative results by spoiling the groundwater of the surrounding area. Therefore Union groundwater regulation relating to pollution must be seen at both macro and micro level to understand the implications of extraction, recharge and pollution.

- The role of Union government is not limited to supporting the standards of environmental agencies. The Union government drafts national water policies, funds watershed programmes, provides model laws for the States to govern groundwater, supports research activities and exchanges information pertaining to groundwater from various sources. There is definitely scope for further cooperation with the States in matters of groundwater, more specifically in the regime of information sharing and standard setting. This may pave the way for determining effective ways to implement aquifer recharge programmes.

- There is a need to engage with other stakeholders, specifically farmers and local bodies (Janakarajan & Moench 2006). As beneficiaries of most of the recharge programmes they must be consulted and opinion must be sought. Though consultations with other stakeholders are suggested, it is not done under most of the circumstances. It is important to trap the institutional memory of local bodies and persons associated with management of water bodies. Information and opinion from the farmers and local bodies are to be given due consideration in the decision making process. The beneficiaries must understand the consequences of any project which arrives to their village or place. The full potential of research centres to be used to arrive at a more informed decision making. There is a lack of multidisciplinary approach in the decision making process relating to water bodies protection in general and groundwater governance in particular.

5.4.1.6 Concluding remarks

Based on the experiences discussed above, it may be concluded that a plain reading of Indian and Tamil Nadu laws may mislead a reader that Indian laws and polices support MAR is an important tool for sustaining water supplies for all kinds of users.
But the barriers for effective groundwater protection are many:

- There is no legislation to effectively manage the extraction, usage, pollution and recharge of groundwater. In the absence of a clearly defined legal rights and duties, it is a very complex set of unpredictable ad hoc rules which regulate the groundwater sector.
- The institutional responsibilities are not properly defined or they are very reluctant to involve in proactive steps (including MAR) to protect the groundwater.
- There are institutional inabilities such as lack of staff and corruption.
- Cooperation, information sharing and subsidarity are followed at a negligible level.
- Scientific and technical understanding about groundwater has not been converted into law.

- There are barriers beyond the predictability of state, such as rainfall, urbanization, industrialization and pollution.

The following are suggested to have a sustainable legal, policy and institutional framework for MAR.

- A law to govern groundwater may be (re)enacted. This law may adopt the latest model provided by Planning Commission of India with modifications suitable for Tamil Nadu.
- In addition to groundwater enactment, an independent authority may be created to accord all water extraction. Extraction licenses may be granted with a mandate to provide MAR structures.
- Inter-state, inter-departmental and State-Union cooperation must be strengthened to foster a uniform policy and philosophy relating to water planning and management.
- The role of local self-government must be enhanced and the decision making must be at the lowest possible level (The above said institutions and laws must facilitate this).
- All surface water bodies must be surveyed and made as encroachment free. Conversion or development of existing water resources must be subjected to the approval of Authority and local bodies. All groundwater extractions must be monitored as for as possible and practicable.
- Local Self Government may be given autonomy to implement MAR on scientific and technical feasibilities, and taking note of water requirement.
- Land use may be integrated with water use, and land utility permissions must be accorded after taking note of water requirements, pollution and recharge possibilities.

5.4.2 Workshop on Stakeholder interests in Chennai

A project workshop informed representatives of public, corporate, and local bodies, government officials and other stakeholders about a key problem for Chennai, the intrusion of seawater in groundwater; wells close to sea have already problems. This problem is part of the general issue of water scarcity. Managed aquifer recharge (Sharma 2011) may prevent and reduce seawater intrusion and provide additional water sources. As outlined above, on the paper Indian laws and polices support MAR as an important tool for sustaining water supplies for all kinds of users. In particular, the State of Tamil Nadu spearheaded in groundwater recharge, e.g. by providing a favourable atmosphere and legal framework for rainwater harvesting (RWH). However, as the participants at the workshop confirmed, barriers still exist.

As follow-up to the workshop, 25 representatives of relevant stakeholder groups (government, academia, and private sector) informed about their own perceptions for securing in a sustainable way the future water supply of Chennai. The Tables 32 and 33 in the Appendix 4 summarize the results about the options and about the applied criteria to assess these options. Respondents were highly interested, as can be seen from their willingness to answer more than 120 questions (including questions to check consistency).

Applying a recently developed project-oriented sustainability assessment framework (Starkl et. al., 2013), the questions about the views of the respondents were put into the context of specific approaches to resolve the problem of water scarcity in Chennai. In this context, respondents felt the urgency of the considered problem. Thereby, four respondents came from academia (students, professors), eleven were experts (working e.g. as hydrologists for the government or as consultants), seven were rural practitioners (farmers, landlords) and three suppressed that information. In order to protect the anonymity of respondents, names, age (between 20 and 70+) and gender (four women) are not reported. The figure 13 below illustrates the vivid discussions at the workshop.

Figure 13 Stakeholder Workshop

With one exception (no answer), all respondents confirmed the need of improvement of the existing water supply system (56% asking for substantial improvements) and 80% support preparing an integrated water resources management (IWRM) plan highlighting e.g., how the MAR approach could be integrated in the water supply of Chennai.

However, for the details of such a plan, opinions differed: There was a tendency to agree that groundwater usage regulations should be linked with land usage regulations (72%), that current groundwater recharge measures in Chennai would not be adequate (68%), that existing laws might need some modification or might even be insufficient for groundwater conservation and protection (68%), and that legal and policy measures based on geographical and hydrological conditions would be better than the present regime (52%).

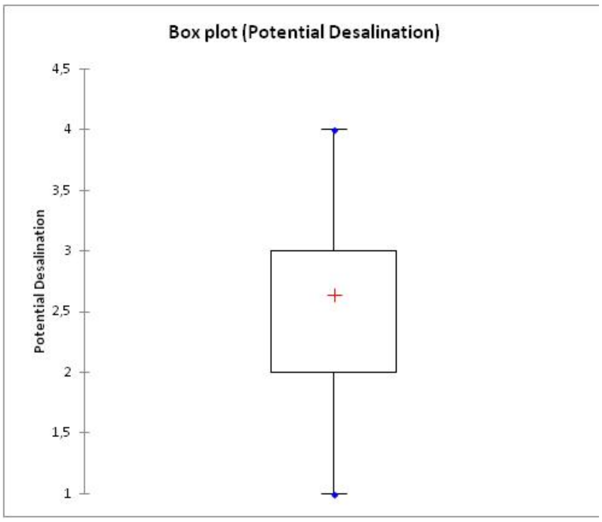
The study therefore analysed the stakeholder perceptions in relation to the (mostly technical) options for improving the water supply system. In particular, respondents were asked in more detail about six approaches that were current themes of the public discourse: These were four non-MAR approaches, namely desalination plants, non-structural policy instruments (water pricing, banning or licensing of groundwater extraction, policies to enforce or support changing to less water demanding crops), increasing capacity of reservoirs, urban RWH on roofs, and two MAR options, namely groundwater recharge through check dams and groundwater recharge through newly constructed ponds. Respondents assessed the potential of technologies and ranked them by their preferences (based on the source map above).

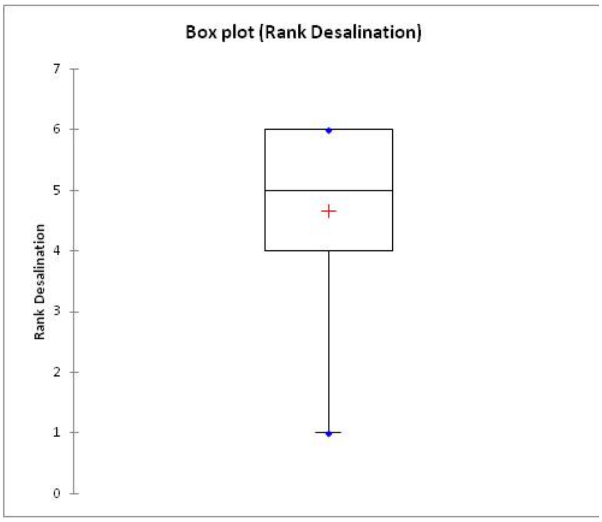
In terms of acceptability, one of these technologies and one policy turned out to be problematic. Thereby, low acceptability of a technical option for a respondent is defined by low or very low potential and a ranking amongst the last two options.

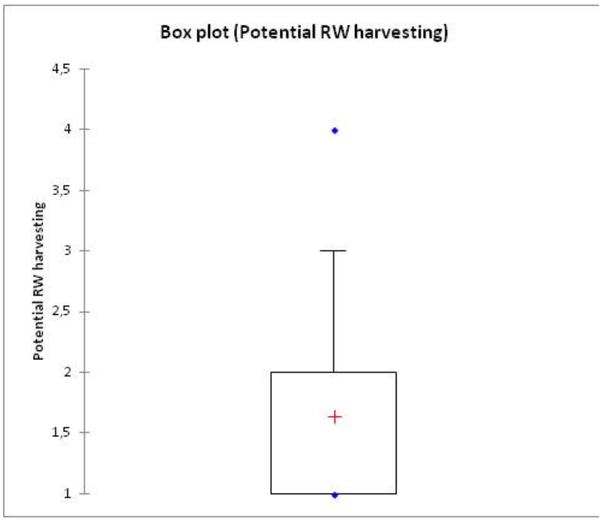
- Desalination plants had low acceptability for 56% of respondents (for most of them due to the high costs).
- Non-structural policy had low acceptability for 40% of respondents..
- All other options appear to be acceptable: For check dams, rate of low acceptability was 8%, for ponds and reservoirs 4%, and for RWH 0%.

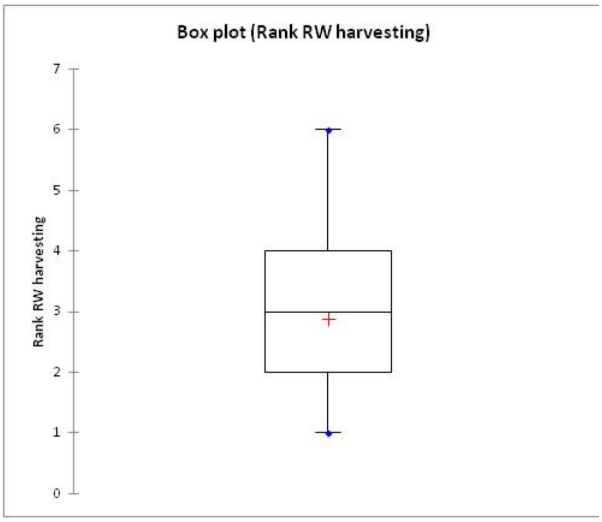
In addition, respondents made several specific proposals for mitigating water scarcity in Chennai. In order to reduce demand, some suggested to use metering in apartment complexes and big hotels, to control demand by licensing, to encourage toilets that use less water for flushing, to recycle grey water for domestic purposes (toilet flushes), to do more awareness raising for water saving, or to combine several approaches (e.g. enhancing technical measures by excess water pricing or similar policies to reduce demand). For groundwater recharge they proposed clearing existing ponds from silt and sand and recharging also storm-water (currently drainage transports it to the sea) or treated wastewater. Moreover, water recycling should be simplified by separating wastewater according to its sources. Other suggestions were interlinking the rivers of Chennai and transporting water from distant sources.

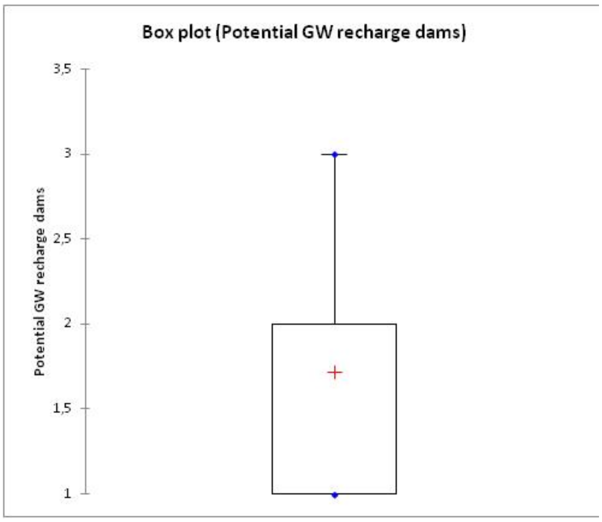
The figure 14 below summarizes the respondents’ preferences in terms of potentials (1 = very high, 2 = high, 3 = low, 4 = very low) and ranks (1 = most preferred, 6 = least preferred).

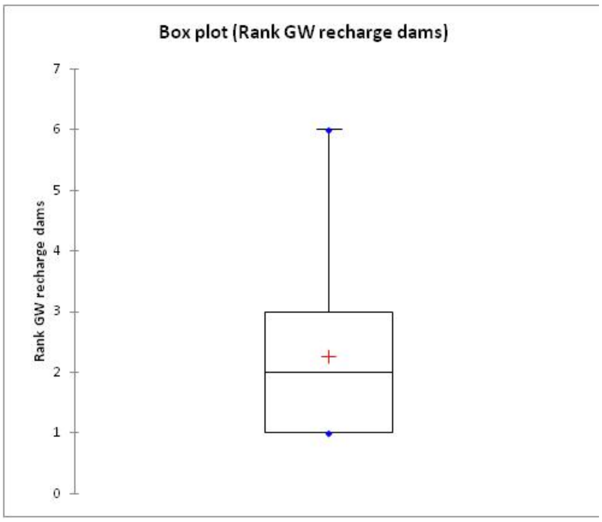

Box plot (Potential Desalination)
Potential Desalination
4,5
4
3,5
3
2,5
2
1,5
1


Box plot (Rank Desalination)
Rank Desalination
7
6
5
4
3
2
1
0


Box plot (Potential RW harvesting)
Potential RW harvesting
4,5
4
3,5
3
2,5
2
1,5
1


Box plot (Rank RW harvesting)
Rank RW harvesting
7
6
5
4
3
2
1
0


Box plot (Potential GW recharge dams)
Potential GW recharge dams
3,5
3
2,5
2
1,5
1


Box plot (Rank GW recharge dams)
Rank GW recharge dams
7
6
5
4
3
2
1
0

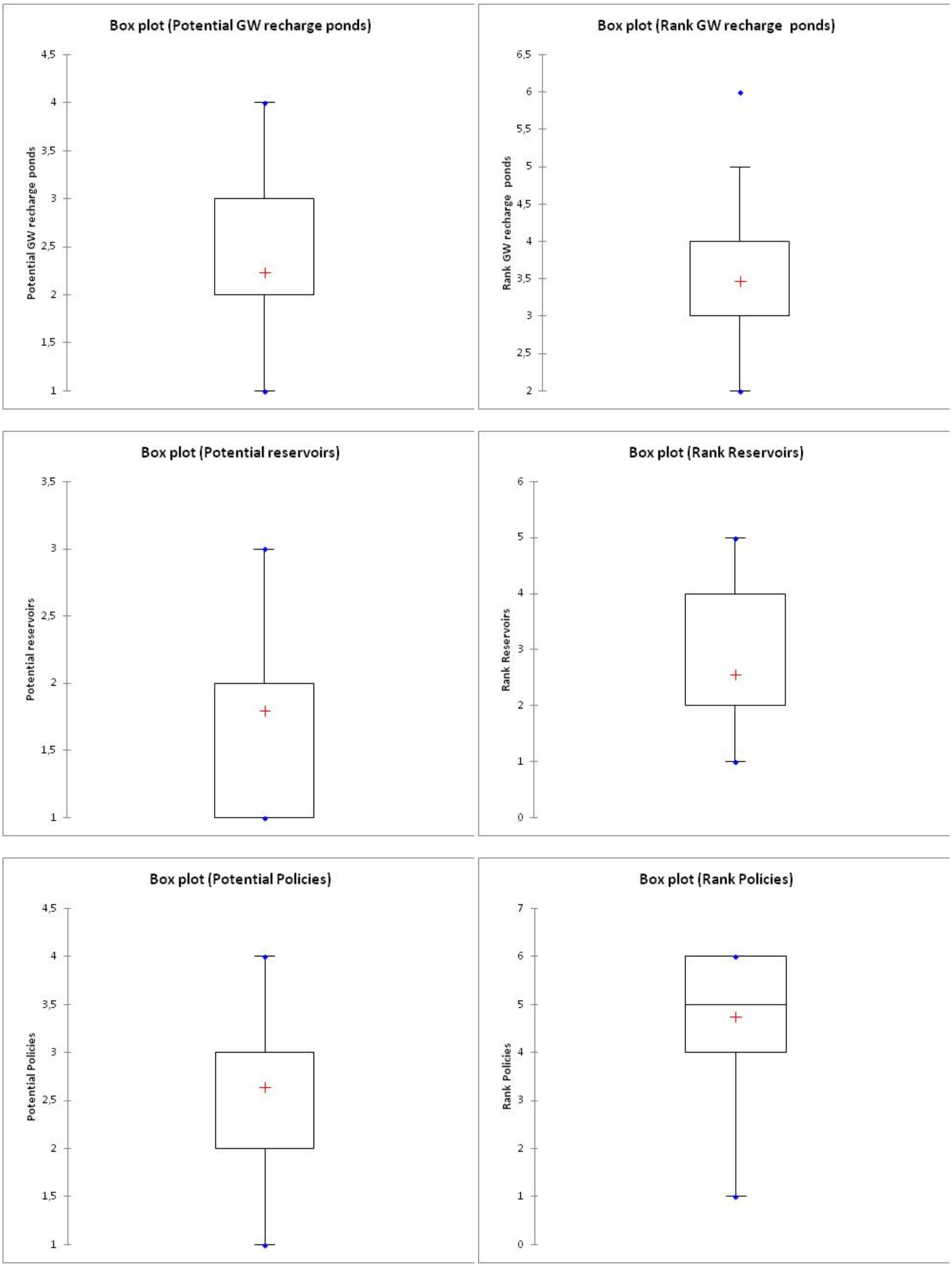


Figure 14 Box plots of preferences (potential, rank) about the options

Explanation: The box plots (generated in Excel with the XL-STAT add-in) display the minimal (best) and maximal responses (dots), the mean value (red +), median (black line), the first to third quartile (box – it may hide the median) and the 95% confidence interval (short line segments).

In order to figure out the reasons for these preferences, respondents were asked about their motivation, both specifically for each technical approach, and generally, about the importance of key criteria. They thereby assessed for each technical approach, the aspects of human health, environment, economy (costs and economic impact), social equity, and practicability (implementation and related institutional issues). Further, respondents were asked to rank the importance of these five criteria and they had the opportunity to explain in their own words each of their assessments. Health aspects, such as water quality, were most important for 64% of respondents. However, their perceptions on what health risks would matter for each technical option differed. For instance, some approved of desalination, as it provides clean water, while others disapproved, as it does not provide natural water (perceived as healthy). For RWH, some were concerned about possible contamination, if used as drinking water, while others, who focused on other domestic uses, were not concerned. Similarly for reservoirs and to a lesser extent for ponds, some were concerned about water contamination, e.g. due to dumping of waste. Amongst the remaining respondents, for 16% the impact on the environment was most important, for 8% costs and economic impact, for 4% social equity and two respondents (8%) did not identify their most important criterion. None considered practical and institutional aspects as most important, but for 60% it was least important.

Milton Friedman's non-parametric test (with Bonferroni correction for the significance, conducted in MS Excel with XL-STAT add-in) was used to check, if respondents consistently valued a certain alternative respectively a certain criterion higher than another.

- At 95% significance, for the potentials (25 responses), desalination had a significantly lower potential than RWH, check dams and reservoirs, and non-structural policies had a significantly lower potential than RWH and check dams. Similarly for the ranks (25 responses), desalination and non-structural policies had significantly lower ranks than RWH, check dams and reservoirs.
- At 95% significance, for the ranks (24 responses), health had significantly higher rank than practicability, social equity and costs, whereby also environment and social equity ranked significantly higher than practicability.

The figure 15 below summarizes the respondents' preferences for the criteria in terms of the ranks (1 = most important).

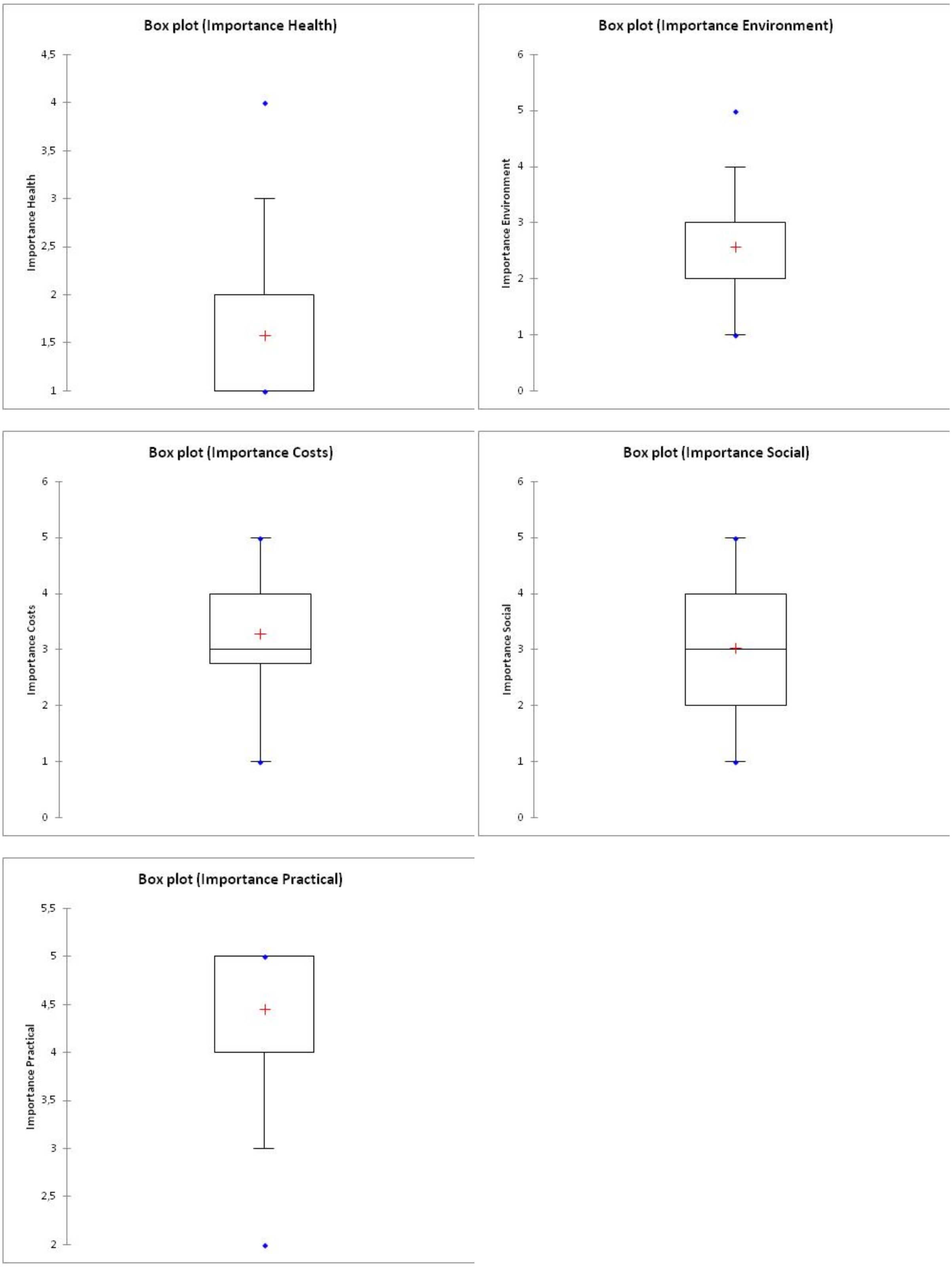


Figure 15 Box plots of criteria ranks

Explanation: The box plots (generated in Excel with the XL-STAT add-in) display the minimal (best) and maximal responses (dots), the mean value (red +), median (black line), the first to third quartile (box) and the 95% confidence interval (short line segments). As data are discrete, the median may coincide with a quartile.

For the interpretation of the survey it should be recalled that it was not intended to be a representative opinion poll for any specific group. Rather, this was an explorative study, where a sample of 10 to 30 respondents suffices (Isaac & Michael, 1995). Its purpose was to figure out the major motivations that may drive stakeholders in future decision-making. Overall, the different questions for mitigating water scarcity pointed in the same direction: Desalination and non-structural policies (e.g. water pricing) were problematic, while RWH, groundwater recharge with check dams and increasing capacity of reservoirs were generally acceptable. The major motivation of the stakeholder representatives was concern for health and, to a lesser extent, for environment, while practicability was least important. Further (e.g. for ponds), some farmers feared the loss of arable land without adequate compensation (not considering the advantages of a higher groundwater table for themselves).

6 References

Aellen V. (2011). Etude Hydrogeologique Et Modelisation D'un Bassin Versant En Inde Master En Hydrogéologie Et Géothermie Spécialisation En Hydrogeology Centre D'hydrogéologie Et Géothermie Université De Neuchâte.

Amerasinghe, P.; Weckenbrock, P.; Simmons, R.; Acharya, S.; Drescher, A.; Blummel, M. 2009. *An atlas of water quality, Health and agronomic risks and benefits associated with "wastewater" irrigated agriculture: A study from the banks of the Musi River, India*. Available at http://wwiap.iwmi.org/Data/Sites/9/DOCUMENTS/PDF/bmz_india_finalatlas_27oct09.pdf(accessed on September 10, 2012).

Buechler S, Devi G, Raschid L (2002) Livelihoods and Wastewater Irrigated Agriculture - Musi River in Hyderabad City, Andhra Pradesh, India, UA-Magazine, Dezember 2002

Buechler, S. and Devi, G. (2003b) The impact of water conservation and reuse on the household economy. In: Proceedings of the 8th International Conference on Water Conservation and Reuse of Wastewater, Indian Water Works Association. 2003

Buechler, S. and Mekala, G.D. (2005): Local responses to water resource degradation in India: groundwater farmer innovations and the reversal of knowledge flows. In: The Journal of Environment and Development 14 (4): 410–438.

Amerasinghe A. Weckenbrock P., Simmons R., Acharya S. and Blummel M. (2008). 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.

ANZECC & ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality: Volume 3 - Primary Industries. Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand, Canberra.

Ayers R.S., and Westcott, D.W. (1994) Water quality for agriculture. FAO irrigation and drainage paper 29 Rev 1. http://www.fao.org/docrep/003/t0234e/t0234e00.htm.

Bhushan C., Bhardwaj A. and Misra S.S. (2013) State of Pesticide Regulations in India, Centre for Science and Environment, New Delhi.

Biggs T.W. and Jiang B. (2009) Soil Salinity and Exchangeable Cations in a Wastewater Irrigated Area, India. Journal of Environmental Quality Vol 38: 887-896.

Brocklehurst, C, Pandurangi, A and Ramanathan L (2002) Tariff Subsidies in South Asia: Tariff Structures in Six South Asian Cities: Do They Target Subsidies Well?, Water Tariffs and Subsidies in South Asia, Paper 3, World Bank

Butterworth, J, Ducrot, R, Faysse, N and Janakarajan, S (Editors) (2007).Peri-Urban WaterConflicts: Supporting dialogue and negotiation. Delft, The Netherlands, IRC international Water and Sanitation Centre (Technical Paper series; no 50).128 p.

CCRBF (2008) Annual Report 2008. Cooperation Centre for Riverbank Filtration (CCRBF), Haridwar / Dehradun, Uttarakhand, India

Central Ground Water Board (CGWB) (2007) Groundwater brochure of Ranga Reddy district, Andhra Pradesh. Government of India, Ministry of Water Resources.

Centre for Science and Environment (CSE) (year unknown)Hyderabad – The Water – Waste Portrait, download under http://cseindia.org/userfiles/hyderabad_portraits.pdf, last access on 27.2.2013

Chennai Metropolitan Water Supply and Sewerage Board (2011) Chennai Metropolitan Water Supply and Sewerage Board (2011): "Advanced Water Treatment Technologies – Chennai Initiatives". Workshop conducted by MoUD, New Delhi. 3 November (http://www.urbanindia.nic.in/programme/uwss/uiww/ppt_3rd_meeting/cmwssb_chennai_ppt.pdf, accessed on 14.2.2013)

Cullet, P. (2012). Groundwater Regulation in Uttar Pradesh: Beyond 2010 Bill. New Delhi: Environmental Law Research Society.

Cullet, P. (2012). Is Water Policy the New Water Law? Rethinking the Place of Law in Water Sector Reforms. 43/2 IDS Bulletin .

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. Hydrogeol J., 18(4), 973-983.

Deliverable D2.3 (2013). Report on field investigations on the performance of MAR techniques under the conditions in India. Deliverable of project Saph Pani, downloadable at www.saphpani.eu.

Deliverable D6.1 (2013). Report on initial sustainability assessment. Deliverable of project Saph Pani, downloadable at www.saphpani.eu.

Devi G, Samad M, Davidson B, Boland AM (2009) Valuing a Clean River - A case study of Musi River, Hyderabad, India, Paper presented at the 53rd Annual Conference of Australian Agricultural and Resource Economics Society Cairns, Australia, 13-16 February, 2009

Ensink JHJ, Scott CA, Brooker S, Cairncross S (2010) Sewage disposal in the Musi-River, India: water quality remediation through irrigation infrastructure, Irrigation & Drainage Systems; Jun2010, Vol. 24, Issue 1/2, p.65

Essl, L., M. Starkl, P. C. Kimothi, C. Sandhu and T. Grische (2014). River bank filtration and managed aquifer recharge as alternative water supply technologies for India: SWOT analysis. *Water, Science and Technology: Water Supply.* In press.

Gale I. and Dillon P. (2005) Strategies for Managed Aquifer Recharge (MAR) in semi-arid areas, NESCO-IHP, Paris.

Gabella N.A., Page D., Dillon P, Vanderzalm J., Barry K. And Levett K. (2010) Operational Residual Risk Assessment for the Bolivar ASR recycled water project CSIRO: Water for a Healthy Country National Research Flagship.

George, B. Malano, H. and Davidson, B. (2007) Integrated water allocation: Economic modelling at a catchment scale. Apaper presented to the annual conference of modelling and simulation society of Australia and New Zealand, Christchurch, March, 2007.

Government of India (GoI) (2013) Monthly mean maximum & minimum temperature and total rainfall based upon 1901-2000 data. India Meteorological Department, Ministry of Earth Sciences. Accessed 03 Apr. 2013, http://www.imd.gov.in/doc/climateimp.pdf.

Greater Hyderabad Municipal Corporation (GHMC) (2006) Hyderabad City Development Plan, download under http://www.ghmc.gov.in/downloads/cdpdefault.asp (last access 26.02.2013)

Havelaar A.H. and Melse J.M. (2003) Quantifying public health risks in the WHO Guidelines for Drinking-Water Quality: a burden of disease approach, Report 734301022/2003, RIVM, Bilthoven, Netherlands.

Havelaar A.H., Van Duynhoven Y.T.H.P., Nauta M.J., Bouwknegt M., Heuvelink A.E., De Wit G.A., Nieuwenhuizen M.G.M., Van de Kar N.C.A.J. (2004) Disease burden in the Netherlands due to infections with Shiga-toxin producing Escherichia Coli. Epidemiol. Infect. 132: 467-484.

Havelaar A.H., Van Olphen M., and Schijven J.F. (1995) Removal and inactivation of viruses by drinking-water treatment processes under full-scale conditions. Water Science and Technology 31: 55-62.

Herczeg AL and Dighton JC (1998). Radon-222 concentrations in potable groundwater in Australia. Water (journal of the Australian Water Association) 28 (May–June).

HMDA – Hyderabad Metropolitan Development Authority (2013), Available from: http://www.hmda.gov.in/hcip1.html, Retrieved: Accessed August 2013

HMWSSB (year not known) Sewerage System in Hyderabad - maintained by HMWSSB, download under http://cseindia.org/userfiles/HMWSSB_presentation.pdf (last access 26.02.2013)

Hyderabad Metropolitan Water Supply and Sewerage Act N°15 of 1989, Available from: available from: http://www.lawsofindia.org/pdf/andhra_pradesh/1989/1989AP15.pdf, accessed on August 2013

Howard G, Pedley S. and Tibatemwa S. (2006) Quantitative microbial risk assessment to estimate health risks attributable to water supply: Can the technique be applied in developing countries with limited data? Journal of Water and Health 4(1):49-65.

Howard G., Ahmed M.F., Teunis P., Mahmud S.G., Davison A. and Dan Deere (2007) Disease burden estimation to support policy decision-making and research prioritization for arsenic mitigation. Journal of Water and Health 5(1): 67-81.

IWMI/NGRI/BRGM (2013) Periodic Report M1-M18. Saph Pani – Enhancement of natural water systems and treatment methods for safe and sustainable water supply in India.

IS 10500 (2004) Indian drinking water guidelines. 2nd revision, Bureau of Indian Standards, New Delhi

Isaac, S., Michael, W.B. (1995). Handbook in Research and Evaluation, EDITS, San Diego

Jacobi, J.; Drescher, A.W.; Amerasinghe, P. 2009. Crop diversity as a livelihood strategy? The case of wastewater irrigated vegetable cultivation along the Musi River in periurban Hyderabad, India. In: Biophysical and socioeconomic frame conditions for the sustainable management of natural resources, Tropentag, October 6-8, 2009,Hamburg, Germany. Available at www.tropentag.de/2009/abstracts/links/Jacobi_iMdV2JnR.pdf (accessed in March, 2012).

Jain.S.K. (2012). Harnessing the Managed Aquifer Recharge Potential for Sustainable Groundwater Management in India. India Water Week 2012 - Water, Energy and Food Security: Call for Solutions. New Delhi.

Jampani, M., P. Amerasinghe and P. Pavelic. 2014. Elucidating changes in land-use patterns, crop choices and farmer perceptions in a wastewater-dominated peri-urban agricultural system in India. Proceedings on the Seminar on Development Trends in Urban and Peri-Urban Agriculture (UPA"), held on 8 August 2013, at ISEC, Bangalore (in press).

Janakarajan.S, & Moench, M. (September 16, 2006). Are Wells a Potential Threat to Farmer's Well-being? Case of Deterioting Groundwater Irrigation in Tamil Nadu. Economic and Political Weekly .

Kimothi PC, Dimri DD, Adlakha LK, Kumar S, Rawat OP, Patwal PS, Grischek T, Sandhu C, Ebermann J, Ruppert M, Dobhal R, Ronghang M, Kumar P, Mehrotra I, Uniyal HP (2012) Development of Riverbank Filtration in Uttarakhand. J. Indian Water Works Association, Special issue on River Bank Filtration, 13-18.

Kulkarni, H., & Shankar, V. (February 7, 2009). Groundwater: Towards an Aquifer Management Framework. Economic and Political Weekly .

Kumar A., Usha N., Sawant P.D., Tripathi R.M., Raj S., Mishra M. Rout S., Supreeta, P., Singh J., Kumar S. and Kushwaha H. S. (2011) Risk assessment for natural uranium in subsurface water of punjab state, India. Human and Ecological Risk Assessment 17(2):381-393.

Koonan, S. (2010). Groundwater-Legal Aspects of Plachimada Dispute. In P. cullet, A.Gowlland-Gualtieri, R. Madhav, & R. Usha, Water Governance in Motion:

Towards Socially and Environmentally Sustainable Water Laws. New Delhi: Cambridge University Press India Pvt. Ltd.

Larsson, D.G.J., de Pedro, C., Paxeus, N., 2007. Effluent from drug manufactures contains extremely high levels of pharmaceuticals. *Journal of Hazardous Materials* 148, 751-755

Lodder W.J. & de Roda Husman A.M. (2005) Presence of noroviruses and other enteric viruses in sewage and surface waters in the Netherlands. Applied and Environmental Microbiology 71(3): 1453–1461.

Mangen M-J. J., van Duynhoven Y.T.H.P., Vennema H., van Pelt W., Havelaar A.H. and de Melker H.E. (2010) Is it cost-effective to introduce rotavirus vaccination in the Dutch national immunization program? Vaccine 28(14): 2624-2635.

Massuel S., George B., Gaur A. and Nune R. (2007) Groundwater Modelling for Sustainable Resource Management in the Musi Catchment, India. Proceedings, International Congress on Modelling and Simulation, 10-13 December 2007, Christchurch, New Zealand, p. 1429-1435.

McCartney M., Scott C., Ensink J., Jiang B. and Biggs T. W., (2008) Salinity implications of wastewater irrigation in the Musi River catchment in India. Cey. J. Sci. (Bio. Sci.) 37 (1): 49-59.

Morris S.K., Awasthi S., Khera A., Bassani D.G., Kang G., Parashar U.D., Kumar R., Shet A., Glass R.I., Jha R. & for the million death study collaborators (2012) Rotavirus mortality in India: estimates based on a nationally representative survey of diarrhoeal deaths. Bulletin of the World Health organization 90(10): 720-727.

NHMRC–NRMMC (National Health and Medical Research Council and Natural Resource Management Ministerial Council) (2004). Australian Drinking Water Guidelines, NHMRC and NRMMC, Canberra.

NRMMC–EPHC–AHMC (2006) Australian guidelines for water recycling (Phase 1): Managing Health and Environmental Risks, Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and Australian Health Ministers' Conference, Canberra.

NRMMC–EPHC–NHMRC (2009) Australian guidelines for water recycling: Managed health and environment risk (Phase 2): Managed Aquifer Recharge, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.

Oragui J. I., Mara D. D., Silva S. A. and Konig A. M. (1989) A new technique for the enumeration of rotaviruses in wastewater samples. Water Sci. Technol. 21: 99-104.

Parashar U.D., Gibson C.J., Bresee J.S. and Glass R.I. (2006) Rotavirus and severe childhood diarrhoea. Emerging Infectious Diseases 12(2): 304-306.

Parimalarenganayaki, S. and Elango, L. (2013) Impact of recharge from a check dam on groundwater quality and assessment of suitability for drinking and irrigation purposes, Arabian Journal of Geosciences, DOI 10.1007/s12517-013-0989-z.

Rimhanen-Finne R., Vuorinen A., Marmo S., Malmberg S. and Haenninen M.-L. (2004) Comparative analysis of Cryptosporidium, Giardia and indicator bacteria during sewage sludge hygienization in various composting processes. Applied Microbiology 38(4):301-305.

TERI (2010) Review of current practices in determining user charges and incorporation of economic principles of pricing for Urban Water Supply, prepared for the Ministry of Urban Development, Government of India, New Delhi

Perrin J., Ahmed S., Dinis L., Aellen L., Amerasinghe P., Pavelic P. and Schmitt R. (2011). Groundwater processes in a micro-watershed influenced by wastewater irrigation, peri-urban Hyderabad. Hyderabad, National Geophysical Research Institute (NGRI), Bureau de recherches géologiques et minières (BRGM), International Water Management Institute (IWMI). IFCGR/IWMI 2009 – 2010. 54 pp.

Sakthivel, P. (2012). Water Supply: Law and Governance in Chennai. In R.K.Mishra, & S. Sahu, Water Governance. New Delhi: Allied Publishers.

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: Mémoire, Swiss Federal Institute of Technology.

Sharma, S. (2011). Managed Aquifer Recharge:Introduction. Delft: UNESCO-IHE, Institute of Water Studies.

Sharma, S. (2011). Managed Aquifer Recharge: Introduction. Delft: UNESCO-IHE, Institute of Water Studies.

Sandhu C, Grischek T (2012) Riverbank filtration in India – using ecosystem services to safeguard human health. Water Science & Technology: Water Supply 12(6), 783-790.

Sandhu C, Grischek T, Voltz T (2012) Indo-German collaboration in bank filtration: eight years of projects, exchanges and training. 39. International Association of Hydrogeologists Congress Abstracts, 67, Niagara Falls, Canada, 16.-21.09.2012.

Saph Pani D1.1 (2012) Guidelines for flood-risk management of bank filtration schemes during monsoon in India. Saph Pani Deliverable D1.1. Available: http://www.saphpani.eu/downloads ; accessed: September 2013

Saph Pani D1.2 (2013) Database of relevant pollutants in urban areas and their attenuation at RBF sites. Saph Pani Deliverable D1.2. Available: http://www.saphpani.eu/downloads ; accessed: September 2013

Starkl, M., Brunner, N., López, E, Martínez-Ruiz, J.L. (2013). A planning-oriented sustainability assessment framework for peri-urban water management in developing countries. Water Research, 47 (20), 7175-7183.

Starkl, M., P. Amerasinghe, L. Essl, M. Jampani, D. Kumarand S. R. Asolekar (2013). Potential of natural treatment technologies for wastewater management in India, *Journal of Water, Sanitation and Hygiene for Development*, 03.4, 500-511.

Sprenger, C., Parimala Renganayaki, S., Elango, L., Schneider, M., (2014). Hydrochemistry and stable isotopes during salinity ingress and refreshment in surface- and groundwater from the Arani–Koratallai (A-K) basin north of Chennai (India). Environmental Earth Sciences.

Tanaka H., Asano T., Schroeder E. D., and Tchobanoglous G. (1998) Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data. Water Environ. Res. 70:39–51.

Tate J.E., Chitambar S., Esposito D.H., Sarkar R., Gladstone B., Ramani S., Raghava M.V., Sowmyanarayanan T.V., Gandhe S., Arora R., Parashar U.D. and Kang G. (2009) Disease and economic burden of rotavirus diarrhoea in India. Vaccine (27(5): F18-F24.

TERI (2010) Review of current practices in determining user charges and incorporation of economic principles of pricing for Urban Water Supply, prepared for the Ministry of Urban Development, Government of India, New Delhi

UNDP (1987). Hydrogeological and Artificial Recharge Studies, Madras- India, Technical Report.

van Pelt W., Friesema I., Doorduyn Y., de Jager C. and van Duynhoven Y.T.H.P. (2008) Bilthoven: National Institute of Public Health and the Environment; 2008. Report No.: Internal report.

van Rooijen D. J.; Turral, H. and Biggs, T. W. (2005): Sponge city: water balance of mega-city water use and wastewater use in Hyderabad, India, Irrigation and Drainage 54, p81–p91

World Health Organization (WHO) (2006) Safe use of wastewater, excreta and greywater. In Wastewater use in agriculture-Volume 2. World Health Organization, Geneva.

World Health Organization (WHO) (2008) The global burden of disease: 2004 update. World Health Organization, Geneva.

World Health Organization (WHO) (2009) Risk Assessment of Cryptosporidium in Drinking Water. World Health Organization, Geneva.

World Health Organization (WHO) (2011) Guidelines for drinking-water quality: Volume 1 Recommendations 3rd edn. World Health Organization, Geneva.

World Health Organization (WHO) (2012) World health statistics. World Health Organization, Geneva.

World Bank (2012a) Life expectancy at birth, total (years). http://data.worldbank.org/indicator/SP.DYN.LE00.IN. Accessed 12 Feb. 2013.

World Bank (2012b) Mortality rate, infant (per 1,000 live births). http://data.worldbank.org/indicator/SP.DYN.IMRT.IN. Accessed 12 Feb. 2013.

Wyroll.P. (2012). India's Groundwater Crisis. Canberra: Global Water Forum.

Zimmermann T (2011) Wastewater irrigation in Hyderabad, India: Economic costs and benefits, BA Thesis, Humboldt Universität zu Berlin, Geographisches Institute

7 Appendix

7.1 Appendix 1: Table of cases decided by Courts relating to groundwater and MAR

Title of the Case, Citation, Facts and Issues	Court decision relating ground water (*MAR* specific portions are in italics)
K.P Vijayan Vs. The District Revenue Officer, **(1997) 2 SCC 87** The petitioner was in the possession of land classified as *Oorani* (water body). The petitioners raised constructions and applied for *patta* (revenue document describing possession). Meanwhile, an order of eviction was passed by the administration. The eviction order was challenged in the Court.	The petitioners have been given notice as per the Encroachment Act and procedures have been followed. Accordingly there is no illegality or irregularity in the order of eviction. It is always open to the petitioners to work out their remedy by seeking alternate sites, by approaching the concerned authorities. Anybody who is in occupation of water courses, river beds, etc has no right to continue.
Uppliyanthittu Kamarajar Nagar Vs. The District Collector **AIR 2001 SC 3215** The petitioner is an Association and its members are the encroachers of land which has been classified as a 'tank *poramboke*', wherein *Sirunaickenkulam* Tank is located. Petitioners, have been in possession of the respective occupations for more than two decades. They have constructed houses, for which basic amenities have been provided. They have also made representations to the Government to grant *patta* for their respective occupation. The administration passed eviction orders.	The court held that the writ petitions are dismissed and the court directed the removal of encroachment and *restore the irrigation tanks.*
S. Jagannath Vs. Union of India **(1997) 2 SCC 87** The petitioner has sought the Enforcement of coastal zone regulation notification dated February 19, 1991 issued by the government of India, stoppage of intensive and semi-intensive type of prawn farming in the ecologically fragile coastal areas, prohibition from using the waste	The central government shall constitute an authority to protect the ecologically fragile Coastal areas, sea shore, water front and other coastal area in accordance with “the precautionary principle" and "the polluter pays". All aquaculture industries/shrimp culture industries/shrimp culture ponds operating/set up in the coastal Regulation

and wet lands for prawn farming and the constitution of a national coastal management authority to safeguard the marine life and coastal areas.	zone as defined under the CRZ notification shall be demolished and removed. *Detrimental implication on local fauna and flora and ground water shall not be allowed.*
Palaniappan Vs. The District Collector **1997 (2) SCALE 493** The case of the petitioner is that he has purchased the property by way of an unregistered sale deed and put up a construction .He has been residing in that house and paying tax to the authorities regularly and the same was acknowledged by the State. But the revenue administration passed an eviction order without issuing any show cause notice.	The petitioner is not entitled to seek any remedy for conversion of the impugned notice, under the Land Encroachment Act and there is substantial compliance of the provisions of the Tamil Nadu Protection of Tanks and Eviction of Encroachment Act and Rules, 2007. Hence, the writ petition failed. The court emphasized on Article 51-A (g) of the Constitution which makes it a fundamental duty of every citizen "to protect and improve the natural environment including forests, lakes, rivers and wild life" and this duty can be enforced by the Court.
Pachai Perumal Vs. The District Collector **2004 CrLJ 2582** Section 133 of the Code of Criminal Procedure cannot be invoked in a case where there is a water withdrawal for sale. There is no public nuisance involved and the provision of law invoked to ban sale of water is arbitrary.	The court held that in order to protect the groundwater from the persons, who are using it for commercial purpose for gaining profit from the agriculturists in the state, who in turn, are suffering for lack of water not only for agricultural purposes but also for drinking purposes and also in the interest of public, it is appropriate to give a direction to the Government not to allow any person to draw and sell the groundwater till the notification is issued. Accordingly, there shall be a direction to the State Government, not to allow any person to draw and sell the groundwater until the Tamil Nadu Groundwater (Development and Management) Act, 2003, is notified. (Subsequently, the Act is repealed)

L.Krishnan Vs. State of Tamil Nadu **2005 (4) CTC 1.** Petitioner has encroached into the *Odai Poromboke*. The *Tahsildar* has ultimately reported that all the encroachments including that of the petitioner are liable to be removed by taking necessary steps under the Tamil Nadu Land Encroachment Act.	The court directed the State Government to identify all natural water resources in different parts of the State and wherever illegal encroachments are found, initiate appropriate steps in accordance with the relevant provisions of law for *restoring such natural water storage resources* which have been classified as such in the revenue records to its original position so that the suffering of the people of the State due to water shortage is ameliorated.
T.S Senthil kumar Vs The Government of Tamil Nadu **1992 W.L.R. 728** The Constitutional validity of the Tamil Nadu Protection of Tanks and Eviction of Encroachments Act, 2007 was challenged as it does not provide sufficient opportunity for the encroachers.	The court upheld the Constitutionality of the Act, and declared, Art 51A (g), Art 48- A, public trust doctrine, sustainable development were taken into consideration which protect the environment and water bodies.
Era Soundara Pandian Vs. Mrs. Lakshmi **Order dated 16/11/2011 in Crl.R.C (MD).No.191 of 2010** A motor pump set was removed citing a provision of the Tamil Nadu Groundwater (Development and Management) Act, 2003 which was not notified.	The court held that the respondents have not acted with malafide intention because drawing water from public connection and sale of it during water scarcity is against local body laws. *The case assures that commercial exploitation of ground water during water scarcity is against the ground water management and development.*
Sakthi Vs. Karuppaiah **Order dated 29 August 2011 in Crl.RC.(MD)No.460 of 2011** The respondents encroached certain water channels. Criminal proceedings were initiated against encroachers. The *locus standi* of the petitioner was questioned.	*Damage to public property and any mischief to water supply or public drainage are punishable.* It does not require competency to initiate complaint.
Velammal Residential School Vs. The Executive Engineer **Order dated 28 March in W.P (MD) No.12140 of 2011**	The court considered the safety of the school and also ensured that there is no encroachment of the water course. A

A school administration has constructed certain protective constructions on a water course to avoid inundation during rainy season. A small portion of land was also encroached for a compound construction.	*delicate balance of encroachment and protection of water body* is done by the Court.
S. Amutha Vs. The District Collector **Order dated 18 January 2010 in W.P (MD) No.402 of 2010** The petitioner is a long resident of a house situated in a water course *poramboke* land. The petitioners sought the recognition of their housing in revenue records which was denied by the authorities.	The order for eviction is justified. However the considerations of the petitioner are taken into account.
Consumer Action Group Vs. Project Director… **Order dated 22 July 2010 in W.P.No.17915 of 1993** The petitioner contended that Chennai City and its surrounding areas were facing acute water shortage. The ground water resources are drying up and Chennai being a coastal town with the current rates of depletion, there is a possibility of sea water intrusion into the fresh water resources. Petitioners sought the government to take efforts to remove encroachments.	The Court held to take emergent action for removal of such encroachments to be taken. It would be open to the petitioners as well as other public spirited persons to approach the administration at various levels, with details of encroachments in the water bodies, for the purpose of removal of such encroachments and to *restore the water bodies in larger public interest* as there is a duty imposed under Art 48 A and 51 A.
S. Kulanthaivel Vs. The District Revenue Officer **Order dated 03 December 2009 in W.P.No.68 of 2005** A part of the land was classified as a water body *poromoke* land by the revenue administration in revenue proceeding during 1940s. But the occupier argued that no such water body existed and their family owned it for a long time.	The Court relied only on a revenue proceeding. *No scientific evidence was sought by the Court to declare the nonexistent of a water body.*

7.2 Appendix 2: Summary of Governmental Orders Chennai

Summary of Government Orders related to Groundwater issued by the Office of the Chief Engineer; State Ground and Surface Water Resources Data Centre, Water Resources Organisation, Public Works Department, Government of Tamil Nadu.

1) Chief Engineer's Circular- Cir No.CE 1/ 2010/DD(G)/ dated 25 January 2010

The circular provides instructions as to conduct of pump test for withdrawal permissions. The number of hours relating to pump test is also specified. This order prohibits pump test during rainy season.

2) Chief Engineer's Circular-Cir No.CE 2/2010/DD (G)/ dated 19 March 2010

This order is regarding the award of groundwater availability certificates for more than 10,00,000 litres per day to firm/ industry/ organization for their usage. The certificate must be issued only after recording water levels every month and water quality test during pre-monsoon and post monsoon periods. A comparative analysis is also to be made.

3) Chief Engineer's Circular- Circular No. CE-3/ 2010/ DD (G)/ dated 5 April 2010

This order issues relating to misuse of free electricity for groundwater withdrawals. The free electricity issued to agriculture should not misuse for the purpose of industrial or commercial purpose.

4) Chief Engineer's Circular- Cir NO. CE-4/2010/ DD(G) dated 17 May 2010

This order is about avoiding fraudulent practices relating to No-Objection certificate from the State Pollution Control Board by suppressing the expiry of "Groundwater Availability Certificate". The order seeks periodical reports from officials.

5) Chief Engineer's Circular- Cir No.-5/2010/DD(G)/ dated 02 June 2010

The order is about restraining Groundwater Availability Certificate near coastal areas. The borderline or line of separation of zones is fixed at perpendicular distance of 10 Km from the sea coast beyond which only Groundwater drawal proposal should be considered.

6) Public Works (R2) Department G.O. (Ms). No. 84 dated 02 April 2008

The order is about implementation of artificial recharge schemes through existing dug wells in the identified blocks - as over exploited, Critical, Semi-critical with assistance through National Bank for Agriculture and Rural Development (NABARD) and lead banks. The objective of the scheme is to recharge the existing dug well using rainfall run offs from the agricultural fields to facilitate augmentation of groundwater situation in the affected areas which in turn will help to improve the overall irrigated agricultural land productivity . In Tamil Nadu the scheme is implemented in 232 blocks identified as over exploited, Critical, Semi critical. The beneficiaries are identified as farmers who have dug wells in their agricultural lands. The subsidy amount is proposed to be disbursed by NABARD. Committees are identified to facilitate the smooth conduct of the programme.

7) PUBLIC WORKS (R2) DEPARTMENTG.O. (Ms). No. 52 dated 02 March 2012

This order is about estimation of groundwater availability and categorisation as per the Union government directives. Appropriate rain water harvesting and artificial recharge schemes should be carried out in the categories viz , Over exploited , Critical , Semi Critical and Safe blocks of Tamil Nadu. While carrying out the above schemes, priority should be given to marginal quality and bad quality areas so as to avoid further deterioration.

7.3 Appendix 3: Selected Groundwater Laws of other States

State Legislation, Applicability & Purpose	Groundwater Protection and Regulation	Specific reference to MAR
Andhra Pradesh Andhra Pradesh Water, Land and Trees Act, 2002 (Applicable to use of groundwater, surface water, protection and conservation of water sources)	Ground water contamination in any manner by anyone is prohibited. [sec.19] Direct disposal of waste waters into the aquifers, is prohibited. [sec.19(2)]	To improve the ground water resources, by harvesting and recharge. The Authority may issue guidelines for constructing appropriate rainwater harvesting structures in all residential, commercial and other premises and open spaces [sec.17(1)]
Kerala Kerala Ground Water (Control and Regulation) Act, 2002 Applicable to certain notified areas [sec.6(1)]	Grant of Permit to extract and use ground water [sec.7]	
Himachal Pradesh Himachal Pradesh Ground Water (Regulation and Control of Development and Management) Act, 2005 Applicable to notified areas, to regulate and control the development and management of ground water	Establishment of an authority(sec.3) Licence to extract groundwater[sec.6]	Identify the areas of ground water recharge and issue guidelines for adoption of rain water harvesting for ground water recharge in such areas [sec.15(1)]
West Bengal West Bengal Ground Water Resources (Management, Control and Regulation) Act, 2005 Applicable to the State of West Bengal, to manage, control and regulate indiscriminate extraction of ground water in West Bengal	Authorities at various levels [sec. 3] Sinking of wells for extracting or using ground water [sec.7]	State Level Authority to issue certificate for recharge of ground water [sec.8(2)(c)]

Chhattisgarh Chhattisgarh Ground Water (Regulation and Control of Development and Management) Act, 2012 Applicable to the State of Chhattisgarh, to improve the ground water situation	Establishment of an authority(sec.4) Permission to extract groundwater [sec. 7]	The Authority may identify the recharge worthy areas in the State and issue necessary guidelines [sec.20(1)]

8.3 Appendix 4: Results of stakeholder surveys in Hyderabad

Table 32 Results of the Stakeholder Survey on Options to Mitigate Water Scarcity

No	Potential of Option (1 = highest)						Rank of Option (1= best)					
	Desalination	RWH	check dams	ponds	reservoirs	Policies	Desalination	RWH	check dams	Ponds	reservoirs	Policies
1	2	1	2	2	1	2	6	3	2	5	1	4
2	3	2	1	3	2	4	5	2	1	4	3	6
3	3	1	2	2	2	1	6	1	2	5	3	4
4	3	2	1	2	1	3	6	4	1	3	2	5
5	3	2	2	2	1	3	5	3	2	4	1	6
6	3	1	1	2	1	2	6	1	4	3	2	5
7	3	1	3	2	2	1	6	1	3	4	2	5
8	3	2	2	4	2	4	4	5	4	3	2	1
9	3	1	2	2	2	3	6	3	1	2	4	5
10	3	2	2	2	2	2	5	2	1	3	4	6
11	3	1	2	3	2	3	5	4	1	3	2	6
12	4	4	1	1	1	1	6	4	1	3	2	5
13	3	2	1	2	2	4	5	4	1	3	2	6
14	2	2	2	3	3	2	3	2	3	3	2	2
15	2	2	3	2	2	2	1	4	6	2	5	3
16	3	1	2	2	3	4	6	2	1	3	5	4
17	2	1	1	3	1	4	3	1	5	4	2	6
18	3	3	1	3	2	2	5	4	1	3	2	6
19	1	1	1	1	1	3	5	2	1	3	4	6
20	3	1	3	2	1	2	6	2	5	4	1	3
21	3	2	2	3	3	2	6	2	1	3	4	5
22	3	3	2	3	1	3	2	4	3	6	1	5

23	1	1	1	1	3	4	1	6	3	4	2	5
24	1	1	1	1	2	2	3	1	2	4	5	6
25	3	1	2	3	2	3	5	5	2	3	1	4

Table 33 Results of the Stakeholder Survey on Criteria

No	Rank by Importance (1 = most iportant)					Option w.r. to Health (1 = best)						Other Interests of Stakeholders						
	Health	Environment	Costs	Equity	Practical	Desalination	RWH	check dams	Ponds	reservoirs	Policies	Stakeholder	Laws suffice	Geo-hydro important	GW recharge	IWRM Plan requred	Land usage matters	Improvement
1	1	4	3	2	5	2	1	2	3	2	3	U	N	Y	Y	Y	Y	1
2	3	1	4	2	5	3	2	2	2	2	3	E	Y	Y	N	Y	Y	1
3	1	2	5	3	4	3	1	2	2	2	2	A	N	Y	N	Y	Y	1
4	1	3	2	5	4	3	2	2	2	1	2	E	N	-	N	Y	-	2
5	1	3	4	2	5	3	2	2	2	2	3	A	N	Y	N	Y	Y	1
6	-	-	-	-	-	2	1	2	1	-	-	E	-	-	-	-	-	2
7	1	2	3	4	5	-	1	1	2	1	-	U	-	-	-	Y	-	2
8	1	3	2	4	5	2	2	1	2	2	3	P	-	-	-	-	-	2
9	1	2	4	3	5	3	1	1	1	2	2	E	N	Y	N	-	Y	1
10	1	2	3	4	5	3	2	1	2	2	2	E	N	Y	Y	Y	Y	1
11	1	3	5	3	4	2	2	2	2	1	2	P	N	N	N	Y	N	1
12	4	5	3	1	2	4	1	1	1	1	2	P	N	N	N	Y	Y	2
13	1	3	4	2	5	2	1	1	2	2	4	P	Y	N	Y	Y	Y	2
14	3	2	3	3	3	2	2	2	2	2	2	E	N	Y	N	Y	Y	2
15	2	1	3	5	4	2	2	1	2	2	1	A	N	Y	N	Y	Y	1
16	1	2	4	3	5	3	-	-	1	1	1	P	N	Y	N	Y	Y	2
17	2	4	1	3	5	1	1	1	2	1	2	E	Y	N	N	Y	Y	1
18	2	1	5	3	4	4	2	1	2	2	3	P	N	N	Y	N	Y	1
19	1	4	2	3	5	3	3	2	3	2	2	P	N	Y	Y	Y	Y	1
20	1	2	4	3	5	-	1	2	2	2	2	E	-	N	N	Y	Y	1
21	1	2	5	3	4	2	3	2	2	2	2	E	N	Y	N	Y	Y	1
22	1	3	2	4	5	2	2	2	2	1	1	E	Y	Y	N	Y	Y	-
23	4	5	1	2	3	2	3	2	2	2	2	E	N	N	N	N	N	1
24	2	1	3	4	5	4	1	2	1	1	1	A	N	Y	N	Y	Y	2
25	1	2	4	2	5	2	1	1	2	1	2	U	N	N	N	Y	N	2

Explanation: Stakeholder A academia, E expert, P practitioner, U unknown; Improvement needed: 2 yes, 1 strongly yes

7.4 Appendix 4: Risk Assessment Case study Musi River
Musi river maximal risk assessment calculations

E. coli O157:H7

Annex 7-1 Level of risk for E.coli O157:H7 per person per year

Paramenters	Indication	Crop ingestion	Spray ingestion	Drinking water
Th.C organisms per liter/per gram in source water/crop	n	75	10^7	10^7
Calculated E.coli O157:H7 per liter in source water	N*0.9*0.08	5.4E+00	7.2E+05	7.2E+05
Log reduction (UV, decay)	PT	0.47[1)]	0	0
Organisms in source	C_D	1.84E+00	7.20E+05	7.20E+05
Exposure per event in liter	V	100	0.001	4
Dose per event	d	2.0E+02	8.0E+02	3.2E+06
Number of events per year	n	365	365	365
Dose response constants	Beta-Poisson			
	α	0.49[2)]	0.49[2)]	0.49[2)]
	β	1.90E+05	1.90E+05	1.90E+05
	N_{50}	5.92E+05[2)]	5.92E+05[2)]	5.92E+05[2)]
Risk of infection per event (day)	$P_{infs,d}$	4.8E-04	1.9E-03	7.4E-01
Risk of infection per year	$P_{infs,yr}$	1.6E-01	4.9E-01	1.0E+00
Ratio of illness/infection	$P_{ill/inf}$	0.25[3)]	0.25[3)]	0.25[3)]
Risk of illness per year	$P_{ills,yr}$	4.0E-02	1.2E-01	2.5E-01
Disease burden per case	db	0.46	0.46	0.46
Susceptible fraction	sfr	1	1	1
DALY's	DB	**1.8E-02**	**5.6E-02**	**1.1E-01**

*$1-(1-P_{infs,d,n})^n$

1)WHO (2006), 2)Haas et al. (2000), 3)Haas et al. (1999)

Cryptosporidium

In opposite to Howard et al. (2007), *Cryptosporidium* numbers in the Musi River were assumed to be equal to WHO (2011) numbers in sewage of 10^4 (Range: 1 – 10,000) rather than applying a sewage E.coli/*Cryptosporidium* ratio as no statistical correlation in numbers between E.coli and *Cryptosporidium* oocysts was found in sewage sludge (Rimhanen-Finne et al. 2004).

Annex 7-2 Level of risk for Cryptosporidium per person per year

Parameters	Indication	Crop ingestion	Spray ingestion	Drinking water
Cryptosporidium organisms per liter/per gram in source water/crop	n	10000	10000	10000
Log reduction (UV, decay)	PT	3.5[1)]	0	0
Organisms in source	C_D	3.16E+00	1.00E+04	1.00E+04
Exposure per event in liter	V	100	0.001	4
Dose per event	d	3.16E+02	1.00E+01	4.00E+04
Number of events per year	n	365	365	365
Dose response constants	exponential			
	r	0.059[2)]	0.059[2)]	0.059[2)]
	N_{50}	1.17E+01	1.17E+01	1.17E+01
Risk of infection per event (day)	$P_{infs,d}$	1.00E+00	4.46E-01	1.00E+00
Risk of infection per year	$P_{infs,yr}$	1.0E+00	1.0E+00	1.0E+00
Ratio of illness/infection	$P_{ill/inf}$	0.7[3)]	0.7[3)]	0.7[3)]
Risk of illness per year	$P_{ills,yr}$	7.0E-01	7.0E-01	7.0E-01
Disease burden per case	db	0.0020	0.0020	0.0020
Susceptible fraction	sfr	1	1	1
DALY's	DB	**1.4E-03**	**1.4E-03**	**1.4E-03**

$^{*}1-(1-P_{infs,d,n})^{n}$

[1)]WHO (2006), [2)]Messner et al (2001), [3)]Havelaar and Melse (2003)

Rotavirus

Today, rotavirus infection primarily occurs in infants and children under 2 years of age and is the most common cause of severe diarrhoea in infants and young children worldwide and of diarrhoeal deaths in developing countries (Parashar et al. 2006). According to Tate et al (2009), about 2 million Indian children below the age of 5 had diarrhoea associated with rotavirus and had to be admitted as outpatients. Between 457,000 to 884,000 showed signs of severe diarrhoea (avg. 33 %) and had to be hospitalized. About 122,000 to 153,000 (avg. 6.9 %) children aged < 5 died of rotavirus infection. WHO (2012) estimates the mortality of children aged < 5 yrs in India due to Diarrhoea to 220,480 (13% of total deaths of 1,696,000) in 2010. This means that approximately 55 to 69 % (122,000 to 153,000, Tate et al. 2009) out of 220,480 (WHO 2012) diarrhoeal deaths in children aged <5 in India are attributed to rotavirus infection and mortality increased from 4.1 per 1000 live births (3.32 in North India) in between 2001 and 2003 (Morris et al. 2012) to 5.1 to 5.6 children per 1000 live births between 2005 and 2007 (Tate et al. 2009). However, in order to be consistent with the approach in Uganda (Howard et el 2006), the disease burden for rotavirus was calculated using global incidence data for the different rotavirus outcome (88 % mild, 14.4 severe, 0.7 % death) from the 1980's (Havelaar & Melse 2003). The burden of disease increases by 1 log_{10}-unit when data from Tate et al. (2009) is used. No data was found for numbers of rotavirus in sewage in India so that numbers were estimated based on values found in the Netherlands. Rotavirus numbers measured in sewage per litre vary between 2.0E04 PDU/L in the Netherlands (95th percentile, Lodder & de Roda Husman 2005) and 9.0E04 FFU/L in Brazil (geometric mean, Oragui et al. 1989). The average hospitalization (confirmed prevalence) of children aged < 5 associated with rotavirus in the Netherlands is estimated 4.2 per 1000 for the years 1997 to 2007 (van Pelt et al. 2008 in Mangen et al. 2010) and is 5.3 times lower than 22.2 per 1000 live births in India (Tate et al. 2009). Therefore, figures for rotavirus in sewage in the Netherlands were multiplied with a factor of 5.3 to account for a higher prevalence in India compared to the Netherlands and rotavirus numbers in the sewage in India were estimated to 10^5 PDU/L.

Annex 7-3 Level of risk for rotavirus per person per year

Parameters	**Indication**	**Crop ingestion**	**Spray ingestion**	**Drinking water**
Rotavirus organisms per liter/per gram in source water/crop	n	100000	100000	100000
Log reduction (UV, decay)	PT	0.47[1)]	0.00	0.00
Organisms in source	C_D	3.41E+04	1.00E+05	1.00E+05
Exposure per event in liter	V	100	0.001	4
Dose per event	d	3.4E+06	1.0E+02	4.0E+05
Number of events per year	n	365	365	365
Dose response constants	Beta-Poisson			
	α	0.253[2)]	0.253[2)]	0.253[2)]
	β	0.426[2)]	0.426[2)]	0.426[2)]
	N_{50}	6.2	6.2	6.2
Risk of infection per event (day)	$P_{infs,d}$	9.8E-01	7.5E-01	9.7E-01
Risk of infection per year	$P_{infs,yr}$	1.0E+00	1.0E+00	1.0E+00
Ratio of illness/infection	$P_{ill/inf}$	0.9[3)]	0.9[3)]	0.9[3)]
Risk of illness per year	$P_{ills,yr}$	9.0E-01	9.0E-01	9.0E-01
Disease burden per case	db	0.46	0.46	0.46
Susceptible fraction	sfr	0.13	0.13	0.13
DALY's	DB	**5.4E-02**	**5.4E-02**	**5.4E-02**

[*] $1-(1-P_{infs,d,n})^n$

[1)] WHO (2006), [2)] Haas et al. (2000), [3)] Haas et al. (1999)

Musi river risk assessment

Mean water quality values were compared against guideline values for drinking water (IS 10500), short-term-irrigation values (STV) and native groundwater values with green, orange and red indicating low, uncertain and high risks respectively. Risk was rated uncertain when 1) mean values are equal to guideline value or 2) positive detection (e.g. pesticides) indicate contamination below guideline values but number of samples are insufficient to make reliable conclusions or 3) investigation is yet to be done. Blanc fields indicate that parameter/hazard does not apply to that endpoint.

Maximal risk assessment incl. water quality for irrigation canal water and native groundwater

Parameter	n	Min	Max	Mean	IS 10500	Gw_{ref}	WHO (2006) no restrictions	WHO (2006) slight to med restr.	ADI JMPR mg/kg bw	TMDI canal as % ADI	TDMI GW as % ADI	Crop ingestion	Spray ingestion	Drinking water	Fodder Plants	Veg. Plants	Fodder Soil	Veg. Soil	Aquifer
Physical characteristics																			
pH (pH units)	2	6.99	7.59	7.29	6.5-8.5	6.9	6.5-8	6.5-8											
Conductivity (µS/cm)	5	1153	1465	1320		820	1700-2600*	1700-2600*											
Turbidity (NTU)																			
Major Ions																			
Ca^{2+} (mg/L)	3	45.1	78.76	59.9	75	51.9													
Mg^{2+} (mg/L)	3	28.1	30.4	28.9	30	27.8													
Na^{+} (mg/L)	3	123.4	167.4	152.0		72.0	69 (3 meq/L)	207 (9meq/L)											
K^{+} (mg/L)	3	0	17.9	11.3		2.8													
SO_4^{2-} (mg/L)	3	46.5	71.9	58.3	200	42.2													
Cl^{-} (mg/L)	3	160.3	207	182.2	250	45.2	142 (4 meq/L)	355 (10 meq/L)											
HCO_3^{-} (mg/L)	3	165	497	282		279	90	500											
F^{-} (mg/L)	1			0.8	1	1.3	1	1											
SAR	3	2.7	4.5	3.8		2.1	>1200EC	>1200EC											
Nutrients																			
TOC (mg/L)																			

N as NO_3^- (mg/L)	3	0.07	37.0	19.0	10	11.8	5	5-30			
N as NO_2^- (mg/L)	1			20.6		BLQ	5	5-30			
N as NH_4^+ (mg/L)	1			22.4		0.4	5	5-30			
P as PO_4^- (mg/L)	1			1.2		BLQ	0.8-12.5**				
Microbiological											
TTC (cfu/100mL)				1E06							
Pesticide residues (µg/L)											
alpha-HCH	2			BLQ	0.01	0.02			0.005		8E-05
beta-HCH	2			BLQ	0.04	0.07			0.005		3E-04
gamma-HCH	2			BLQ	2	0.01			0.005		4E-05
delta-HCH	2			BLQ	0.04	0.02			0.005		8E-05
Heptachlor	2			BLQ		BLQ					
Heptachlor epoxide B	2			BLQ		BLQ					
gamma-chlordane	2			BLQ		BLQ					
Endosulphan I	2			BLQ	0.4	BLQ					
4,4-DDE	2	0.01	0.02	0.02	1	BLQ			0.01	3E-05	
Butachlor	2			BLQ	125	0.01					
Endrin	2			BLQ		BLQ					
4,4-DDD	2	0.06	0.09	0.08	1	BLQ			0.01	2E-04	
Endrin Aldehyde	2			BLQ		BLQ					
4,4-DDT	2			BLQ	1	0.01			0.01		2E-05
Endrin Ketone	2			BLQ		BLQ					
Methoxychlor	2			BLQ		BLQ					
Endosulphan II	2			BLQ	0.4	BLQ					
Malathion	2	0.04	0.05	0.05	190	0.01			0.3	3E-06	7E-07
Atrazine	2			0.01	2	BLQ			0.02	1E-05	
Simazine	2			BLQ		BLQ					

Metalaxyl	2			0.02		BLQ			0.08										
Metolachlor	2			BLQ		BLQ													
Monocrotophos	2			BLQ		BLQ													
Parathion Methyl	2			BLQ	0.3	0.02			0.000 25		2E-03								
Diazinon	2			BLQ		BLQ													
Benthiocarb	2			BLQ		BLQ													
Benfuracarb	2			BLQ		BLQ													
Carbaryl	2			BLQ		BLQ													
Carbofuran	2			BLQ		BLQ													
3-Hydroxy Carbofuran	2			BLQ		BLQ													
Methomyl	2			BLQ		BLQ													
Thiodicarb	2			BLQ		BLQ													
Propoxure	2			BLQ		BLQ													
Thiobencarb	2			BLQ		BLQ													
Methiocarb	2			BLQ		BLQ													
Aldicarb	2			BLQ		BLQ													

BLQ, below detection limit

*values spinach and paddy rice/perennial grass (ANZECC & ARMCANZ 2000)

**guideline value ANZECC & ARMCANZ (2000)

Operational residual risk assessment recovered mixed groundwater

Parameter	n	Min	Max	Mean	95^{th} perc.	IS 10500	Gw_{ref}	WHO (2006) no restrictions	WHO (2006) slight to med restr.	ADI JMPR mg/kg bw	TMDI canal as % ADI	Crop ingestion	Spray ingestion	Drinking water	Fodder Plants	Veg. Plants	Fodder Soil	Veg. Soil
Physical characteristics																		
pH (pH units)	11	6.42	7.22	6.8	7.2	6.5-8.5	6.9	6.5-8	6.5-8									
Conductivity (µS/cm)	14	934	1460	1226	1441		820.0	1700-2600*	1700-2600*									
Turbidity (NTU)																		
Major Ions																		
Ca^{2+} (mg/L)	11	16.8	138.03	59	126	75	51.9											
Mg^{2+} (mg/L)	11	28.2	53.8	41	52	30	27.8											
Na^{+} (mg/L)	11	91.2	160.1	109	137		72.0	69 (3 meq/L)	207 (9meq/L)									
K^{+} (mg/L)	11	1.6	4.5	2	4		2.8											
SO_4^{2-} (mg/L)	11	69.1	123.1	92	114	200	42.2											
Cl^{-} (mg/L)	11	78	196.4	131	189	250	45.2	142 (4 meq/L)	355 (10 meq/L)									
HCO_3^{-} (mg/L)	11	128	515	252				90	500									
F^{-} (mg/L)	3	0.97	1.59	1		1	1.3	1	1									
SAR	11	1.7	4.6	2.8	4.1		2.1	>1200EC	>1200EC									
Nutrients																		
TOC (mg/L)																		
N as NO_3^{-} (mg/L)	11	2.87	27.1	12.9	25.0	10	11.8	5	5-30									
N as NO_2^{-} (mg/L)	3			0.0		BLQ	0.0	5	5-30									
N as NH_4^{+} (mg/L)	3	0.00	0.6	0.4		0.4	0.4	5	5-30									
P as PO_4^{-} (mg/L)						BLQ	BLQ	0.8-12.5**										
Microbiological																		
TTC (cfu/100mL)																		
Pesticide residues (µg/L)																		

alpha-HCH	1			BLQ		0.01	0.02			0.005								
beta-HCH	1			BLQ		0.04	0.07			0.005								
gamma-HCH	1			BLQ		2	0.01			0.005								
delta-HCH	1			BLQ		0.04	0.02			0.005								
Heptachlor	1			BLQ			BLQ											
Heptachlor epoxide B	1			BLQ			BLQ											
gamma-chlordane	1			BLQ			BLQ											
Endosulphan I	1			BLQ		0.4	BLQ											
4,4-DDE	1			BLQ		1	BLQ			0.01								
Butachlor	1			BLQ		125	0.01											
Endrin	1			BLQ			BLQ											
4,4-DDD	1			BLQ		1	BLQ			0.01								
Endrin Aldehyde	1			BLQ			BLQ											
4,4-DDT	1			BLQ		1	0.01			0.01								
Endrin Ketone	1			BLQ			BLQ											
Methoxychlor	1			BLQ			BLQ											
Endosulphan II	1			BLQ		0.4	BLQ											
Malathion	1			BLQ		190	0.01			0.3								
Atrazine	1			BLQ		2	BLQ			0.02								
Simazine	1			BLQ			BLQ											
Metalaxyl	1			BLQ			BLQ			0.08								
Metolachlor	1			BLQ			BLQ											
Monocrotophos	1			BLQ			BLQ											
Parathion Methyl	1			BLQ		0.3	0.02			0.00025								
Diazinon	1			BLQ			BLQ											
Benthiocarb	1			BLQ			BLQ											
Benfuracarb	1			BLQ			BLQ											

Carbaryl	1			BLQ			BLQ											
Carbofuran	1			BLQ			BLQ											
3-Hydroxy Carbofuran	1			BLQ			BLQ											
Methomyl	1			BLQ			BLQ											
Thiodicarb	1			BLQ			BLQ											
Propoxure	1			BLQ			BLQ											
Thiobencarb	1			BLQ			BLQ											
Methiocarb	1			BLQ			BLQ											
Aldicarb	1			BLQ			BLQ											

BLQ, below detection limit

*values spinach and paddy rice/perennial grass (ANZECC & ARMCANZ 2000)

**guideline value ANZECC & ARMCANZ (2000)

Operational residual risk assessment return flow water

Parameter	n	Min	Max	Mean	95^{th} perc.	IS 10500	Gw_{ref}	WHO (2006) no restrictions	WHO (2006) slight to med restr.	ADI JMPR mg/kg bw	TMDI canal as % ADI	Crop ingestion	Spray ingestion	Drinking water	Fodder Plants	Veg. Plants	Fodder Soil	Veg. Soil
Physical characteristics																		
pH (pH units)	24	6.55	44.3	8.6	7.5	6.5-8.5	6.9	6.5-8	6.5-8									
Conductivity (µS/cm)	28	1076	1723	1477	1660		820.0	1700-2600*	1700-2600*									
Turbidity (NTU)																		
Major Ions																		
Ca^{2+} (mg/L)	22	7	179.2	54	116	75	51.9											
Mg^{2+} (mg/L)	23	27.2	59.51	44	57	30	27.8											
Na^{+} (mg/L)	23	95.2	262.8	192	249		72.0	69 (3 meq/L)	207 (9meq/L)									
K^{+} (mg/L)	23	0	15.5	5	15		2.8											
SO_4^{2-} (mg/L)	23	54.1	155.2	91	125	200	42.2											
Cl^{-} (mg/L)	23	95.9	272.5	194	245	250	45.2	142 (4 meq/L)	355 (10 meq/L)									
HCO_3^{-} (mg/L)	22	110	742	387				90	500									
F^{-} (mg/L)	8	0.79	2.26	1	2	1	1.3	1	1									
SAR	20	1.8	7.6	4.8	7.2		2.1	>1200EC	>1200EC									
Nutrients																		
TOC (mg/L)																		
N as NO_3^{-} (mg/L)	23	0.00	19.9	7.7	17.5	10	11.8	5	5-30									
N as NO_2^{-} (mg/L)	8			0.0			BLQ	5	5-30									
N as NH_4^{+} (mg/L)	8	0.00	14.2	3.7	4.1		0.4	5	5-30									
P as PO_4^{-} (mg/L)	8	0.00	1.1	0.2	1.0		BLQ	0.8-12.5**										
Microbiological																		
TTC (cfu/100mL)																		
Pesticide residues (µg/L)																		

alpha-HCH	1			BLQ		0.01	0.02			0.005								
beta-HCH	1			BLQ		0.04	0.07			0.005								
gamma-HCH	1			BLQ		2	0.01			0.005								
delta-HCH	1			BLQ		0.04	0.02			0.005								
Heptachlor	1			BLQ			BLQ											
Heptachlor epoxide B	1			BLQ			BLQ											
gamma-chlordane	1			BLQ			BLQ											
Endosulphan I	1			BLQ		0.4	BLQ											
4,4-DDE	1			BLQ		1	BLQ			0.01								
Butachlor	1			BLQ		125	0.01											
Endrin	1			BLQ			BLQ											
4,4-DDD	1			BLQ		1	BLQ		0.02	0.01								
Endrin Aldehyde	1			BLQ			BLQ											
4,4-DDT	1			BLQ		1	0.01			0.01								
Endrin Ketone	1			BLQ			BLQ											
Methoxychlor	1			BLQ			BLQ											
Endosulphan II	1			BLQ		0.4	BLQ											
Malathion	1			BLQ		190	0.01		0.2	0.3								
Atrazine	1			0.03		2	BLQ		45	0.02	1E-08							
Simazine	1			BLQ			BLQ											
Metalaxyl	1			0.03			BLQ			0.08								
Metolachlor	1			BLQ			BLQ											
Monocrotophos	1			BLQ			BLQ											
Parathion Methyl	1			BLQ		0.3	0.02			0.00025								
Diazinon	1			BLQ			BLQ											
Benthiocarb	1			BLQ			BLQ											
Benfuracarb	1			BLQ			BLQ											

Carbaryl	1			BLQ			BLQ											
Carbofuran	1			BLQ			BLQ											
3-Hydroxy Carbofuran	1			BLQ			BLQ											
Methomyl	1			BLQ			BLQ											
Thiodicarb	1			BLQ			BLQ											
Propoxure	1			BLQ			BLQ											
Thiobencarb	1			BLQ			BLQ											
Methiocarb	1			BLQ			BLQ											
Aldicarb	1			BLQ			BLQ											

BLQ, below detection limit

*values spinach and paddy rice/perennial grass ANZECC & ARMCANZ (2000)

**guideline value ANZECC & ARMCANZ (2000)

7.5 Appendix 5: Case Study Haridwar: Full Risk Assessment Report

WATER FOR A HEALTHY COUNTRY RESEARCH FLAGSHIP
www.csiro.au

Haridwar risk assessment

Managed Aquifer Recharge and Water Safety plan

Rico Bartak, Declan Page, Cornelius Sandhu, Peter Dillon and Thomas Grischek

Citation

Bartak R, Page D, Sandhu C,Dillon P, Grischek T (2013)

Haridwar risk assessment: Managed Aquifer Recharge and Water Safety plan. CSIRO, Australia.

Copyright and disclaimer

Important disclaimer

Table of Contents

Figures

Tables

Appendices

Acknowledgments

This study forms part of the SAPH PANI research project supported by the European Commission under the sixth research framework programme (Contract-No. 282911). The authors acknowledge support from the CSIRO Water for a Healthy Country Program. AusAid Public Sector Linkages Project “Water Quality Guidance for Managed Aquifer Recharge in India”, and the “Managed Aquifer Recharge and Stormwater Use Options” Research Project of the Goyder Institue for Water Research. The authors gratefully acknowledge helpful comments from reviewers.

Executive summary

The principle aim of this study is to 1) assess risks and hazards to the drinking water supply of the city of Haridwar in northern India and 2) develop a water safety plan based on the identified risk and hazards that can be used for other existing and planned bank filtration and MAR sites in India.

Risk and hazards are identified according to the Australian Guidelines for Water Recycling: Managed Aquifer-Recharge (NRMMC–EPHC–NHMRC 2009) and supplemented with a quantitative microbial risk assessment (QMRA).

The main part of Haridwar city is supplied to almost 50 % with water originating from the Ganga River. The Ganga water quality meets the permissible limits according to the Indian drinking water guideline after subsurface treatment via riverbank filtration and disinfection. However, main risks to the drinking water supply arise from increasing pollution of the Ganga River, particularly with pathogens, monsoon floods, pollution by on-site facilities, and from the water distribution system.

It was found that the risk associated with drinking water from Haridwar riverbank filtration system after sufficient travel time is below the national diarrhoeal incidence for all three reference pathogens (E.coli O157:H7, rotavirus and *Cryptosporidium*). However, risk associated with rotavirus and Cryptosporidium are above the regional South-East Asian diarrhoeal incidence and far above the WHO (2011) reference level for advanced countries.

Highest risk is associated with rotavirus, the lowest with E.coli O157:H7. Short travel times (< 30 d), extreme events such as loss of disinfection and direct contamination are identified as hazards and will require additional treatment.

Preventive measures such as improvement of disinfection efficiency, well protection and improved well sanitation reduce the identified risks significantly.

1 Introduction

The Saph Pani project addresses the improvement of natural water treatment systems such as river bank filtration (RBF), managed aquifer recharge (MAR) and wetlands in India building on a combination of local and international expertise. The project aims to enhance water resources and water supply particularly in water stressed urban and peri-urban areas in different parts of India.

The objective is to strengthen the scientific understanding of the performance-determining processes occurring in the root, soil and aquifer zones of the relevant processes considering the removal and fate of important water quality parameters that are important to human health. Evaluation includes the hydrologic characteristics (infiltration and storage capacity) as part of work package 1 along with the integral importance in the local or regional water resources management concepts. The socio-economic value of the enhanced utilisation of the attenuation and storage capacity will be evaluated taking into account long-term sustainability issues as a further part of Work Package 6.

Saph Pani focuses on a set of case study areas in India covering various regional, climatic, and hydrogeological conditions as well as different treatment technologies. The site investigations include hydrological and geochemical characterisation and depending on the degree of site development water quality monitoring or pre-feasibility studies for new treatment schemes. Besides the actual natural treatment component the investigation can encompass also appropriate pre- and post treatment steps to treat the water to a potable standard or avoid clogging of the sub-surface structures. The experimental and conceptual studies will be complemented by modelling activities which help to support the transferability of results.

This report fulfils the requirements for Task 6.2 Assessment of risks to human health and environment at the Haridwar case study site.

This RBF risk assessment and Water Safety Plan was developed for an existing riverbank filtration site in northern India in order to 1) assess risks and hazards to the drinking water supply of the city of Haridwar and 2) develop a water safety plan that can be used for other existing and planned bank filtration and MAR sites in India. It also serves to present a prototype of the type of water safety plan appropriate for other Saph Pani project sites and for the development of water quality guidance for the Central Pollution Board of India. To the extent that stormwater from urban areas contributes to source water in Haridwar bank filtration this also serves as a satellite site of the Goyder Institute for Water Research project on Managed Aquifer Recharge and Stormwater Use Options.

This report is structured to address risk assessment for managed aquifer recharge following the Australian Guidelines for Managed Aquifer-Recharge (NRMMC–EPHC–NHMRC 2009). This makes use of a risk management framework which is consistent with the WHO water safety plans (WHO 2011).

Chapter 2 describes the project site and the way bank filtration is operated. Chapter 3 keys out the stages for project assessment and completes preliminary assessment that indicates the investigations required to meet the needs of a risk assessment. Chapter 4 describes the investigation undertaken and chapter 5 outlines the stages of the risk assessment undertaken. Conclusions and the consequent water safety plan are presented in chapter 6.

Note that the report is structured as though the Haridwar Bank Filtration facilities are being constructed, although they have been in existence since the late 1970s or early 1980s. Data from existing operations are introduced under investigation. This approach allows a consistent risk assessment framework for new and existing sites.

2 Site description

River bank filtration (RBF) has been used in Haridwar since the 1980s as an alternative to surface water abstraction and to supplement groundwater abstraction (Sandhu et al. 2012). The usage of bank filtration in India offers the benefit of a significant reduction in turbidity and coliform in the source water that is directly supplied after disinfection without the needs for further extensive post-treatment.

This case study has been made for an existing riverbank filtration site in northern India in order to 1) assess risks and hazards to the drinking water supply of the city of Haridwar and 2) develop a water safety plan that can be used for other existing and planned bank filtration and MAR sites in India.

2.1 Geography and climate

Haridwar (population ~200,000) is located 200 km northeast of New Delhi in the state of Uttarakhand and is an important site of religious significance. About 550,000 primarily religious people visit Haridwar daily to take a bath in the Ganga in close proximity to the riverbank filtration wells at Har Ki Pouri and approximately 25 m upstream at Triveni Ghat in Rishikesh. Every 6 years the Ardth Kumbh and Kumbh Mela are held in Haridwar. During this 1-4 - month long period, Haridwar is the destination of more than 5 Million Hindu pilgrims and thus hosting the world's biggest Hindu gathering, which involves a ritual bath in the holy river Ganga (Dash et al. 2010). Haridwar city is the core part of the Haridwar Urban Agglomeration including residential and industrial suburban areas and the administrative headquarters of the larger Haridwar District.

The city of Haridwar is situated on the Ganga flood plain along the Ganga River at the foot of the western Himalayan Mountains at a mean Elevation of 314 m above sea level. Haridwar is also located at the southeast boundary of the Rajaji National Park and is surrounded by largely forested, hilly areas. The climate is subtropical and can be distinguished into 4 distinct seasons: winter season is from December to February with minimum temperatures in between 6.1^{o}C and 10.5^{o}C, summer season is from March to May with maximum temperatures between 30^{o}C and 40^{o}C (temperature data from Roorkee observatory), monsoon season from June to September and post monsoon from October to December. Average annual rainfall in Haridwar is 1,256.2 mm, though most of the rainfall, with about 1,053 mm (84 %), occurs as intense rainfall events (CGWB 2009) during the monsoon period.

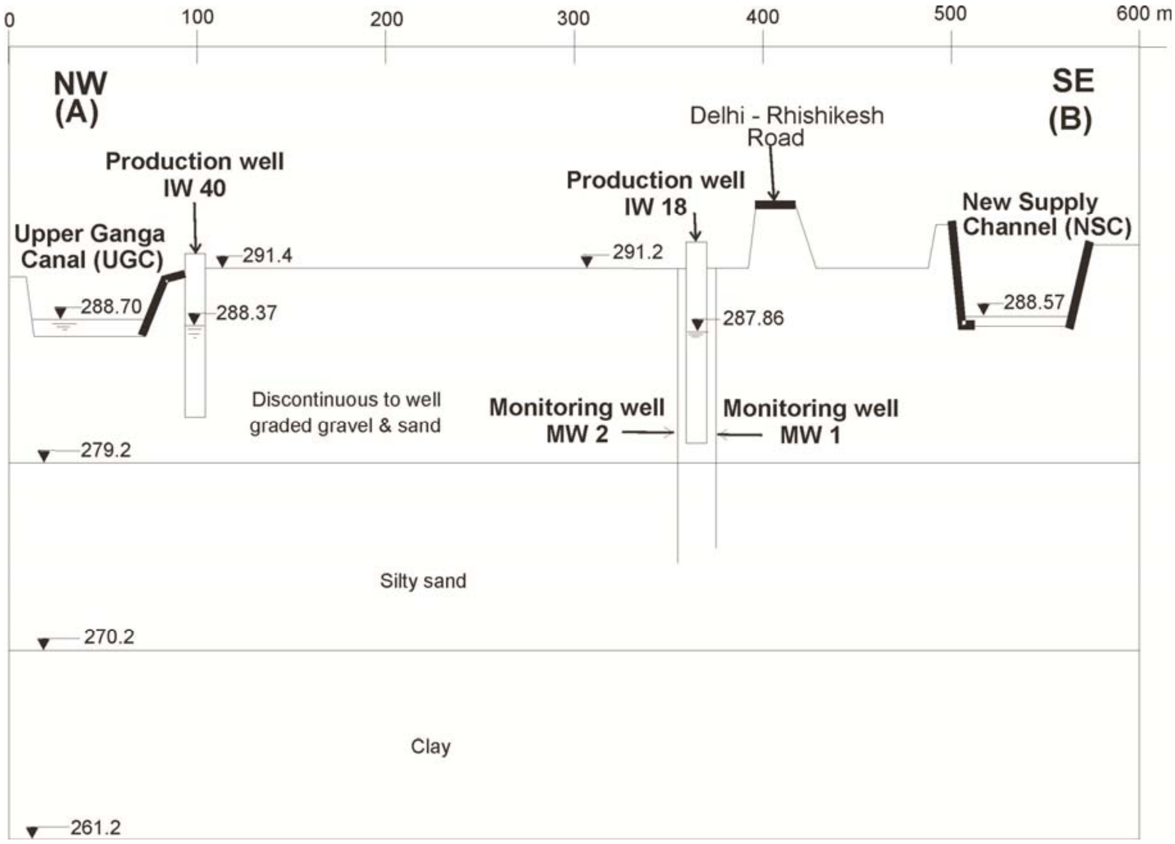
2.2 Aquifer description

The study site is situated in the Gangetic alluvial plains at the foot hills of the Shiwalik sandstone hills. The alluvium is compromised by unconsolidated to semi-consolidated deposits of coarse to fine sand, silt and clay (CGWB 2009). Groundwater occurs under unconfined, confined and semi-confined conditions. The Haridwar district aquifer system consists of 4water bearing layers that are separated by confining layers of clay in the western part of the district. The thickness of the confining layers decreases from west to east until the two uppermost and the two lower aquifers merge to one double layer aquifer system, as present in Haridwar (CGWB 2009). At the study site, the uppermost unconfined, alluvial aquifer mainly consists of sand and gravel (95 – 98 % of 0.075 – 4.75 mm) but also includes large fluvial stones and boulders adjacent to the Ganga River (Dash et al. 2010). The upper 12 m of the unconfined aquifer mainly consists of well graded gravel and sand. The lower part is compromised by silty sand (Figure 1). The shallow aquifer on Pant Dweep Island has a total thickness of 21 m, a saturated thickness of 17 m and the hydraulic conductivity (K-value) was estimated to be in the range of 1.2 – 4.7x10^{-4} m/s. The aquifer base consists of plastic clay with sand (Dash et al. 2010, Sandhu et al. 2011a). The main source of groundwater recharge is rainfall but is also supplemented by infiltration from irrigation channels and irrigation return flow (CGWB 2009). Groundwater recharge, measured as difference between pre- and post-monsoon groundwater elevation, varies from

0.14 m in at a depth of < 1m below surface (thus, the uppermost, unconfined aquifer) to 1.64 m at a depth of > 48 m below surface (confined aquifer) (CGWB 2009).

The target aquifer was demonstrated by Dash et al. (2010) to be in hydraulic connection with the Ganga River, UGC and NSC; but the majority of riverbank filtrate originates from the UGC. Sediments that compromise the river beds of the Ganga River, UGC and NSC are silt, fine sand, coarse gravel, cobbles and boulders. Clogging of the UGC canal bed is considered negligible because 1) bed material is excavated regularly and 2) riverbed scour is sufficient to prevent clogging as flow velocities are > 1 m/s and canal water gradient is about 3 ‰ (Sandhu et al. 2010). The K value of the UGC canal bed was estimated by Sandhu et al (2010) to be in the range of $4x10^{-6}$– $7x10^{-3}$ m/s (0.3 – 600 m/d) and is similar to the adjacent aquifer. The riverbeds of the NSC and the Ganga River (in, and in the near vicinity of < 1 km of the Bhimgoda Reservoir only) show higher silt contents and suffer riverbed clogging due to the Ganga River flow regulation at the Bhimgoda Barrage reservoir (right of Pant Dweep Island, Figure 2) (Dash et al. 2010, Sandhu et al. 2010), which was constructed in 1983 (Arvind techno 2013) to replace the old weir. It is mainly used for the purpose of irrigation and water is diverted from the Ganga during base and flood flow into the 7.000 km long Upper Ganga Channel distribution network (PCGI 2003).

The stage of groundwater development was estimated at 96.4 % in March 2004 (CGWB 2009) and categorized as "critical" (CGWB 2009). Groundwater development 150 km East of Haridwar was recently estimated at 164 % (Singhal et al. 2010) and groundwater levels in Bahadrabad (approximately 15 km SE of Haridwar) are already declining due to extensive groundwater abstraction. Therefore, future groundwater management plans are recommended to include rainwater harvesting and MAR practices to sustain groundwater resources (CGWB 2009).



Source: Sandhu (2013, in preparation)

Figure 1 Cross section A-B during monsoon

2.3 Source water description

The Ganga River rises as the Bhagirathi River from the Gangotri glacier in the western Himalayan Mountains and flows south east through North India into Bangladesh, where it discharges into the Bay of Bengal. The Ganga River is the largest river in India and also considered to be one of the most polluted rivers in the world.

The sources of water in the Ganga at Haridwar include snow melt from the Himalayas, run off from rural and urban areas and groundwater discharge. Hence there are a number of influences on water quality and Ganga River water quality reflects a range of both anthropogenic impacts such as pathogens and nutrients from untreated sewage discharge and natural impacts such turbidity from bank scouring during monsoon. Also during religious festivals in the base flow period up to 5 million visitors may wash themselves in the Ganga at and immediately upstream of Haridwar.

The Ganga River flow range is perennial and average discharge at Haridwar is 200 to 300 m^3/s from October to May with slightly higher discharge during post-monsoon period. Average discharge increases from June to September on average to about 1,500 m^3/s with recorded peak flows of > 5,900 m^3/s (Das Gupta 1975).

2.4 Site configuration

The Haridwar potable water distribution network was built in 1927 with the construction of 3 pumping wells and 1 storage reservoir (2,270 m^3). In the 1980's it was decided to supplement groundwater abstraction in order to meet the increased water demand by the use of alternative sources of water. Until now, groundwater is mainly abstracted by vertical groundwater wells (colloquially called "tube wells") from the second, confined aquifer (UJS, personal communication). Because Ganga River water does not meet microbial and physical criteria for drinking water, it is not suitable to use directly as a source of supply. Constructing a water treatment plant for directly abstracted surface water would have required a very large investment. Thus recognising the capability of the large-diameter caisson wells to abstract large volumes (high storage capacity) of "clear" water (extremely low turbidity and very low total and faecal coliform counts compared to direct surface water use), it was decided to construct large-diameter (~10 m) caisson wells.

Consequently, RBF offers the possibility of 1) high productivity by the installation of large diameter wells and 2) sustainable improvement of microbial and physical water quality parameters by subsurface treatment. As of 2013, the total drinking water production of > 64,000 m^3/d is sourced from 22 large diameter, bottom entry caisson wells (~10 m) which receive water as riverbank filtrate from the Ganga River (>43.000 m^3/d) and 50 vertical groundwater wells (21,000 m^3/d) (Dash et al. 2010, Sandhu et al. 2011a). Wells are operated discontinuously depending upon yield and water demand requirements seasonally. The discharge of the 7 – 10 m deep caisson wells ranges from 0.01 to 0.047 m^3/s (Dash et al. 2010, Sandhu et al. 2011a). Figure 2 shows the production wells located along the upper Ganga River and on the 3.3 km long and 190 – 310 m wide Pant Dweep Island. The distance between caisson wells and the upper Ganga riverbank ranges between 10 – 50 m. On Pant Dweep Island, wells are in 15 – 110 m to the Upper Ganga Canal (UGC) receiving Ganga water from UGC, New supply channel (NSC) and Ganga River (Sandhu 2011a, Sandhu 2012a). As the Ganga River water infiltrates into the aquifer towards the abstraction wells, surface water quality is improved. The abstracted water is disinfected at the well using sodium hypochlorite (and in rare cases bleaching powder), and supplied to the distribution network directly during the day and into the "clear water" storage reservoirs at night. A central water work is thus absent and water is distributed from the point of abstraction. Drinking water from the RBF wells is supplied to the main part of the city of Haridwar only, and not to the suburban areas.

Source: Cnes/Spot Image, DigitalGlobe, Global Eye via Google Earth (2013), well locations from Sandhu & Grischek (2013), Sandhu et al. (2011a)

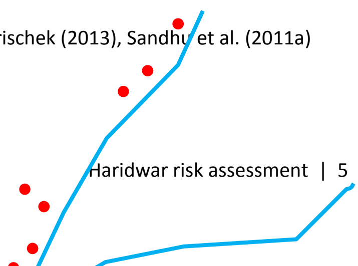


Figure 2 Site map of Haridwar RBF scheme incl. location of cross section A-B

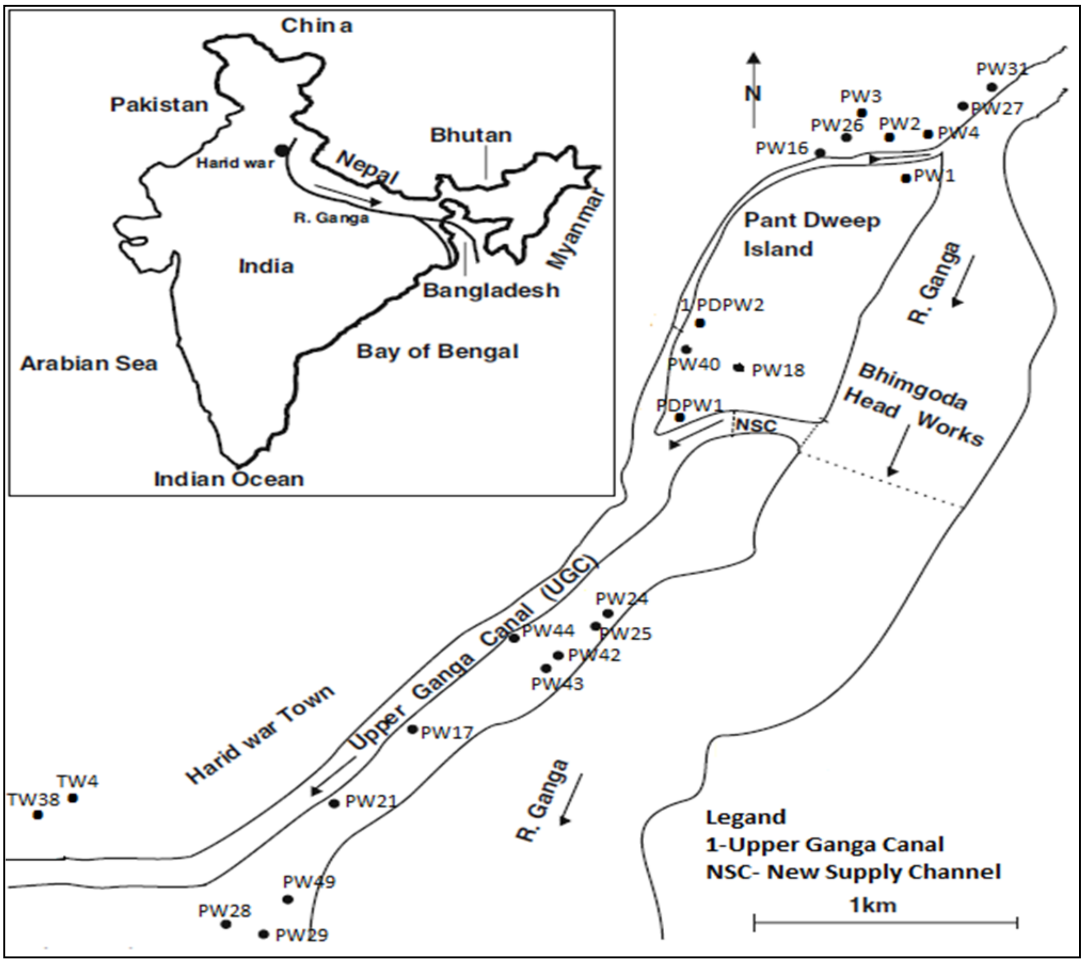


Figure 3 Site map of Haridwar RBF scheme incl. well locations (from Saini 2011)

Table 1 Haridwar riverbank filtration system components

Component	Haridwar system
1. Capture zone	Ganga River (riverbank filtrate) and groundwater
2. Pre-treatment	Riverbank filtration; passage through soil and aquifer; passage through soil and aquifer for groundwater
3. Recharge	Induced infiltration from Ganga River
4. Subsurface storage	Unconfined, alluvial aquifer
5. Recovery	Extraction from aquifer via 22 caisson
6. Post-treatment	Chlorination
7. End use	Drinking water supply

2.5 Post-treatment

Disinfection in Haridwar is performed by adding hypochlorite (and in rare cases bleaching powder) as disinfectant directly at the well heads before discharge into the mains. Additional disinfection points are distributed within the network. This is an important step in drinking water treatment in order to protect the drinking water from microbiological hazards within the distribution network. Indian drinking water guidelines require as minimum concentration of 0.2 mg/L free chlorine at the consumer end point (IDWG 2004). However, when protection against viral infection is required minimum free chlorine concentration should be at least 0.5 mg/l (IDWG 2004).

2.6 Drinking water supply network

The drinking water distribution network in Haridwar is divided into 6 Zones (A, B, C, D, E1 and E2). Approximately 42 % of Zones A, B and C including areas of religious importance have 24 h water supply at "sufficient" pressure and quantity of more than 135 lpcd (liter per capita and day) (JNNURM 2006).

The remaining areas face intermittent supply and scarcity in both water quantity and pressure and thus have considerable increased risk of contamination. Water supply in the most underdeveloped areas is only 1 to 4 hours a day at "insufficient" pressure. More developed Zones including D and E1 are supplied 4 to 6 hours with water at acceptable pressure. It is estimated that in total 32,000 households are connected to the drinking water network. About 47 % of the population lives in informal housing where a total of 450 drinking water stand posts each serve about 20 household. In 2006, about 85% of the population of Haridwar was supplied with drinking water from the mains (JNNURM 2006).

The network compromises 12 storage reservoirs, an estimate of 200 km pipeline network and 8 km of feeder mains from wells. Pipes are laid under and above the ground and sometimes alongside sewer canals (JNNURM 2006). Therefore, traffic and sewer leakage are a high risks to the drinking water quality and human health. Water loss had not been studied yet by the operating municipality to estimate a reasonable figure. However, it is agreed that line and production losses are about 30 % or more in 2006 (JNNURM 2006). A small survey conducted in 2007 by Fischer & Milde (2007) investigated the distribution network in terms of leakages and which technologies can be efficiently used under Indian conditions to detect leakages. A total of 40 leaks were detected in 2007 after the investigation of 11.8 km piping (~5% of the network) but only 8 leaks were resolved. The survey also concluded that the volume of water losses from leaks in the network were negligible compared to the consumer end-point of use due to leaking or defective plumbing fittings (joints, valves, washers etc.) or simply by letting water run out of the taps even when it was not used for any specific purpose because of the extremely low tariff imposed on the consumer.

The major reasons for water and pressure losses listed by the (JNNURM 2006) are:

- Insufficient pumping head,
- Unauthorized tapping,
- Misuse of water,
- Outlived service life,
- General leakage from joints and valves,
- Wastage through stand post by removal of taps,
- Consumption and supply not recorded or documented.

3 Stage 1 Entry level assessment

An entry level assessment is useful for all new managed aquifer recharge projects to reveal the information gaps that need to be filled in order to assess the risk and the prospective measures required. In the case of the established Haridwar riverbank filtration scheme, it was decided to document this entry level assessment to determine whether there are any remaining gaps that need attention, and to provide a prototype report that could be followed for new and existing managed aquifer recharge projects. Table 2 and Table 3 show the completed entry-level risk assessment for the Haridwar RBF site, as per section 4.3 of the MAR Guidelines (NRMMC–EPHC–NHMRC, 2009). The first part of an entry level assessment is viability assessment (Table 2). The second part of the entry level assessment is to determine the degree of difficulty of the project (Table 3). This second checklist of questions identifies the investigations required in order to assess the risk and identify prospective measures required.

Table 2 Haridwar entry level assessment part 1—Viability

	Attribute	Answer
1	**Intended water use**	
	• Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans?	✓ Yes –River bank filtrate from Ganga River intended for use as drinking water supplies.
2	**Source water availability and right of access**	
	• Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	✓ Yes – Ganga river water is readily available, ambient groundwater is also used as source water. Drinking water supplies has highest priority for resources and Haridwar requirement is < 0.4 %* of Ganga base flow.
3	**Hydrogeological assessment**	
	• Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	✓ Yes – The alluvial unconfined, riparian aquifer is in connection with the Ganga River, UGC and NSC.
	• Is the project compatible with groundwater management plans?	✓ Yes – RBF has been used in Haridwar since 1980s as essential part of the drinking water management. Management plans would require adaption if in future a conflict with drinking water supply was identified.
4	**Space for water capture and treatment**	
	• Is there sufficient land available for capture and treatment of the water?	✓ Yes – Existing water treatment and supply throughout wells located along both Pant Dweep Island and Ganga riverbank.
5	**Capability to design, construct and operate**	
	• Is there a capability to design, construct and operate a managed aquifer recharge project?	✓ The Uttarakhand State Water Supply & Sewerage Organization - Uttarakhand Jal Sansthan (UJS) has experience to operate and maintain RBF wells. The Corporation Centre for Riverbank Filtration has expertise to investigate water quantity and quality issues and works closely with UJS Water along with Central Groundwater Board (CGWB) →Go to Table 3

*= drinking water production (64Tm^3/d)/base flow (17.28Mm^3/d)

Table 3 Haridwar entry assessment part 2—Degree of difficulty

Question	Haridwar answers	Investigations required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	No – environmental values of the aquifer include drinking and ecosystem support. The aquifer is the source of water to Haridwar drinking water. Require Stage 2 investigations to assess risks.	Ganga River (source) water quality evaluation for parameters relevant to drinking water
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	No – Ganga River water quality does not meet the Indian drinking water standards for turbidity and pathogens. Require Stage 2 investigations to evaluate hazard attenuation processes during riverbank filtration	Source water quality evaluation, including natural attenuation processes
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon or total nitrogen >10 mg/L, and is soil or aquifer free of macrospores?	No – source water is of poor quality only during monsoon when riverbed scour is high. Additionally, UGC riverbed sediment is excavated annually and clogging has low risk.	None
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	No –groundwater has evidence of fecal contamination in low numbers. Require Stage 2 investigations to evaluate groundwater quality, sources of any contaminants and protective measures required.	Groundwater quality evaluation with reference to (w.r.t.) Indian drinking water guidelines
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	Yes – target aquifer is used for drinking water supply through wells and groundwater dependant ecosystems. Require Stage 2 investigations to assess the risk to groundwater quality.	Groundwater quality evaluation w.r.t. Indian drinking water guidelines
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10000 mg/L, or (b) The salinity criterion for uses of recovered water?	No – mean value of 299 mg/l TDS (Table 5) is expected to be a mix of fresh water from both Ganges River and groundwater.	None
7 Reactions between source water and aquifer		
Is redo status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Yes – generally groundwater is similar to source water in this area. However variations in redox status and temperature may occur seasonally, potentially releasing iron and manganese. Recommend Stage 2 investigations to evaluate geochemical reactions.	Geochemical evaluation

8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Yes – Require Stage 2 investigations to evaluate other users, assess risk to them and risks to the MAR operations.	Identify other users and assess related risks
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	Yes – the unconfined aquifer has a water table of 4 m within an urban area.	None
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	Yes – unconfined aquifer with recovered water used for drinking water supplies. Require Stage 2 investigations to assess the protection of groundwater quality.	Urban land use, wastewater treatment and risk assessment for hazards present in the catchment infiltrating unconfined aquifer
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Yes – aquifer or riverbed can contain ferrous or manganiferous sediment. Require Stage 2 investigations to assess the potential consequences of iron and manganese dissolution.	Geochemical evaluation
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	Yes –sites in Patna, Srinagar and Haridwar have been operated successfully for several years.	None
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Yes – proponents have history of operating drinking water supplies and groundwater exploitation. Structured approach to, and concept of risk management not yet fully implemented. The Corporation Centre for Riverbank Filtration (CCRBF) is assisting with water quality studies	Information for local operator training to be developed, and to identify and address potential risks for drinking water supply

In summary of the Stage 1 assessment, the following investigations listed in Table 4 were identified as necessary in proceeding to Stage 2 if the Haridwar project was conceived as a new project. In reality much of the information is already available from operational experience over a number of years and as studies already undertaken by researchers in the Corporation Centre for Riverbank Filtration (CCRBF). The results of these investigations and operational experience are described in section 4.

Table 4 Summary of Stage 2 investigations required in Haridwar

Issue (relates to questions in Table 3		Investigations required at stage 2	Discussed in section
1	Does source water quality meet the requirements for the environmental values of ambient groundwater?	Source water quality investigation	4.1.1
2	Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Source water quality investigation	4.1.1
4	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Groundwater quality investigation	4.1.2
5	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	Riverbank filtrate quality investigation	4.1.3
7	Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Geochemical evaluation	4.2
8	Are there other groundwater users, groundwater–connected ecosystems or a property boundary near (within 100–1000 m) the MAR site?	Assessment of other users in the vicinity and likely interference effects	4.3
10	Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	Assessment of urban and rural land uses and potential groundwater quality hazards	4.4
11	Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	Geochemical evaluation	4.2
13	Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	Information for local operator training to be developed, and to identify and address potential risks for drinking water supply incl. a water safety plan	5.1,5.2

4 Stage 2 Investigations

4.1 Water quality assessment

Two separate water quality investigations were performed in 2005/06 (Dash et al. 2010, Indian Institute of Technology, Roorkee (IITR) and Sandhu & Grischek 2012, Sandhu (2013), one within the framework of a IITR-master thesis (Saini 2011) and one in 2012 (National Institute of Hydrology (NIH), Roorkee, unpublished data). Eleven samples were taken from the Ganga River/New Supply Canal (NSC), Upper Ganga Canal (UGC), Well 18 (IW18) and 2 monitoring wells in 5 m distance on either side of IW18 along cross section A-B (Figure 2) during monsoon and non-monsoon by Dash et al. (2010). Different surface water, groundwater and riverbank filtration samples were taken by IIT Roorkee, Sandhu (2013), and NIH (2012). Water quality evaluated in this section is an analysis of the combined data set from these studies and interpreted as per 95th percentile except otherwise stated.

4.1.1 SOURCE WATER QUALITY ASSESSMENT

Total hardness varies from 90 to 120 mg/l $CaCO_3$ and is of good quality according to the Australian drinking water guidelines (NRMMC 2011) and mainly calcium and bicarbonate based (Apx Table A.1). The pH-value is 7.8 to 8.7, weakly basic and exceeds the drinking water limit during non-monsoon (Table 5). Values for major ions and TDS (112 – 155 mg/l TDS) are up to 0.5 times lower during monsoon due to dilution and meet the requirements (TDS = 500 mg/l, Ca^{2+}=75 mg/l, Mg^{2+}=30, Cl^{-}=250 mg/l, So_4^{2-}=200 mg/l) for drinking water throughout the year. Nitrate concentration is < 10 mg/l and below drinking water limit of 45 mg/l. Turbidity is strongly influenced by surface run-off and exceeds permissible limit of 5 NTU for drinking water during monsoon when turbidity was 54 times higher than during non monsoon and increased from 39 to 142 NTU (Apx Table A.1).TOC varies from 1 to 1.3 mg/l and is comparatively lower than most European rivers. Additionally GC-MS screening in 2005 did not reveal any noticeable contamination due to organic chemical contaminants (Sandhu 2013). This could however be different for locations downstream of Haridwar that may be influenced by the State Industrial Development Corporation of Uttarakhand (SIDCUL) industrial area which is situated downstream of the RBF wells and considerably away from the river.

The UGC water quality is similar to the Ganga River. However, total and thermotolerant coliform (Th. C.) enumeration in the UGC is 1.6 to 2.2 times higher compared to the Ganga River, which could be attributed to religious bathing in the UGC and presumably discharge of untreated domestic sewage. Total and thermotolerant Coliform bacteria counts increased up to 1.4 log_{10} during monsoon (Dash et al. 2010) and values in the range of 4,300 to 230,000 TC/100 ml and 1,500 to 93,000 Th. C./100ml monsoon (Dash et al. 2010) are clearly above the limit for drinking water of 0 MPN per 100 ml (IDWG 2004).

Table 5 Summary of critical source water parameters derived from Sandhu (2013), NIH (2012) and Saini (2011)

	UGC Monsoon				UGC Non monsoon				IDWG (2004)
Physical characteristics	**n**	**mean**	**95^{th}**	**Stdev**	**n**	**mean**	**95^{th}**	**Stdev**	**limit**
pH (pH units)	3	7.53	7.77	0.25	8	8.20	**8.72**	0.57	**6.5 - 8.5**
Turbidity (NTU)	2	**98.8**	**142.2**	68.2	6	**18.4**	**39.0**	14.3	**5**
Microbiological									
TC (MPN/100mL)	1	**>2400**			11	**9163**	**23500**	8545	**0**
ThC (MPN/100mL)	1	**>2400**			10	**7390**	**22150**	8218	**0**

4.1.2 GROUND WATER QUALITY ASSESSMENT

The groundwater quality was measured once in April 2006 for production well TW 50 (Sandhu 2013), located on the west bank of the UGC across Pant Dweep Island and monthly between January and April 2011 (Saini 2011) in 2 neighbouring (appr. 150 m distance) groundwater tube (see Figure 3 for location). Groundwater from tube well TW 4 and TW 50 is distinctly different from TW 38 in terms of physical characteristics such as pH, EC, TDS, total hardness and alkalinity and for major ions such as calcium, magnesium, sodium, potassium, sulphate and chloride (Apx Table A.2). Major ions and physical parameters that are mainly determined by multivalent ions and bicarbonate are significantly higher in TW 38 than in TW 4. At the given the presence of a multi-aquifer system, it is assumed that groundwater in TW 04, which has lower values for physical characteristics and major ions, is influenced by groundwater recharge (precipitation) and thus, from the unconfined aquifer whereas TW 38 is from the lower, confined aquifer.

Groundwater hardness from the upper aquifer has good quality in terms of total hardness (NRMMC 2011), is weekly basic (8.23) and characterized by a EC of 317 µS/cm, a slightly elevated turbidity (1.24 NTU), low nutrients (TOC = 1.0 mg/l, NO_3^- = 1.7 mg/l and NH_4^+ = 0.1 mg/l) and meets requirements for drinking water except for heavy metals such as iron, copper, lead and cadmium (IDWG 2009) and microbiological parameters. Average iron concentration (n=4, Deepali & Joshi 2012) is 0.73 mg/l and exceeds guideline value. Th.C and TC are less than 2 MPN/100 ml and may exceeded the guideline value of 0 MPN per 100 ml.

Groundwater from the confined aquifer exceeds guideline values for physical and chemical water parameters such as TDS (592 mg/l), total hardness (461 $CaCO_3$/l), alkalinity (422 mg $CaCO_3$/l), calcium (130 mg/l) and magnesium (32 mg/l) as well as for heavy metals and microbiological parameters (Table 6). It is characterized as water with increasing scaling problems in terms of total hardness (NRMMC 2011). The pH-value is neutral. Nitrate concentration is < 10 mg/l and below drinking water limit of 45 mg/l. TOC concentration is very high with 3.7 mg/l and could be an indicator for infiltration of waste or sewage into the aquifer or even the result of lubrication oil used in the vertical line shaft pumps leaking down along the impeller shaft. However, average iron concentration (n=4, Deepali & Joshi 2012) is lower than the upper aquifer and equal to the guideline value (0.3 mg/l). Turbidity is 1.5 NTU and high for groundwater.

Table 6 Summary of critical ground water quality parameters derived from Saini (2011) and Sandhu (2013)

	Saini (2011) TW 4				Saini (2011) TW 38				Sandhu (2013) TW-50		IDWG (2004)
Physical characteristics	**n**	**mean**	**95th**	**Stdev**	**n**	**mean**	**95th**	**Stdev**	**n**	**Value**	**limit**
TDS (mg/L)	3	120.09	144.30	24.66	3	**522.83**	**592.15**	70.42			**500**
TH (mg/L $CaCO_3$)	4	105.91	126.45	19.27	4	**367.80**	**461.88**	101.22			**300**
Alkalinity (mg/L CaCO3)	3	92.67	109.40	17.01	3	**373.33**	**422.00**	49.33			**200**
Major Ions											
Ca^{2+} (mg/L)	4	30.36	37.30	6.71	4	**98.02**	**130.39**	36.48	1	**101.00**	**75**
Mg^{2+} (mg/L)	4	7.15	7.87	0.63	4	**29.37**	**32.41**	2.64	1	18.00	**30**
Metals and metalloids											
Fe (mg/L)*	4**	**0.73****			4***	**0.25-0.37*****					**0.3**
Cu (mg/L)*	4**	**0.05****			4***	**0.009-0.082*****					**0.05**
Ni (mg/L)*	4**	b.d.l.**			4***	b.d.l.***					0.02
Pb (mg/L)*	4**	**0.06****			4***	b.d.l.-**0.462*****					**0.01**
Cd (mg/L)*	4**	**0.003****			4***	**0.01-0.07*****					**0.003**
Microbiological											
TC (MPN/100mL)	4	<2	<2		4	<2	<2				0
ThC (MPN/100mL)	4	<2	<2		4	<2	<2				0

b.d.l. below detection limit
*Deepali & Joshi (2012)
**GW-samples from Industrial area Hetampur, fairly similar EC, higher Ion concentration
***GW-samples from Railway colony and Nirmala Chawni, fairly similar EC, higher Ion Concentration

4.1.3 RIVERBANK FILTRATE WATER QUALITY ASSESSMENT

Water quality improvement during riverbank filtration strongly depends upon travel time in the subsurface but also on the ratio of riverbank filtrate to groundwater. This is determined by the local hydrogeology, hydraulics and site specific factors such as riverbed clogging and distance to the riverbank. The riverbank filtrate is treated with nothing other else than chlorine and supplied directly as drinking water to Haridwar.

4.1.3.1 TRAVEL TIME

Minimum travel times in Haridwar for RBF wells on Pant Dweep Island were estimated using a groundwater flow model and verified with EC as tracer. Estimated travel times are reported to be between 2 and more than 100 days (Dash et al. 2010, Sandhu et al. 2011a). Wells that are located close to the river- /canal bank on Pant Dweep Island (IW16, IW26, IW40) experience shorter average travel times (~30 d) whereas wells such as IW 18 experience travel times between 77 and 126 days (Dash et al. 2010, Sandhu et al. 2010, Sandhu et al. 2011a). The travel time towards the RBF-wells is strongly influenced by discharge and is shorter during monsoon (high discharge), medium during non-monsoon (base flow) and longer during riverbed dredging (no flow in UGC, reduced abstraction rate) (Sandhu et al. 2010).

4.1.3.2 RIVERBANK FILTRATE TO GROUNDWATER RATIO

Generally, the portion of bank filtrate in the wells increases with decreasing distance to the river. Upon their location relative to the river, the RBF wells in Haridwar receive up to > 70 % bank filtrate from the Ganga River on Pant Dweep Island (Sandhu et al. 2012a). The remaining portion is compromised by old bank filtrate (Sandhu et al. 2010) and/or groundwater. Wells in northern direction of Pant Dweep Island along the UGC-riverbank receive less bank filtrate and more landside groundwater.

4.1.3.3 RIVERBANK FILTRATE WATER QUALITY

Critical source water quality parameters such as pH-value, turbidity and microbial counts improved significantly by RBF and groundwater mixing when compared to the Ganga (Apx Table A.3). Overall, the pH-value meets the guideline values for drinking water (IDWG 2009) in non-monsoon and monsoon. Turbidity is reduced below 10 NTU and below the permissible limit for drinking water but reasonably often above the required limit for drinking water (5 NTU) in 6 out of 22 wells. Values for turbidity range from 1.7 to 8.3 NTU in post-monsoon, from 1.4 to 9.3 NTU in pre-monsoon and from 1.6 to 6.7 NTU in monsoon. Turbidity particularly exceeded the guideline value in wells with iron values above 0.6 mg/l. However, turbidity measurements may also be affected by quality control as Dash et al. (2010) reported turbidity values for IW 18 in the range of 0.4 to 0.6 NTU for non and monsoon period whereas recent measurements vary from 1.0 to 2.9 NTU (NIH 2012).

Microbial water quality improved up to 4.7 $\log_{10}$ units (Dash et al. 2010) but is above the required limit for drinking water and requires disinfection. 95^{th} Values for TC and Th. C. in 22 wells are in the range of 0 to 2206 MPN/100 ml and vary from 1 to 2206 MPN/100ml for single wells upon monsoon period and quality control. Generally, RBF in Hardwar is capable of providing water with Th.C. counts below detection limit as seen in wells IW 02, 03, 04, 15, 16, 18 (Dash et al. 2010), 21, 25, 28, 40, 43 and 44. However, microbial contamination ranges inconsistently between period and upon quality control from nearly or below detection limit (0 - 1 MPN/100ml) to 1E02/1E03 in PDPW 01, PDPW 02 and IW 40. This may be explained by 1) effect of monsoon floods resulting in riverbed scour, removal of favourable attachment sites for microorganism, shortened travel times and direct ingression as well as quality control and by 2) contamination by on-sight facilities.

Physical characteristics that were identified as critical in groundwater such as Ca^{2+}, Alkalinity, TDS, iron and manganese are frequently (TDS) to reasonably often above the guideline value for drinking water (IDWG) (Apx Table A.3). TDS guideline values are exceeded mainly in summer pre-monsoon period in wells IW 01 to 04 by up to 22 mg/l. These well receive a presumably large portion of groundwater and show little improvement for TDS, total hardness and alkalinity due to mixing with bank filtrate. Guideline value for total hardness is exceeded in 4 RBF wells with a high portion of groundwater (IW 01 to 04) but also in summer season on Pant Dweep Island in PDPW 01, which is estimated to receive a high portion of bank filtrate (>70 %). Generally, Ganga source water EC, TDS and alkalinity on Pant Dweep Island deteriorated towards the abstraction well, which is assumed to be caused by mineral dissolution (Dash et al. (2010). Another explanation is mixing with groundwater from the semi-confined second aquifer: According to data from Dash et al. (2010), average EC and Ca^{2+} values range in non-monsoon and monsoon period from 250 to 152 µS/cm (factor 1.6) and 32.9 to 21.7 mg/l (factor 1.5) in the Ganga River whereas no significant seasonal change was observed for both monitoring wells (MW1 & MW2) and well IW18 on Pant Dweep Island as values ranged from 338 to 340 µS/cm and 50 to 51.4 mg/l, 367 to 377 µS/cm and 52.8 to 46.2 mg/l and 441 to 432 µS/cm and 57.2 to 60 mg/l respectively.

Mean alkalinity exceeds the requirements for drinking water (IDWG 2009) reasonably often but is below the permissible limit. Limestone is not present at the site but is found 50 km in northern direction around the city of Dehradun in the surface water catchment of the Bandal River, which is a tributary of the Ganga and joins it a few kilometres upstream of Haridwar.

Heavy metals such as copper, nickel, led and cadmium ware not present in the RBF-wells. However, removal of iron and manganese during subsurface passage is insufficient due to unfavourable redox conditions and guideline values are exceeded reasonably often in most of the wells. Highest 95th percentile iron values were in the range of 2.5 mg/l (IW 04), 3.7 mg/l (IW 02) and 5.72 (IW 25) during monsoon and coincide with elevated turbidity values. However, median iron values in IW 02 and IW 25 are 0.3 and 0.04 mg/l and average iron concentration is equal or below the guideline limit. Manganese was found in concentrations between 0.1 and 0.68 mg/l with median values in wells that exceed guideline value from 0.01 to 0.39 mg/l.

In order to evaluate the disinfection in Haridwar, residual chlorine concentration was investigated as point measurement at 17 locations in the Mayapur district (Zone C) distribution network by Grossman & Rother (2008). Total and free chlorine was measured each using chlorine test strips. The investigation showed that disinfection is generally insufficient; free chlorine median concentration was 0.07 mg/l (minimum requirement is = 0.2 mg/l) and 95 % of the samples had a concentration below 0.5 mg/l.

4.2 Geochemical evaluation

In the Ganga River total organic content (TOC) is very low (1.0 – 1.3 mg/l) indicating low potential for iron or manganese dissolution due to microbial degradation of biodegradable organic carbon in the riverbed. However, the riparian aquifer is oxic to anoxic with dissolved oxygen concentration of 1.3 mg/l (95th percentile, n=5) and nitrate concentration in the range of 1 to 10 mg/l. Although someone would not expect such oxygen depletion caused by TOC in the Ganges River, unknown organic soil content or iron-rich minerals in the riverbed or the aquifer below can cause oxygen depletion.

Sediment leaching and removal efficiency for pathogens was investigated in column test with sediment from the river bed and the aquifer (Dash et al. 2010). Tests were performed with local canal water under oxic redox conditions in the laboratory. Leaching of EC as function of travel time was found to be exponentially and very strong for the riverbed sediment and linear and rather weak for the aquifer. Thus, the increase in electric conductivity towards the wells during RBF was explained by mineral dissolution (Dash et al. 2010). An alternative explanation is mixing with groundwater from the semi-confined aquifer. The annual average increase per travel distance equals 0.4 to 0.7 µS/(cm m) from the point of infiltration towards the monitoring wells (252-315 m) and 12.9 to 19.4 µS/(cm m) from the monitoring wells towards the well (5 m) (data from Dash et al. 2010, not shown). This corresponds to an exponential increase in EC whereas Dash et al. (2010) observed linear mineral dissolution for aquifer material. Thus, the sudden increase in EC (TDS, Alkalinity) could be explained by upward flow of groundwater.

4.3 Assessment of other groundwater users

Pant Dweep is a lowly-populated area primarily used as meeting point for the Kumbh Mela, the mass Hindu pilgrimage. There are no other residential groundwater wells reported on Pant Dweep Island or in the direct proximity of wells located along the Upper Ganga River (UPJN 2006). This area has a 24 h drinking water supply and there is no need for residents to use dug wells. Based on the hydraulic conditions of the riparian aquifer, the abstraction of riverbank filtrate is sustainable as the aquifer is recharged immediately by the Ganga River water.

4.4 Assessment of urban land uses and risks to groundwater quality

According to the Haridwar Master Plan (HMP 2001), Pant Dweep Island with an area of 575 ha is a designated meeting point for the Ardh Kumbh Mela and the Kumbh Mela. Every 6 years more than 5 million Hindus pilgrim to Haridwar to bathe the Ganga River and take part in various ceremonies (Dash et al. 2010). In addition to the Mela, ~550,000 pilgrims visit the island every day to bathe in the Ganga River (Dash et al. 2010).

Risks that arise from mass gathering such as Kumbh Mela are:

- Insufficient sanitation and unsanitary human defecation in the immediate area around the wells due to non-existent well head or source protection zones
- Coliform and thermotolerant coliform peaks in the Ganga River,
- Peak water demand resulting in reduced travel times in the aquifer and decreased aquifer treatment
- Inaccessibility of wells and instrumentation during extreme flood events (e.g. September 2010)
- Illegal tapping and unauthorized access to wells.

Pant Dweep is an area with open-scrub vegetation (HGM 2004). The national highway from Roorkee to Dehradun is within the well catchment area and posses another unknown potential risk to the groundwater quality. Vehicular accidents in the vicinity of some wells are common. Consequently, fuel and oil spills are a general threat to the groundwater quality. Additionally, the infiltration of non treated surface run-off can contain high levels of polycyclic hydrocarbons, zinc, cadmium, copper and led from abrasion of tyres, leakage from operation fluids, brake dust and exhaust fumes. All of these risks are discussed in the next section.

The Shivalik foot hills are populated and defined by the presence of dense to fairly dense rain forest that turns into open scrub vegetation in SW-direction (HGM 2004). Ranipur and State Industrial Development Corporation of Uttarakhand(SIDCUL) are located at the bottom of the foothills in N to NW direction from central Haridwar. Ranipur district is located around the Bharat Heavy Electricals Limited (BHEL) heavy electric and power plant equipment manufacturer. As identified per section 4.1.2, groundwater in this area exceeds values for iron, copper, lead and cadmium.

4.5 Well inspection

Some of the wells caisson suffers damages caused by settling and flooding as cracks and openings are visible near the surface (e.g. IW 40). Well IW 40 is also used as public washing place and wash water can directly ingress into the well caisson and causes microbial contaminations. Some wells have no caisson coverage and caisson intake is left open. Other wells are used for housing but without sufficient sanitation. Cattle, insufficient sanitation and unsanitary defecation practises during religious events near the water supply wells are common. However, the practical implementation of source protection zones (SPZs) on the ground cannot be realized easily because it is extremely difficult to acquire land for SPZs. This is more a socio-cultural issue than a technical issue.

4.6 Summary

In conclusion, several years of operation and various studies have improved the understanding of the hazards for Haridwar riverbank filtration. However some specific questions remain concerning groundwater quality, capture zones for RBF well, redox geochemistry and pathogen capabilities.

5 Stage 3 Risk assessment

5.1 Maximal risk assessment

The risk assessment is presented in the order of the twelve key hazards outlined in the Australian MAR Guidelines (NRMMC–EPHC–NHMRC 2009). A semi-quantitative risk assessment was performed for each of the hazards for human health and environmental endpoints, with green, orange and red indicating low, uncertain and high risks respectively (Table 8). The white boxes indicate that that hazard does not apply to that endpoint.

The maximal risk assessment for the human health end point was conducted by comparing Ganga River and groundwater water quality data for hazards 1 to 7 to the Indian Standards for Drinking Water (IDWG 2004). For the environmental endpoint, the environmental value with most stringent water quality requirements for the identified hazards was "drinking water source without conventional treatment but after disinfection" (class A, water quality targets according to the Central Pollution control Board (CPCB) for water bodies). Therefore the quality of Ganga water was compared to water quality targets according to the Central Pollution control Board (CPCB) (Table 7). For hazards 8 to 12, the risks were assessed based on their potential impacts on the aquifer or biosphere as described in the Australian MAR Guidelines.

Table 7 Criteria for the environmental endpoint risk assessment

Designated best use	Class of water	Criteria
Drinking water source without conventional treatment but after disinfection	A	• Total Coliform Organism MPN/100ml < 50s • pH between 6.5 - 8.5 Dissolved Oxygen >6mg/l • Biochemical Oxygen Demand 5 days @ 20°C < 2mg/l
Outdoor bathing (organized)	B	• Total Coliform Organism MPN/100ml < 500s • pH between 6.5 - 8.5 Dissolved Oxygen >5mg/l • Biochemical Oxygen Demand 5 days @ 20°C < 3mg/l
Drinking water source after conventional treatment and disinfection	C	• Total Coliform Organism MPN/100ml < 5000 • pH between 6 to 9 • Dissolved Oxygen >4mg/l or more • Biochemical Oxygen Demand 5 days @ 20°C <3 mg/l

Source: CPCB

Table 8 Maximal risk assessment for Haridwar, India

	MAR Hazards	Human endpoint – drinking water	Environmental endpoint – aquifer
1.	Pathogens – present in high levels	H	H
2.	Inorganic chemicals – Fe, Mn, total hardness and alkalinity exceeded guideline values	U	U
3.	Salinity and sodicity – both surface water and groundwater are fresh	L	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – none likely present at levels of concern for drinking water	L	L
5.	Organic chemicals – presence of pesticides and organic hydrocarbons	U	U
6.	Turbidity and particulates – source water is very turbid during monsoon (operational risk)	H	H
7.	Radionuclides – low potential for release from aquifer sediments or presence in the source water	U	U
8.	Pressure, flow rates, volumes and groundwater levels – enhanced gravitational recharge in an unconfined aquifer		L
9.	Contaminant migration in fractured rock and karstic aquifers – this is an alluvial aquifer		L
10.	Aquifer dissolution and stability of well and aquitard – pumping wells observed to be stable after 30 years		L
11.	Aquifer and groundwater-dependent ecosystems – natural existing groundwater flow through riparian aquifer		L
12.	Energy and greenhouse gas considerations – sustainable low energy gravitational system.		L

(1) Pathogens:

For pathogens, it was found that faecal contamination was evident in the source water at high levels due to untreated waste water discharge and will have to be removed to protect human health and the environment.

(2) Inorganic chemicals:

Iron concentration is low but causes deterioration in taste. Higher concentrations may stain laundry and cause incrustations (NRMMC 2011). No risk to human health unless iron values exceed 3 mg/l (NRMMC 2011). However, residual iron and manganese concentration can cause chlorine depletion, as chlorine is a strong oxidant. Groundwater pollution by heavy metals in the proximity of the SIDCUL area is of low risk as RBF wells are located further upstream on the opposite site of the canal bank.

(3) Salinity and sodicity:

(3) is of low risk since TDS is <600 in both groundwater and surface water.

(4) Nutrients:

Nutrients are of low risk since TOC is low (<1.3 mg/l) and nutrients are below limits for drinking water.

(5) Organic chemicals:

(5) are a potential hazard to human health in terms of potential oil and fuel spills along the national highway as well as infiltration of stormwater containing polycyclic hydrocarbons. This is rated as uncertain as not sufficient data is available and further investigations are required to determine the need for any measures to protect human health and the environment. Only a small number of industries dealing with organic chemicals are found upstream of Haridwar and the presence of organic chemicals including pesticides in the Ganga River was not confirmed by a GC-MS screening in 2005 (HTWD unpublished).

(6) Turbidity and particulates:

(6) turbidity possesses a high risk for human health and the environmental endpoint as source water is very turbid particularly during monsoon period and values are above both guideline values.

(7) Radionuclides:

Radionuclides are unlikely to be present in high levels in the quaternary, alluvial aquifer and is expected to pose a low risk but absence of data only allows risk to be declared unknown.

(8) Pressure, flow rates, volumes and groundwater levels:

Hydraulic hazards are assessed to present a low risk, because the riparian aquifer is unconfined, recharge is only induced and limited not by pressure but by abstraction rate and riverbed clogging. If clogging persisted abstraction could draw more groundwater from the unconfined aquifer beneath the city resulting in water quality deterioration. However very high flows in the monsoon season scour the stream and the canal bed and restore hydraulic conductivity and thus, prevent the accumulation of a clogging layer. This itself can cause reduced travel times.

(9) Contaminant migration in fractured rock or karstic aquifers:

The recharged aquifer is alluvial and the risk of this is low.

(10) Aquifer dissolution and stability of well and aquitard:

The unconfined, recharged aquifer is compromised by alluvial sand and gravel so this has low potential risk for aquifer dissolution or well stability.

(11) Aquifer and groundwater-dependent ecosystem:

(11) is of low risk as there is an already existing natural Grange River recharge into the alluvial aquifer.

(12) Energy and greenhouse gas considerations:

RBF is considered a sustainable low energy gravitational system that uses natural attenuation processes to reduce surface treatment, energy and greenhouse emissions as such compared to engineered treatment options the risks are considered comparatively low.

5.2 Residual risk assessment

The Stage 2 semi-quantitative residual risk assessment for the Haridwar recharge system was performed using the same approach as for the maximal risk assessment but with inclusion of all the barriers including riverbank filtration as natural treatment step and chlorine disinfection. Overall, the quality of the source water improved after riverbank filtration. Existing operational data indicates sufficient removal of turbidity and pathogens, although the effectiveness of the disinfection is questionable given the low disinfection residuals in the distribution system. Contaminant migration from human defecation during Kumbh Mela and risk associated with floods such as direct contamination into wells remain high risks to human health. Additionally, stormwater infiltration and pesticides need to be investigated to confirm the concentrations in the water supply.

Table 9 Residual risk assessment for Haridwar, India

	MAR Hazards	Human endpoint – drinking water	Environmental endpoint – aquifer
1.	Pathogens – present in high levels	H	H
2.	Inorganic chemicals –iron, manganese, alkalinity, TDS and total hardness exceed guideline value reasonably often but are below health guideline values	L	L
3.	Salinity and sodicity – both surface water and groundwater are fresh	L	L
4.	Nutrients: nitrogen, phosphorous and organic carbon – none likely present at levels of concern for drinking water	L	L
5.	Organic chemicals – presence of organic hydrocarbons	U	U
6.	Turbidity and particulates – source water is very turbid during monsoon (operational risk)	H	H
7.	Radionuclides – low potential for release from aquifer sediments or presence in the source water	U	U
8.	Pressure, flow rates, volumes and groundwater levels – enhanced gravitational recharge in an unconfined aquifer	L	L
9.	Contaminant migration in fractured rock and karstic aquifers – this is an alluvial aquifer		L
10.	Aquifer dissolution and stability of well and aquitard – pumping wells observed to be stable after 30 years		L
11.	Aquifer and groundwater-dependent ecosystems – natural existing groundwater flow through riparian aquifer		L
12.	Energy and greenhouse gas considerations – sustainable low energy gravitational system.		L

(1) Pathogens:

For pathogens, it was found that faecal indicators were evident in the riverbank filtrate at levels above the drinking water guideline. This is attributed to 1) insufficient removal efficiency during subsurface passage, 2) contamination by on-site facilities and the absence of source protection zones (SPZs) and 3) effect of monsoon floods.

RBF-well IW 40 is an example for contamination by on-sight facilities. The well caisson suffers damages caused by settling and flooding as cracks and openings are visible near the surface. The well is also used as public washing place and wash water can directly ingress into the well caisson and causes microbial contaminations. As summarized and highlighted by Howard et al. (2003), general insufficient sanitation, well house housing and cattle around the well combined with poor well maintenance and well designs such as open lids, no coverage, no well head sealing and leakages offer especially during wet season multiple ingressions points for surface runoff and whatever it might contain. Unsanitary defecation and the use of unsealed pit latrines in the direct proximity of the RBF wells during Kumbh Mela are a potential contamination although sampling did not coincide with the last Khumb Mela in 2010. Seepage from unsealed pit latrines into the sandy to gravely shallow aquifer is likely in the absence of a protective clay layer and pathogen removal may insufficient after short travel times towards the RBF well. Furthermore, monsoon-floods poses a risk for direct contaminations into the wells as well as indirect effects on water quality improvement through riverbed scour, enhanced recharge, flow in unsaturated zones, remobilisation through shear forces and decreased travel times (Grischek 2011).

The highest extreme monsoon flood-event (in terms of surface water level of the Ganga and corresponding wide-spread inundation of river-side land) was recorded at 296 m above sea level by the gauging station of the Central Water Commission (CWC), located around 1 – 2 km upstream of Pant Dweep Island, on 19 September 2010 (CWC 2010). During that monsoon (August – September 2010), most of the abstraction structures that pump-out water directly from rivers in the north Indian mountainous state of Uttarakhand, were also submerged. Around the period 18 – 21 September 2010, the ground surface around some of the RBF wells in Haridwar was inundated by the flood-waters of the Ganga (from North to South: IW 31, 27, 42, 43, 25, 24; the remaining wells are protected by a flood-protection embankment along the Ganga). As long as these wells were inaccessible due to the flood-water surrounding them, they ceased operation. This lead to an interruption of the water supply for at least 2 – 3 days because the well operators were forced to abandon the wells and shut down the pumps (due to the inclement danger from the approaching flood-water). After the flood-water receded, a visual inspection by UJS revealed damage to the base of the wells. It was also visually observed that the water in the wells had become turbid, presumably due to direct seepage of the flood-water down the well shaft, or through cracks and fissures in the wall of the caisson. There after the turbid water was pumped out of the wells via a bypass, until no more visible turbidity was observed. On Pant Dweep Island, only IW 18 has a generator that provides back-up power to the pumps and disinfection system. Of the remaining wells, only IW 24 and 25 are provided back-up power together from one generator (the wells are located close to one-another) and IW 42 and 43 are together provided back-up power by another generator. However, during that flood these generators could not be accessed / operated because they were also inundated by the flood. Thus this highlights the fact that extreme flood events and subsequent direct contamination and inaccessibility of the wells are a risk in Haridwar. Accessibility to the wells during a flood in Haridwar is important because currently there is no on-line system to monitor bacteriological contamination to the wells and turbidity peaks cannot be easily detected in time.

(2) Inorganic chemicals:

Iron and manganese concentration exceed reasonably often the guideline value of 0.3 mg/l and 0.1 mg/l (IDWG 2009) and can cause deterioration in taste and odour. Higher concentrations may stain laundry and cause incrustations (NRMMC 2011). WHO (2011) has no health guideline value proposed for iron. Insufficient data is available to determine health-based guideline value (NRMMC 2011). Mild adverse effects in animals after long term iron exposure and iron poisoning in children by medical iron supplement have been observed. Australian guidelines consider no risk to human health unless iron values exceed 3 mg/l (NRMMC 2011). Iron present in this concentration will cause deterioration in colour in taste and is unlikely to be ingested in large quantities that cause health risks. However, median iron values in IW 02 and IW 25 are 0.3 and 0.04 mg/l and average iron concentration is far below concentration of health concern (NRMMC 2011). Manganese was found in concentrations between 0.1 and 0.68 mg/l. A health-based guideline value of 0.25 mg/l was derived when considering that 10 mg/d can be safely consumed (WHO 1973) and 10% of daily intake is attributable to the consumption of 4 l of water (NRMMC 2011). Median values from wells that exceed guideline value are between 0.01 and 0.39 mg/l. Average values from wells PDPW 01 and IW 16 are above health-based guideline values. However, manganese is the least toxic element (IPCS 1981) and measured manganese concentrations are above values that cause deterioration in taste and odour and water with such concentrations of manganese is unlikely to be consumed in quantities that may cause health risks. In summary, risk of iron and manganese for water quality in terms of colour, smell and taste is high. However, iron and manganese concentrations are below levels that pose a risk to human health and risk associated with iron and manganese is rated low.

Alkalinity exceeds guideline value reasonably often in 9 out of 22 wells. Alkalinity is at its maximum in summer pre-monsoon period. Values above the guideline value range from 219 to 414 mg $CaCO_3$/l but are below the maximum permissible limit in the absence of an alternative water source of 600 mg/l (IDWG 2009). However, alkalinity is of low risk unless alkalinity exceeds in terms of TDS the palatability of drinking water (1,200 mg/l, WHO 2011). High alkalinity gives water an unpleasant soda-like taste and may cause carbonate incrustation if ph-value is not adjusted according to the carbonic acid equilibrium. In America, Germany and Australia alkalinity is only regulated in terms of TDS, EC and hardness.

(3) Salinity and sodicity:

Generally, (3) is of low risk since TDS is <500 in the RBF wells. However, salinity frequently exceeds the guideline value slightly (<521 mg/l) in wells IW 01, 02, 03, 04 that receive a high portion of groundwater but is below the permissible limit of 2000 mg/l. WHO (2011) rates a TDS concentration < 600 mg/l as good (>1,200 mg/l is rated unacceptable) and TDS levels in major Australian cities range from < 100 to > 750 mg/l (NRMMC 2011).

(4) Nutrients:

Nutrients are of low risk since TOC is low and nutrients such as nitrate and ammonia are below limits for drinking water.

(5) Organic chemicals:

(5) are a potential hazard to human health in terms of potential oil and fuel spills along the national highway as well as infiltration of stormwater containing polycyclic hydrocarbons. This is rated as uncertain as not sufficient data is available and further investigations are required to determine the need for any measures to protect human health and the environment. The presence of organic chemicals in the Ganga River was not confirmed by a GC-MS screening in 2005 (HTWD unpublished).

(6) Turbidity and particulates:

The guideline value for turbidity was exceeded frequently particularly by wells with higher iron and manganese concentrations. Values above the guideline value were between 5.4 and 8.3 NTU in post-monsoon (Oct – Dec), 8.1 and 9.3 NTU in pre-monsoon (Jan – Mai) and 5.2 and 6.7 NTU in monsoon (Jun – Sep). Median and percentile 95^{th} of the 95^{th} percentiles values measured in 22 wells for post, pre and monsoon were between 1.71 and 3.34 NTU and 5.84 and 8.2. An explanation for high turbidity values can be the iron and manganese precipitation contact with dissolved oxygen inside the bottom entry well.

As turbidity is an indicator for pathogens and particularly of importance for protozoan pathogens that are resistant against chlorine, turbidity as indicator for (1) was rated as high risk to human health.

However, the Indian drinking water guideline (IDGW) sets a maximum permissible limit of 10 NTU in the absence of alternative water sources.

(7) Radionuclides:

Radionuclides are unlikely to be present in high levels in the quaternary, alluvial aquifer and the Shivalik sandstone formation. It is expected to pose a low risk but absence of data only allows risk to be declared unknown.

(8) Pressure, flow rates, volumes and groundwater levels:

Hydraulic hazards are assessed to present a low risk, because the riparian aquifer is unconfined, recharge is only induced and limited not by pressure but by abstraction rate and riverbed clogging. If clogging persisted abstraction could draw more groundwater from the unconfined aquifer beneath the city resulting in water quality deterioration. However very high flows in the monsoon season scour the stream and the canal bed and restore hydraulic conductivity and thus, prevent the accumulation of a clogging layer. This itself can cause reduced travel times. In case of floods, Sandhu et al (2012) estimates minimum travel times of < 1 to 30 days.

(9) Contaminant migration in fractured rock or karstic aquifers:

The recharged aquifer is alluvial and the risk of this is low.

(10) Aquifer dissolution and stability of well and aquitard:

The unconfined, recharged aquifer is compromised by alluvial sand and gravel so this has low potential risk for aquifer dissolution or well stability.

(11) Aquifer and groundwater-dependent ecosystem:

(11) is of low risk as there is an already existing natural Grange River recharge into the alluvial aquifer.

(12) Energy and greenhouse gas considerations:

RBF is considered a sustainable low energy gravitational system that uses natural attenuation processes to reduce surface treatment, energy and greenhouse emissions as such compared to engineered treatment options the risks are considered comparatively low.

5.3 Quantitative microbial risk assessment

A quantitative microbial risk assessment (QMRA) is a method to estimate the risk/consequences to human health from an exposure to infectious pathogens (e.g. drinking water). Since there is a variety of infectious pathogens in water, the QMRA is commonly performed for particular reference pathogens that are waterborne transmitted, highly pathogenic, difficult to treat, present in high numbers, immunity resistant or vaccination only available to minor part of the population and for which dose-response relationships exist from epidemiological studies.

Pathogens remain the greatest risk to human health (Table 9) and so a QMRA was performed to assess the risk to human health based on three reference pathogens *E.coli O157:H7* (for bacteria), *Cryptosporidium* (for protozoa) and *rotavirus* (for viruses) (WHO 2011). E.coli O157:H7 was used instead of campylobacter as there are indirect measurements available from direct Th. C. measurements. Cryptosporidium was used similar to the approach in Uganda (Howard et al. 2006) and Rotavirus because it is considered the main cause for severe child diarrhoea in developed and developing countries (Parashar et al. 2003, 2009). However, rotavirus vaccines have been introduced to India and are expected to reduce incidences associated with rotavirus and thus reduce child mortality due to diarrhoeal diseases (Morris et al. 2012). Once this vaccination is available to a majority of the population, immunity to rotavirus will make it not suitable as reference pathogen anymore. This risk is assessed based on the disease burden associated with an exposure (e.g. drinking water) and is quantified as years life lost due to the disease based on disability adjusted life years (DALY's) and as risk per person per year (pppy) consistent with the approach developed by the World Health Organisation

The water exposure was calculated from the pathogen enumeration in the final drinking water consumed and considers RBF and disinfection treatment. Where no direct measurements existed, $\log_{10}$ removal by RBF was assigned based on field and lab studies from literature. Disinfection efficiency was assigned according to Australian guidelines for water recycling (NRMMC–EPHC–AHMC 2006). In opposite to the approach in Uganda (Howard et al. 2006), no additional $\log_{10}$ removal were assigned for disinfection during time in the drinking water network as residual free chlorine was found to be generally low with a median of 0.07 mg/l, below the minimum value of 0.2 mg/l (Grossman & Rother 2008).

Note that the drinking water is a mixture between water supplied by groundwater wells and riverbank filtration wells. However, areas in close proximity to groundwater wells are most likely supplied mainly with groundwater and areas in close proximity to RBF wells mainly with riverbank filtrate. As there is no reliable microbial water quality data available yet for groundwater, the groundwater quality is assumed of being similar to the riverbank filtrate. Therefore, no water quality improvement/deterioration was assigned due to 1) mixing with groundwater towards the RBF wells and 2) mixing with groundwater in the distribution network. Hence, the microbial risk assessment was conservatively conducted for areas supplied to 100 % by water from the RBF wells.According to EPA (2011) the recommended value for daily drinking water ingestion rate per capita is 2.9 litres as average over all ages. Risk assessment studies in areas in India affected by high arsenic concentrations in drinking water consider ingestion rates of 4.5±2.4 l/d (Pokkamthanam et al. 2011), 4.05l/d (Kumar et al. 2011) and 3.12±1.17 l/d (Hossain et al. 2012). In this study, a conservative ingestion in litres of 4 l/d was assumed.

The risk of infection was calculated based on summed dose-response models for both monsoon and non-monsoon period. The annual risk of infection was calculated based on the assumption that each day represents an independent and identical risk (Haas et al. 1999, Petterson et al. 2006).

The probability of illness based on an exposure was then associated with the disease burden per case in DALY's. DALY's per case due to a disease were calculated for *i* outcomes as follows:

$$\text{DALY's per case} = \sum_{n=1}^{i} \text{severity}_i * \text{duration}_i * \text{occurence}_i$$

Figures for severity weights and durations are mainly based on data from the Netherlands (Havelaar & Mesel (2003). To be consistent with existing literature, health consequences beyond diarrhoea and death from diarrhoea, such as haemolytic–uraemic syndrome (HUS), end stage renal disease (ESRD) and immunocompromised –related symptoms for protozoa were excluded (For example the estimated HIV prevalence in India of 0.31% (GoI 2010), in Australia of 0.1 % (The Kirby Institute 2011) and the Netherlands of 0.12 % (HIV monitoring) is low compared to 8 % in Uganda (Howard et al. 2006)). Years life lost due to death were assigned to the life expectancy at birth in India of 65 yrs for 2011 (World Bank 2012a). This is similar to the approach in Uganda (Howard et al. 2006), where life expectancy was 46.4 yrs in 2003 (WHO 2003) and increased to 54 in 2011 (World Bank 2012a). Life expectancy at birth in Australia and the Netherlands was 82 and 81 yrs in 2010 (World Bank 2012a). As believed by Howard et al. (2006), the use of local life expectancy rather than the weighted average of age of death by age group (see Havelaar & Melse 2003) reflects the importance of high cases associated diarrheal diseases that primarily affect children under 2 years (and the elderly) (Hunter 2003, Riley et al. 1983). This is reflected by figures of infant mortality (< 1 yr) in 2008 – 2012 in India of 47 and Uganda of 58 per 1000 live births, which are 12 to 20 times higher compared to 4 and 3 per 1000 live births in Australia and the Netherlands (World Bank 2012b). Note that infant mortality and life expectancy in India varies greatly between rural and urban areas but also between different states. Total infant and child mortality in Haridwar is 72 and 94 per 1000 live births. Figures for urban and rural areas are 47 and 81 (infant mortality) 54 and 111 (child mortality) per 1000 live births (GoI 2011a). Life expectancy varied from 58 years in Madhya Pradesh to 60 in Uttarakhand and 74 in Kerala in 2002 to 2006 (GoI 2011b). Numbers for Uttakharand were not available so that national life expectancy was used instead.

The susceptibility fraction is the proportion of the population susceptible to developing disease following infection. A susceptibility fraction of 100 % for *E.coli* and *Cryptosporidium* is based on the conservative assumption that everyone is susceptible to illness. The figure of 13% for rotavirus is based on infection being common in young children (< 6 years); causing illness and also provides subsequent immunity. The 13% equates to the percentage of the population aged less than six years (GoI 2011c, Havelaar and Melse 2003, NRMMC–EPHC–AHMC 2006).

WHO (2011) defines a upper tolerable reference level of risk of 1.0E-06 DALY's per person per year as health outcome target for water safety plans for locations where the overall burden of disease is mainly derived from waterborne exposure. The reference level of risk corresponds to a 70 year life time waterborne cancer risk. However, WHO (2011) also notes that this tolerable burden of disease target may not be achievable in some circumstances and locations in the near future. In these cases, a less stringent acceptable risk per person per year may be more realistic and still consistent with the goals of providing high-quality, safer water.

WHO (2008) projects the risk associated with diarrheal diseases in South-East Asia to 0.00533 (baseline scenario) per person per year for 2015. The National Commission on Macroeconomics and Health (NCMH 2005) projects the burden of diarrhoeal diseases in India to 0.0218 DALY's for 2016. This risk is significantly higher than the WHO projections for SE-Asia and India is a major contributor to the regional burden of diarrheal diseases. However, the Million Death Study (Bassani et al. 2005) and WHO (2012) give reason to believe that the burden of diarrheal diseases given by NCMH (2005) is still underestimated. NCMH (2005) calculated the burden of disease based among other data on a children under 6 years mortality of 195,046 (SBHI 2002) whereas the Million Death Study (Bassani et al. 2005) projected an average of 0.3 Million deaths national wide based on a nationally representative survey of 1.1 million households between 2001 and 2003. WHO (2012) estimates the children aged < 5 mortality for 2010 to 220,480. Further, life expectancy at birth has increased from 62.9 (NCMH 2005) to 65 (World Bank 2012a). As years life lost (YLL) account for 98.2 % of the calculated DALY's and years life lost due to disability (YLD) only 1.8 % (NCMH 2005), the figure for YLL in India for the age group of < 6 years was recalculated using the diarrheal prevalence derived from the Million Death Study (Bassani et al. 2005) together with a life expectancy of 65 (World Bank 2012a) to gain a current approximate figure of 0.027 DALY's. This estimated current incident of diarrheal diseases in India is more than 4 log_{10} units above the upper limit of the current WHO (2011) reference level of risk of 1.0E-06 DALY's as health outcome for water safety plans. It seems therefore reasonable to adjust the current WHO (2011) reference level of risk to a less stringent, economically and technically more viable value of 0.005 DALY's, the regional SE-Asia incidence for diarrhoeal diseases rather than the national diarrhoeal incidence of 0.027 DALY's.

5.3.1 E.COLI O157:H7

The risk assessment for *E.coli* O157:H7, which is present in the Ganga River (Hamner *et al*. 2007), was based on data from Sandhu 2013, NIH (2012) and Saini (2011) for well IW 18 and 40 as they are characterized by their location to receive a high portion of bank filtrate, intensive studies on travel times and water quality is available and they are assumed to represent both subsurface transport conditions with short (2 – 30 d) and long (77 – 88) minimum travel times.

Table 10 Th. C enumeration in RBF wells IW 18 and 40 in MPN/100ml

Well	IW 18		IW 40	
	mon	Non-mon	Mon	Non-mon
Median	0	3	2	2
95th percentile	6.8	3	13.8	83.1
Min	0	0	0	0
Max	8	3	17	93
Number of samples	4	8	6	12

Given the detected presence of the thermotolerant coliform (Th. C) in water abstracted by RBF wells, the risk assessment is determined by these values. However, the fraction of Th. C compromised by *E. coli* strongly depends on the method of enumeration (Hamilton et al. 2005) and water pollution (e.g. by proportion of sewage to wastes of animal and bird origin in the water). The range of values for the *E. coli*/Th. C ratio from studies with freshwater is shown in (Table 11). It is conservatively assumed that 90% of the Th. C enumeration is compromised by *E. coli* (Hamilton et al. 2005) and that 8% of all *E. coli* are pathogenic (Haas et al., 1999). The Th. C enumeration from the surveillance data are therefore multiplied by 0.90 and then by 0.08. The figures in the in the risk assessment are expressed in organisms per 100 millilitres and therefore this figure is multiplied by 10 in order to gain a final figure.

Table 11 Different E.coli/Th. C ratio in freshwater

Water sample	EC/ThC	E.coli enumeration	Reference

freshwater	0.63-0.77	m-Tec	Rasmussen & Ziegler (2002)
diff. polluted freshwater	0.63	m-Tec	USEPA (2002)
diff. polluted freshwater	0.77	Bio-Rad	Garcia-Armisen (2007)
diff. polluted freshwater	0.80	m-Tec	Hachich et al. (2012)
polluted freshwater	0.82-0.85	EC MUG	Bordalo (1993)
small urban streams	0.84-1.04	Colilert, m-FC-NA-MUG	Hamilton et al. (2005)

Source: modified from Hamilton et al. (2005)

The exposure was transformed into an estimated infection risk based on a dose-response relationship. Usually, the dose-response for *E. coli* O157:H7 is based on Shigella, which is estimated to have a 1.0E-03 risk of infection from exposure to a single organism (Rose and Gerba, 1991; Haas et al., 1999) in (Howard & Pedley 2005). However, the study by Haas et al. (2000) suggests that assuming the dose-response on Shigella is inappropriate and may underestimate the dose response for *E. coli* O157:H7. In this study, the model approach from Haas et al. (2000) was used to calculate the probability of an infection.

The risk of developing illness once infected was assessed as 25 % based on the morbidity ratio for Shigella (Haas et al., 1999). The disease burden for *E. coli* O157:H7 was calculated as summed DALY's of watery diarrhoea, bloody diarrhoea and death from diarrhoea to 0.46 DALY's (Table 12).

Table 12 Disease burden per case in DALY's for E.coli O157:H7

Outcomes	Severity	Duration		Occurence		DALY's
Watery diarrhoea	0.067[1)]	3.4[1)]	d	53[1)]	%	0.00033
Bloody diarrhoea	0.39[1)]	5.6[1)]	d	47[1)]	%	0.00281
Death from diarrhoea	1[1)]	61.8	a	0.7[2)]	%	0.43260
				Disease burden per case		0.46

[1)]Havelaar and Melse (2003), [2)]Kotloff et al. (1999)

The calculated burden of disease associated with estimated E.coli O157:H7 exposure in Haridwar drinking water is 1.3E-06 DALY's for IW 18 (Table 13) and 1.9E-05 DALY's for IW 40 (Apx Table B.1). Both risk associated with E.coli O157:H7 are clearly below the national and regional diarrhoeal incidence. Risk associated with E.coli O157:H7 in IW 18 meets nearly the reference level of risk for advanced countries. IW 40 is characterized by shorter travel times, presumably ingress of washing water from a public washing site and thus, a risk associated with E.coli O157:H7 1 $\log_{10}$ unit above the reference level.

Based on experience, the disinfection units, which are located at the well head, are subject to power outages during monsoon rainfalls and consequent flooding of Pant Dweep Island. The annual risk increases to 7.1E-04 DALY's (risk of infection = 6.3 per 1000) and 1.4E-03 DALY's (1.3 per 100) for IW 18 and 40 when no disinfection is available for 122 d (length of monsoon period from June to September, Apx Table B.2, Apx Table B.3).

Table 13 Level of risk for E.coli O157:H7 for RBF well IW 18 per person per year

		Calculated terms	Non-mon	mon
95th percentile Th.C organisms per liter in source water	n	MPN/100ml x 10	30	68
Calculated E.coli O157:H7 per liter in source water	N	n x 0.9 x 0.08	2.2	4.9
Log reduction provided by Disinfection	PT_{CL}		3[1)]	3[1)]
Drinking water quality	C_D	C_R x (1-PT)	2.16E-03	4.90E-03
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	8.6E-03	2.0E-02
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.49[2)]	0.49[2)]
	β	$ß = N_{50}/ (2^{1/α}–1)$	1.90E+05	1.90E+05
	N_{50}	N_{50}=ß x$(2^{1/α}–1)$	5.92E+05[2)]	5.92E+05[2)]
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-α}$	2.2E-08	5.1E-08
Risk of infection per year	$P_{infs,yr}$	*	1.2E-05	
Ratio of illness/infection	$P_{ill/inf}$		0.25[3)]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	2.9E-06	
Disease burden per case	db		0.46	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db sfr	**1.3E-06**	

*$1-(1-P_{infs,d,nm})^n$ x $(1-P_{infs,d,m})^k$

1)NRMMC–EPHC–AHMC 2006, 2)Haas et al. (2000), 3)Haas et al. (1999)

5.3.2 CRYPTOSPORIDIUM

In opposite to Howard et al. (2007), C*ryptosporidium* numbers in the Ganga River were calculated through mixing with sewage discharge rather than applying a sewage E.coli/*Cryptosporidium* ratio as no statistical correlation in numbers between E.coli and *Cryptosporidium* oocysts was found in sewage sludge (Rimhanen-Finne et al. 2004). *Cryptosporidium* numbers given by the WHO (2011) for raw sewage of 10^4 (Range: 1 – 10,000) together with sewage discharge data for cities upstream from Haridwar for mean base flow (Apx Table B.5). Sewage treatment was taken into account by assigning 0.5 log_{10} removal for Cryptosporidium (NRMMC–EPHC–AHMC 2006). The *Cryptosporidium* numbers were estimated to approximately 64 per litre and rounded up to 1.0E02 organism per litre for non-monsoon (200 m^3/s, 243 d) and were assumed to increase 1 log unit during monsoon (1,500 m^3/s, 122 d) period when animal waste from farms and cattle's is washed off into the Ganges River (Apx Table B.6). These figures correspond to the classification of heavily and grossly polluted waters by Medema et al. in WHO (2009) for *Cryptosporidium* with E.coli numbers usually above 1000 per 100ml and *Cryptosporidium* between 10 and 100 oocysts per litre. WHO (2011) estimates default numbers for thermotolerant coliforms in the range from 1E06 to 1E10 in raw sewage. A measured number of 22,000 Th.C. (95^{th} percentile, Apx Table A.1) corresponds to approximately 2.5E08 Th.C per litre raw sewage when the same calculation as for *Cryptosporidium* was used backwards Th.C. measured in the Ganga.

Hijnen *et al*. (2005) reported that protozoa such as *Cryptosporidium* were removed more efficiently than *E. coli* and viruses in column tests with sand and gravel media. Furthermore, operational and experimental data by Schubert (2002) indicate that transport of protozoan parasites is less or not affected by high water and riverbed scour when compared to viruses. This may be attributed to their comparatively large size and the high removal efficiency by commonly used filtration as treatment for protozoan parasites. Although Smeets et al. (2011) point out that several studies such as Hijnen et al. (2005) failed to statistically correlate the removal of indicator organism with pathogens; variations in removal efficiency between indicator organism and pathogens are similar and can be used for model calibration of pathogen removal. Because removal of cryptosporidium was shown to be higher than E.coli (Hijnen et al. 2005) and variation in removal efficiency is similar (Smeets et al. 2011), it seems reasonable to assign the *E. coli* removal rates of 3.5 log_{10} units and 4.5 log_{10} units (Dash et al. (2010) for *Cryptosporidium* transport towards IW 18 for both non-monsoon and monsoon period respectively. As IW 40 is most likely affected by contamination by on-sight facilities (washing sight) it is difficult to calculate Th.C. removal. However, Th.C numbers measured in IW 40 are 1 log_{10} unit higher in IW 40 compared to IW 18 due to shorter travel times. Therefore, the removal towards IW 40 was conservatively assumed to be 1 log_{10} unit lower as reported for IW 18 by Dash et al. (2010).

Table 14 Log_{10} removal Cryptosporidium and rotavirus

Site	Perth	Remmerden	Zwijndrecht	Nizamuddin Bridge	Haridwar IW 18	Haridwar IW 40
Country	Australia	Netherlands	Netherlands	India	India	India
Reference	Toze et al. (2010)	Havelaar (1995)	Havelaar (1995)	(Sprenger et al. 2006)	(Dash et al. 2010, Sandhu 2013)	(Dash et al. 2010, Sandhu 2013)
Sediment	carbonated sand	sand	sand	sand	sand	sand
Travel time		14	70	~45 (= 50 m / 1.1 m/s)	77 (mon) -88 (non-mon)	2 (mon) - 30 (non-mon)
BF/GW	0/100	80/20	90/10		> 70	> 70
Measurement	diffusion chambers	water sampling	water sampling	water sampling	water sampling	water sampling
Temperature ^oC*	23.2			17 - 24	25.5 - 34.7	27.0 - 34.7

Dissolved oxygen (mg/l)*	7	< 1	< 1	0 - 1	1.4	0.4
pH (pH units)	7.7	7.7	7.4	7 - 7.2	7.1 - 7.5	7.1 - 7.3
Conductivity (µS/cm)	134			800 - 1500	448 - 689	495 - 643
Rotavirus-iInactivation (d^{-1})	-0.0342 (29 d)				2.7 - 2.9 (calc.)	0.1 - 1.0 (calc.)
Cryptosporidium-Inactivation (d^{-1})	-0.0254 (39 d)				2.0 - 2.2 (calc.)	0.1 - 0.8 (calc.)
Virus removal (log_{10})		4*	4*	5*	4 - 5 (assign.)	4 - 5 (assign.)
Cryptosporidium removal (log_{10})					> 3.5 - 4.5 (assign.)	> 3.5 - 4.5 (assign.)
Th.C. removal (log10)		>4.1	>4.1		> 3.5 - 4.5	> 3.5 - 4.5

*entero- and reoviruses
**adeno- and noroviruses
calc. – calculated from Toze et al. (2010)
assign. – assigned values from Th.C. (Dash et al 2010) for Cryptosporidium and from enteric viruses (Havelaar 1995, Sprenger et al. 2006) for rotavirus

Based on these assumptions, the burden of disease by *Cryptosporidium* associated with drinking water in Haridwar is 1.3E-03 and 1.4E-03 DALY's (Apx Table B.7, Apx Table B.8). The estimate risk of infection per year is very high with 6.5 per 10 people and 100% but is associated with a comparatively small disease burden of only 0.002 DALY's (E.coli O157:H7=0.46 DALY's). The calculated risk is 1 log_{10} unit below the national burden of diarrhoeal diseases but 0.5 log_{10} above the regional incident for SE-Asia of 0.005 DALY's (WHO 2012).

5.3.3 ROTAVIRUS

Today, rotavirus infection primarily occurs in infants and children under 2 years of age and is the most common cause of severe diarrhoea in infants and young children worldwide and of diarrhoeal deaths in developing countries (Parashar et al. 2006). According to Tate et al (2009), about 2 million Indian children below the age of 5 had diarrhoea associated with rotavirus and had to be admitted as outpatients. Between 457,000 to 884,000 showed signs of severe diarrhoea (avg. 33 %) and had to be hospitalized. About 122,000 to 153,000 (avg. 6.9 %) children aged < 5 died of rotavirus infection. WHO (2012) estimates the mortality of children aged < 5 yrs in India due to Diarrhoea to 220,480 (13% of total deaths of 1,696,000) in 2010. This means that approximately 55 to 69 % (122,000 to 153,000, Tate et al. 2009) out of 220,480 (WHO 2012) diarrhoeal deaths in children aged <5 in India are attributed to rotavirus infection and mortality increased from 4.1 per 1000 live births (3.32 in North India) in between 2001 and 2003 (Morris et al. 2012) to 5.1 to 5.6 children per 1000 live births between 2005 and 2007 (Tate et al. 2009). In order to be consistent with the approach in Uganda (Howard et el 2006), the disease burden for rotavirus was calculated using global incidence data for the different rotavirus outcome (88 % mild, 14.4 severe, 0.7 % death) from the 1980's (Havelaar & Melse 2003). The burden of disease increases by 1 log_{10}-unit when data from Tate et al. (2009) is used.

No data was found for numbers of rotavirus in the Ganga so that numbers were estimated based on values found in literature (Apx Table B.10). Rotavirus numbers measured in sewage per litre vary between 2.0E04 PDU in the Netherlands (95^{th} percentile, Lodder & de Roda Husman 2005) and 9.0E04 FFU in Brazil (geometric mean, Oragui et al. 1989). Rotavirus numbers in the Ganga were first calculated from following assumptions: The average hospitalization (confirmed prevalence) of children aged < 5 associated with rotavirus in the Netherlands is estimated 4.2 per 1000 for the years 1997 to 2007 (van Pelt et al. 2008 in Mangen et al. 2010) and is 5.3 times lower than 22.2 per 1000 live births in India (Tate et al. 2009).

Therefore, figures for rotavirus in sewage in the Netherlands were multiplied with a factor of 5.3 to account for a higher prevalence in India compared to the Netherlands. Discharge data for raw and treated sewage was available for major cities upstream from Haridwar. Lodder & Husman (2005) reported 0.2 log removal for rotavirus after sewage treatment and rotavirus numbers in the Ganga River were estimated to 720 per litre for a base flow of 200 m^3/s (Apx Table B.11). However, the calculated rotavirus numbers may seem not reasonable for India compared to values measured in the Dutch rivers Maas (350 m^3/s avg. flow) of 200 PDU/l and Waal (1,500 m^3/s avg. flow) of 2000 PDU/l by Lodder & de Roda Husman (2005) and can underestimate numbers in India significantly. Sprenger et al. (2006) found up to 5E05 genom copies per litre of human norovirus in the Yamuna River in Central Delhi. The annual average Th.C numbers in the Yamuna are 2 $\log_{10}$-units higher than in Haridwar and vary between 1E06 to 8E06 MPN/100 ml (CPCB 2006). It is assumed that the Ganga at Haridwar is less polluted than its tributary downstream in Central Delhi and thus a figure for rotavirus numbers of 1E03 was derived for the Ganga at Haridwar when the Delhi Th.C/virus ratio was applied to the Haridwar site. This figure is only slightly above the estimated value derived from numbers in sewage of 720 per litre based on numbers from the Netherlands, which were modified based on the prevalence in both countries. The figure of 1E03 it is therefore assumed to give a realistic estimate for rotavirus numbers in the Ganga at Haridwar. As rotavirus is derived from no other sources than human excreta and numbers are estimated to decrease during monsoon due to dilution by one magnitude of order (ratio base flow 200 m^3/s/peak flow 1,500m^3/s). Note that rotavirus numbers were conservatively assumed to be in the order of figures reported for norovirus in the Yamuna River, although RT-PCR detection (PDU) quantifies DNA of both active and inactive cells.

Due to their size, infectivity and health outcomes, viruses are the most critical microbiological parameter for RBF systems. Hijnen et al. (2005) reported the least removal for MS2 phages, a surrogate for viruses, in column test with sand and gravel compared to other reference microorganism for bacteria and protozoa (Hijnen et al. 2005). However, MS2 removal by dune filtration was estimated to be in the order of 8 $\log_{10}$ after 25 days (Shijven 1999), rotavirus and F-specific RNA bacteriophages were removed >4 $\log_{10}$ and 5 to 6 $\log_{10}$ by RBF after 2 to 10 weeks travel time or 25 to 30 m travel distance in the Netherlands (Havelaar et al. 1995) and adeno- and norovirus numbers decreased up to 5 $\log_{10}$ in central Delhi from 3 - 5E04 per 100 ml to 0 per 2 litre after 50 m travel distance or 45 d travel time (Sprenger et al 2006).

The main mechanism for virus removal is attachment onto favourable sites such as hydroxides and binding organics (Shijven 2000). The virus transport model by Shijven (1999, 2000, and 2001) cannot currently be applied to Haridwar as there are insufficient data available. However, following qualitative assumptions were made based on the existing data:

- Minimum removal (inactivation, no attachment due to scour of favourable attachment sites) towards IW 18 (avg. travel time monsoon: 77 d) and IW 40 (2d) was estimated for monsoon based on rotavirus decay in a carbonate aquifer with similar water chemistry (Toze et al. 2010) to 2.0 and 0.1 $\log_{10}$ units (Table 14).
- *Th.C.* removal data indicates the presence of favourable attachment sites in Haridwar. Maximum removal for non-monsoon was estimated to 5 $\log_{10}$ towards IW 18 based on measurements of somatic bacteriophages as well as adeno- and noroviruses at a field site in Delhi, India (Sprenger et al. 2006) after 45 d of travel time. A 4 $\log_{10}$ unit removal was assigned towards IW 40 as average travel time (30 d) is shorter than at the Delhi field site (Sprenger et al. 2006) but higher than in Remmerden, Netherlands, which is characterized by a similar water chemistry but colder temperatures (14 d) (Table 14).

The annual risk associated with rotavirus was calculated to 1.3E-02 (IW 18) and 5.2E-02 (IW 40) DALY's (Table A.8). The risk associated with IW 18 and minimum monsoon travel times of >77 d is below the national incident for diarrhoeal diseases but above the regional incident for SE-Asia (WHO 2012). Risk associated with IW 40 and minimum travel times of 2 during monsoon period are above the national diarrhoeal incidence. Loss of disinfection or direct contamination during monsoon period will increase the calculated risk of infection to 100 % and that of risk associated with rotavirus to 5.2E-02 DALY's (Apx Table B.11 to Apx Table B.13).

5.3.4 DISCUSSION

The risk for diarrhoeal diseases associated with drinking water in Haridwar does not exceed the national diarrhoeal incidence if a sufficient travel time of 77 d is met for rotavirus. However, the risk associated with rotavirus is above the health target used in this study of 5.0E-03 DALY's, which correspondence to the regional diarrhoeal incidence for South-East Asian in 2010 (WHO 2012). Risks associated with E.coli O157:H7 and *Cryptosporidium* are below the health target applied in this study but far above the WHO (2011) reference level of 1E-06 DALY's for advanced countries.

Highest risk is associated with rotavirus; lowest with *E. coli* O157:H7. This reflects the current high incidence of rotavirus in India that is estimated in this study to account for up to 50 % of the diarrhoeal death among children aged <5 years based on number by Tae et al. (2009) and WHO (2012).

As it can be seen from Table 15, RBF is able to reduce DALY's associated with *E. coli* O157:H7 and Rotavirus. However, risk associated with *Cryptosporidium* is not significantly reduced. This is attributed to the high numbers of organism estimated to be in the source water and the limitation of dose response models as mathematically a risk of infection of 100 % cannot be exceeded although numbers of organism in the Ganga is significantly higher than in the bank filtrate.

However, it should be noted that microbial data was only available for thermotolerant coliforms, which were used to estimate *E. coli* using conversion ratios. Presence in source water, removal rates and exposure are represented by point estimates and do not include variations in time or performance yet. Source water numbers and transport of rotavirus and *Cryptosporidium* is solely based on assumptions and values from literature. Source water numbers were calculated from adjusted sewage numbers in the Netherlands and represent conservative one point estimates. Therefore the final risk estimate for E.coli, rotavirus and *Cryptosporidium* can vary several $\log_{10}$ units upon source water concentration and removal efficiency.

Table 15 Summary disease burden (DALY's pppy)

Reference pathogen	Well	RBF + disnf.	No disinf. [1)]	No Treatment
E.coli	IW 18	1.3E-06	7.1E-04	**1.1E-01**
	IW 40	1.9E-05	1.4E-03	**1.1E-01**
Cryptosporidium	IW 18	1.3E-03	1.3E-03	**1.4E-03**
	IW 40	**1.4E-03**	**1.4E-03**	**1.4E-03**
Rotavirus	IW 18	**1.3E-02**	**5.2E-02**	**5.2E-02**
	IW 40	**5.2E-02**	**5.2E-02**	**5.2E-02**

[1)] for 122 d (Monsoon period from Mai until September)
numbers marked bolt and red are above health target (0.005 DALY's)

6 Conclusion

The risk for diarrhoeal diseases associated with rotavirus is above the adopted health target of 5E-03 DALY's in this study. The highest estimate of risk is associated with rotavirus. According to the calculated DALY's an additional log_{10} removal of 0.5 to 2.8 log_{10} units are required for rotavirus during monsoon. However, this figure may vary significantly depending upon the assumptions taken as discussed in section 5.3.4. The risk associated with *E. coli* O157:H7, which numbers was converted from direct thermotolerant coliform measurements in the RBF wells, is far below the national and regional diarrheal incidence but above the WHO (2011) reference level of risk for advanced countries.

Additional treatment steps can be applied to the source of contamination, well operation or at the tap. Watershed protection such as reducing sewer overflow and limiting discharge of untreated wastewater or human excreta into the Ganga River can reduce pathogen numbers by 0.5 to 1 log_{10} (NHMRC 2011). Another 1 to 2 log_{10} unit removal can be achieved by primary and secondary wastewater treatment (NRMMC–EPHC–AHMC 2006). Currently, ~ 80% of wastewater upstream from Haridwar is discharged untreated into the Ganga River. Well head protection zones, improved well sanitation and protection of well heads against direct contaminations is further necessary as pollution by on-sight facilities is a major threat in terms of pathogen related risks. Optimized well operation during flood event such as increasing abstraction rate of wells with longer travel distance and reduction of abstraction rates at wells along the riverbank is also a potential operation philosophy to minimise risk. Currently when there is a of loss of disinfection or contamination with flood water, mains water is not suitable for direct ingestion and needs to be boiled.

Appendix A System Assessment

A.1 Water quality Assessment

Apx Table A.1 Ganga water quality Haridwar derived from Sandhu (2013), NIH (2012) and Saini (2011)

	UGC monsoon				UGC non-monsoon				IDWG (2004)
Physical characteristics	**n**	**mean**	**95th**	**Stdev**	**n**	**mean**	**95th**	**Stdev**	**limit**
Temperature °C*	3	27.77	32.82	6.41	4	21.05	26.47	4.60	
Dissolved oxygen (mg/l)*	1	8.00			1	12.35			
pH (pH units)	3	7.53	7.77	0.25	8	8.20	**8.72**	0.57	6.5 - 8.5
Conductivity (µS/cm)	9	148	172	15	17	228	281	47	
TDS (mg/L)	2	101.50	111.85	16.26	6	109.92	155.00	31.60	500
TH (mg/L $CaCO_3$)	2	87.00	90.60	5.66	7	90.74	116.50	17.02	300
Alkalinity (mg/L CaCO3)	2	56.00	59.60	5.66	6	68.00	84.00	11.47	200
Turbidity (NTU)	2	**98.8**	**142.2**	68.2	6	**18.4**	**39.0**	14.3	5
Major Ions									
Ca^{2+} (mg/L)	9	27.56	38.60	7.97	18	28.32	34.30	5.74	75
Mg^{2+} (mg/L)	9	5.43	9.60	3.54	18	7.87	10.49	1.99	30
Na^{+} (mg/L)	9	4.01	9.60	3.47	17	6.87	11.40	2.74	
K^{+} (mg/L)	6	1.97	3.20	1.02	17	3.21	6.20	2.07	
SO_4^{2-} (mg/L)	9	34.44	61.20	17.31	18	25.29	33.27	6.94	200
Cl^{-} (mg/L)	8	4.39	9.65	3.53	15	3.63	11.80	4.34	250
HCO_3^{-} (mg/L)	3	34.41	91.02	57.67	3	1.35	1.66	0.32	
Nutrients									
TOC (mg/l)	1	1.00			8	0.79	1.29	0.41	
NO_3^{-} (mg/L)*	3	2.77	3.49	1.18	5	5.82	9.34	3.44	45
NH_4^{+} (mg/L)	2	0.000	0.000	0.000	7	0.006	0.024	0.011	
Metals and metalloids									
Fe (mg/L)*	3	**2.52**	**5.07**	2.70	3	**0.54**	**1.10**	0.58	0.3
Mn (mg/L)	2	**0.20**	**0.27**	0.11	3	**0.02**	**0.03**	0.02	0.1

As (mg/L)							0.01
Ba (mg/L)							0.7
Cu (mg/L)*	1	< 0,01	2	< 0,01			0.05
Ni (mg/L)*	1	< 0,002	2	< 0,002			0.02
Pb (mg/L)*	1	< 0,002	2	< 0,002			0.01
Cr (mg/L)	1	< 0,002	2	< 0,002			0.05
Cd (mg/L)*	1	< 0,005	2	< 0,005			0.003
Zn (mg/L)*	1						5
Microbiological							
TC (MPN/100mL)	1	**>2400**	11	**9163**	**23500**	8545	**0**
ThC (MPN/100mL)	1	**>2400**	10	**7390**	**22150**	8218	**0**

Apx Table A.2 Ground water quality Haridwar RBF site

	TW 4 (Saini 2011)				TW 38 (Saini 2011)				TW 50 (Sandhu 2013)		IDWG (2004)
Physical characteristics	**n**	**mean**	**95th**	**Stdev**	**n**	**mean**	**95th**	**Stdev**	**n**	**Value**	**limit**
Temperature °C*	4**	31.4**			4***	31.0***			1	25.2	
Dissolved oxygen (mg/l)*	4**	0.73**			4***	0.25***			1	2.2	
pH (pH units)	4	7.97	8.23	0.23	4	7.05	7.10	0.05	1	6.96	6.5 - 8.5
Conductivity (µS/cm)	4	254	317	54	4	957	1021	57	1	719	
TDS (mg/L)	3	120.09	144.30	24.66	3	**522.83**	**592.15**	70.42			500
TH (mg/L $CaCO_3$)	4	105.91	126.45	19.27	4	**367.80**	**461.88**	101.22			300
Alkalinity (mg/L CaCO3)	3	92.67	109.40	17.01	3	**373.33**	**422.00**	49.33			200
Turbidity (NTU)	3	0.86	1.24	0.39	3	1.26	1.51	0.42			5
Major Ions											
Ca^{2+} (mg/L)	4	30.36	37.30	6.71	4	**98.02**	**130.39**	36.48	1	**101.00**	75
Mg^{2+} (mg/L)	4	7.15	7.87	0.63	4	**29.37**	**32.41**	2.64	1	18.00	30
Na^{+} (mg/L)	4	4.81	6.05	1.16	4	42.31	44.00	2.06	1	35.60	
K^{+} (mg/L)	4	2.05	5.61	2.94	4	4.34	8.74	4.09	1	3.80	
SO_4^{2-} (mg/L)	4	22.43	29.10	5.75	4	40.74	45.08	5.63	1	22.00	200
Cl^{-} (mg/L)	4	2.23	3.32	0.94	4	44.48	54.31	10.31			250
HCO_3^{-} (mg/L)											
Nutrients											
TOC (mg/l)	4	0.47	1.07	0.50	4	1.54	3.72	1.82	1	1.90	
NO_3^{-} (mg/L)*	4**	1.73**			4***	2.18***					45
NH_4^{+} (mg/L)	4	0.038	0.093	0.048	4	0.000	0.000	0.000			
Metals and metalloids											
Fe (mg/L)*	4**	**0.73****			4***	**0.25-0.37*****					0.3
Mn (mg/L)											0.1
As (mg/L)											0.01
Ba (mg/L)											0.7
Cu (mg/L)*	4**	**0.05****			4***	**0.009-0.082*****					0.05

Ni (mg/L)*	4**	b.d.l.**		4***	b.d.l.***			0.02
Pb (mg/L)*	4**	**0.06****		4***	b.d.l.-**0.462*****			0.01
Cr (mg/L)								0.05
Cd (mg/L)*	4**	**0.003****		4***	**0.01-0.07*****			0.003
Zn (mg/L)*	4**	0.004**		4***	0.05-2.64***			5
Microbiological								
TC (MPN/100mL)	4	<2	<2	4	<2	<2		0
ThC (MPN/100mL)	4	<2	<2	4	<2	<2		0

b.d.l. below detection limit
*Deepali & Joshi (2012)
**GW-samples from Industrial area Hetampur, fairly similar EC, higher Ion concentration
***GW-samples from Railway colony and Nirmala Chawni, fairly similar EC, higher Ion Concentration

Apx Table A.3 Summary of critical riverbank filtrate water quality parameters at Haridwar derived from Saini (2011), NIH (2012) and Sandhu (2013)

Well	PDP W 01	PDP W 02	PW 01	IW 02	IW 03	IW 04	IW 15	IW 16	IW 17	IW 18#	IW 21	IW 24	IW 25	IW 26	IW 27	IW 28	IW 29	IW 31	IW 40#	IW 42	IW 43	IW 44	IDWG (2009)
Physical characteristics																							**limit**
pH (pH units)*	7.29	7.19	7.10	7.19	6.98	7.43	7.00	6.99	7.50	7.08	7.58	7.59	7.49	6.89	6.89	7.50	7.58	6.99	7.09	7.50	7.49	7.76	
pH (pH units)**	7.92	7.79	7.36	7.56	7.55	7.23			8.13		8.22	8.15	8.13	7.19	7.49	8.28	8.36	7.51	7.33	8.10	8.16	8.24	6.5-8.5
pH (pH units)***	7.29	7.19	7.19	7.19	6.90	6.89	6.67	6.89	7.47	7.34	7.54	7.40	7.47	6.90	6.99	7.47	7.49	7.10	7.00	7.39	7.47	7.66	
TDS (mg/L)*	339	373	353	289	**516**	**510**	441	485	217	369	177	238	202	435	463	227	179	346	317	264	242	144	
TDS (mg/L)**	390	366	**513**	**522**	**521**	446			148		148	153	192	395	297	177	161	289	340	167	158	169	500
TDS (mg/L)***	268	389	317	318	436	463	473	453	205	339	194	204	239	404	408	225	185	344	323	246	249	173	
TH (mg/L CaCO3)*	195	292	264	221	**395**	**324**	277	**347**	144	242	127	142	159	298	**319**	133	136	262	235	149	149	136	
TH (mg/L $CaCO_3$)**	**320**	277	**424**	**437**	**399**	**374**			136		119	145	160	299	255	139	141	238	281	137	139	139	300
TH (mg/L $CaCO_3$)***	185	266	209	230	292	288	228	284	125	247	143	127	165	287	280	139	128	238	237	157	164	108	
Alkalinity (mg/L CaCO3)*	189	**259**	**249**	**219**	**374**	**317**	**225**	**332**	138	**223**	125	115	139	**289**	**308**	120	120	**243**	**220**	134	124	109	
Alkalinity (mg/L CaCO3)**	**308**	**289**	**414**	**407**	**406**	**369**			112		115	109	144	**341**	**252**	133	122	**238**	**271**	129	119	133	200
Alkalinity (mg/L CaCO3)***	179	**242**	**230**	**220**	**299**	**287**	**238**	**299**	114	**234**	125	109	133	**287**	**284**	129	122	**242**	**222**	166	141	100	
Turbidity (NTU)*	2.1	4.6	1.7	2.6	**5.9**	2.8	4.1	3.1	**8.3**	2.2	2.7	1.9	2.5	2.2	1.8	2.0	1.8	1.9	2.3	**5.4**	4.1	2.5	
Turbidity (NTU)**	1.4	**9.3**	1.6	1.9	1.5	**8.1**			1.4		1.3	1.7	**8.1**	3.0	1.5	2.2	1.2	1.5	1.7	1.2	3.8	2.0	5
Turbidity (NTU)***	3.3	3.2	3.9	3.1	1.7	3.5	1.6	4.2	**5.2**	2.6	2.9	3.8	**6.7**	3.9	4.5	3.4	2.8	3.0	2.5	3.5	**6.0**	3.3	
Major Ions																							
Ca^{2+} (mg/L)*	54.7	73.4	65.2	62.4	**105**	**82.5**	65.4	**91.8**	39.8	65.3	37.6	34.9	54.3	**84.0**	**80.5**	36.8	46.8	61.4	63.9	38.0	39.2	38.9	
Ca^{2+} (mg/L)**	**93.9**	72.7	**116**	**124**	**106**	**103**			38.9		33.4	40.8	46.5	**83.8**	73.7	38.7	40.1	67.6	**86.0**	36.9	37.3	39.4	75
Ca^{2+} (mg/L)***	44.7	47.0	62.7	47.9	**79.9**	55.8	54.4	**75.7**	36.0	68.5	32.0	33.7	39.1	**76.2**	63.7	40.3	34.0	59.9	**78.0**	42.0	42.3	25.9	
Mg^{2+} (mg/L)*	17.8	26.5	24.7	18.7	**32.6**	**31.2**	27.7	28.7	12.0	20.8	13.4	15.6	13.6	29.2	28.7	11.0	14.6	26.4	25.3	13.8	16.7	12.7	
Mg^{2+} (mg/L)**	20.3	22.8	**32.0**	**30.6**	**42.4**	27.8			9.6		9.5	10.3	13.6	**39.9**	20.1	10.6	9.8	27.2	**34.6**	10.9	12.8	9.6	30
Mg^{2+} (mg/L)***	18.0	**37.4**	24.6	27.3	25.8	**42.1**	27.7	26.6	12.4	24.0	15.4	10.9	16.3	**33.6**	29.3	11.7	13.4	27.1	25.0	12.7	17.8	11.0	
Metals and metalloids																							
Fe (mg/L)**	**0.34**	0.25	0.14	0.12	**0.41**	**0.60**	0.02	**0.42**	0.02	0.07	0.17	**0.58**	0.03	**0.80**	0.24	0.02	0.03	**0.33**	0.01	**0.31**	0.17	0.12	0.3
Fe (mg/L)***	**0.33**	**0.61**	**1.90**	**3.70**	**0.51**	**2.53**	**0.71**	0.27	**1.02**	0.18	0.24	**0.64**	**5.72**	**0.57**	**1.54**	**0.55**	**0.88**	**1.37**	0.27	**1.44**	**0.62**	**0.35**	
Mn (mg/L)**	**0.41**	**0.24**	**0.14**	**0.13**	**0.17**	0.07	0.02	**0.56**	0.03	**0.12**	0.03	0.04	0.02	**0.46**	0.03	0.02	0.02	0.04	**0.17**	0.02	0.03	0.06	0.1
Mn (mg/L)***	**0.45**	**0.12**	0.03	0.02	0.03	**0.21**	0.02	**0.27**	**0.68**	**0.11**	0.04	0.09	0.02	**0.41**	**0.55**	0.06	**0.25**	0.02	**0.10**	0.01	**0.40**	0.01	
Cu (mg/L)*																			< 0.01				0.05
Cu (mg/L)***																			< 0.01				0.05
Pb (mg/L)*																			<				0.01

Pb (mg/L)*																			0.002 <0.002				0.01
Cd (mg/L)*																			<0.0005				0.003
Cd (mg/L)*																			<0.0005				0.003
Microbiological																							
TC (MPN/100mL)*	43	240	4	0	0	21	0		9	84	0	23	0	21	240	0	4	240	0	93	39	0	0
TC (MPN/100mL)**	1	1	1	1	1	4	0	93	11	18	1	1	4	136	1	2	1	4	934	8	1	1	
TC (MPN/100mL)**	418	2206	4	0	0	21	0	0	9	52	0	43	0	23	240	21	22	240	40	89	0	21	
ThC (MPN/100mL)*	43	240	4	0	0	21	0	20	9	3	0	23	0	21	240	0	4	240	0	93	39	0	0
ThC (MPN/100ml)**	1	1	1	1	1	1	0	0	7	3	1	1	2	77	1	2	1	1	50	8	1	1	
ThC (MPN/100ml)***	418	2206	4	0	0	21	0	0	9	7	0	43	0	23	240	21	22	240	14	89	0	21	

* post-monsoon from Oct to Dec (NIH 2012)

** pre-monsoon from Jan to Mai (Saini 2011, NIH 2012)

*** monsoon from Jun to Sep (NIH 2012)

\# supplemented with data from Sandhu (2013)

blank fields indicate no data

Appendix B Quantitative microbial risk assessment

B.1 Risk assessment calculations – E.coli O157:H7

Apx Table B.1 Case level of risk for E.coli O157:H7 in IW 40 per person per year

		Calculated terms	Non-mon	mon
95th percentile Th.C organisms per liter in source water	n	MPN/100ml x 10	831	138
Calculated E.coli O157:H7 per liter in source water	N	n x 0.9 x 0.08	60	10
Log reduction provided by Disinfection	PT_{CL}		3[1)]	3[1)]
Drinking water quality	C_D	C_R x (1-PT)	5.98E-02	9.94E-03
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	2.4E-01	4.0E-02
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.49[2)]	0.49[2)]
	β	$ß = N_{50}/\ (2^{1/\alpha}-1)$	1.90E+05	1.90E+05
	N_{50}	$N_{50}=ß\ x(2^{1/\alpha}-1)$	5.92E+05[2)]	5.92E+05[2)]
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	6.2E-07	1.0E-07
Risk of infection per year	$P_{infs,yr}$	*	1.6E-04	
Ratio of illness/infection	$P_{ill/inf}$		0.25[3)]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	4.1E-05	
Disease burden per case	db		0.46	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db x sfr	**1.9E-05**	

*$1-(1-P_{infs,d,nm})^{n} \times (1-P_{infs,d,m})^{k}$

[1)]NRMMC (2011), [2)]Haas et al. (2000), [3)]Haas et al. (1999)

Apx Table B.2 Case level of risk for E.coli O157:H7 without disinfection in IW 18 per person per year

		Calculated terms	Non-mon	mon
95th percentile Th.C organisms per liter in source water	n	MPN/100ml x 10	30	68
Calculated E.coli O157:H7 per liter in source water	N	n x 0.9 x 0.08	2.2	4.9
Log reduction provided by Disinfection	PT_{CL}		3[1)]	0
Drinking water quality	C_D	C_R x (1-PT)	2.16E-03	4.90E+00
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	8.6E-03	2.0E+01
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.49[2)]	0.49[2)]
	β	$ß = N_{50}/ (2^{1/α}–1)$	1.90E+05	1.90E+05
	N_{50}	N_{50}=ß x$(2^{1/α}–1)$	5.92E+05[2)]	5.92E+05[2)]
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-α}$	2.2E-08	5.1E-05
Risk of infection per year	$P_{infs,yr}$	*	6.2E-03	
Ratio of illness/infection	$P_{ill/inf}$		0.25[3)]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	1.5E-03	
Disease burden per case	db		0.46	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db x sfr	**7.1E-04**	

*$1-(1-P_{infs,d,nm})^n$ x $(1-P_{infs,d,m})^k$

[1)] NRMMC (2011), [2)]Haas et al. (2000), [3)]Haas et al. (1999)

Apx Table B.3 Case level of risk for E.coli O157:H7 without disinfection in IW 40 per person per year

		Calculated terms	Non-mon	mon
95th percentile Th.C organisms per liter in source water	n	MPN/100ml x 10	831	138
Calculated E.coli O157:H7 per liter in source water	N	n x 0.9 x 0.08	60	10
Log reduction provided by Disinfection	PT_{CL}		3[1)]	**0**
Drinking water quality	C_D	C_R x (1-PT)	5.98E-02	9.94E+00
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	2.4E-01	4.0E+01
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.49[2)]	0.49[2)]
	β	$ß = N_{50}/ (2^{1/\alpha}–1)$	1.90E+05	1.90E+05
	N_{50}	N_{50}=ß $x(2^{1/\alpha}–1)$	5.92E+05[2)]	5.92E+05[2)]
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	6.2E-07	1.0E-04
Risk of infection per year	$P_{infs,yr}$	*	1.3E-02	
Ratio of illness/infection	$P_{ill/inf}$		0.25[3)]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	3.2E-03	
Disease burden per case	db		0.46	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db x sfr	**1.4E-03**	

*$1-(1-P_{infs,d,nm})^n$ x $(1-P_{infs,d,m})^k$

[1)]NRMMC (2011), [2)]Haas et al. (2000), [3)]Haas et al. (1999)

B.2 Risk assessment calculations – Cryptosporidium

Apx Table B.4 Disease burden per case in DALY's for Cryptosporidium

Outcomes	Severity	Duration		Occurence		DALY's
Watery diarrhoea	0.067[1)]	7.2[1)]	d	100[1)]	%	0.00132
Death from diarrhoea	1[1)]	61.8	a	0.001[1)]	%	0.00062
				Disease burden per case		0.0020

[1)]Havelaar and Melse (2003)

Apx Table B.5 Waste water discharge upstream from Haridwar

City	Population	Total sewage production	Treatment capacity	Percentage covered	Sewage discharge
Rishikesh	59,671	10,7	6,3	59	Ganga
Dehradun	550,800	76,1	0	0	Ganga
Haridwar	215,260	39,6	18	45	Ganga

Source: modified from (CPCB 2010)

Apx Table B.6 Calculated cryptosporidium concentration in sewage and source water

	Discharge m^3/d	Cryptosporidium n/l
Total treated sewage	24,300	3162[3)]
Total untreated sewage	102,100	10,000[1)]
Ganga (non-monsoon)	17,280,000 ($200 m^3/s$)[2)]	64 → 1E02*

[1)]WHO (2011), [2)]DasGupta (1975) [3)] 0.5 log unit removal (NRMMC–EPHC–AHMC 2006) applied to [1)]
*numbers are assumed to increase by 1 $\log_{10}$ unit in during monsoon (see section 5.3.2)

Apx Table B.7 Level and case level of risk for Cryptosporidium in IW 18 per person per year

		Calculated terms	Non-mon	mon
Cryptosporidium organisms per liter in sewage	n	See Apx Table B.4	10,000	10,000
Estimated Cryptosporidium organisms per liter in Ganga water		See Apx Table B.4	100	1000
Log reduction provided by RBF	PT_{RBF}		3.5	4.5
Log reduction provided by Disinfection	PT_{CL}		0	0
Drinking water quality	C_D	C_R x (1-PT)	3.16E-02	3.16E-02
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	1.26E-01	1.26E-01
Number of events per year	n		243	122
Dose repsonse constants	exponential			
	r		0.059[1)]	0.059[1)]
	N_{50}	Ln(0.5)/-r	11.7	11.7
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	7.44E-03	7.44E-03
Risk of infection per year	$P_{infs,yr}$	*	9.3E-01	
Ratio of illness/infection	$P_{ill/inf}$	P_{infs} x $P_{ill/inf}$	0.7[2)]	
Risk of illness per year	$P_{ills,yr}$		6.5E-01	
Disease burden per case	db		0.0020	
Susceptile fraction	sfr	P_{ill} x db x sfr	1	
DALY's	DB	Pills x db x sfr	**1.3E-03**	

*$1-(1-P_{infs,d,nm})^n \times (1-P_{infs,d,m})^k$

[1)]Messner et al (2001), [2)]Havelaar and Melse (2003)

Apx Table B.8 Level and case level of risk for Cryptosporidium in IW 40 per person per year

		Calculated terms	Non-mon	mon
Cryptosporidium organisms per liter in sewage	n	See Apx Table B.4	10,000	10,000
Estimated Cryptosporidium organisms per liter in Ganga water		See Apx Table B.4	100	1000
Log reduction provided by RBF	PT_{RBF}		2.5	3.5
Log reduction provided by Disinfection	PT_{CL}		0	0
Drinking water quality	C_D	C_R x (1-PT)	3.16E-01	3.16E-01
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	1.26E+00	1.26E+00
Number of events per year	n		243	122
Dose repsonse constants	exponential			
	r		0.059[1]	0.059[1]
	N_{50}	Ln(0.5)/-r	11.7	11.7
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	7.19E-02	7.19E-02
Risk of infection per year	$P_{infs,yr}$	*	1.0E+00	
Ratio of illness/infection	$P_{ill/inf}$	P_{infs} x $P_{ill/inf}$	0.7[2]	
Risk of illness per year	$P_{ills,yr}$		7.0E-01	
Disease burden per case	db		0.0020	
Susceptile fraction	sfr	P_{ill} x db x sfr	1	
DALY's	DB	Pills x db x sfr	**1.4E-03**	

*$1-(1-P_{infs,d,nm})^n \times (1-P_{infs,d,m})^k$

[1]Messner et al (2001), [2]Havelaar and Melse (2003)

B.3 Risk assessment calculations – Rotavirus

Apx Table B.9 Disease burden per case in DALY's for rotavirus

Outcomes	Severity	Duration		Occurrence		DALY's
mild diarrhoea	0.1[1)]	7.0[1)]	d	85.6[1)]	%	0.00164
severe diarrhoea	0.23[1)]	7.0[1)]	D	14.4[1)]	%	0.00064
Death from diarrhoea	1.0	65	a	0.7[1)]	%	0.45500
				Disease burden per case		0.46

[1)]Havelaar and Melse (2003)

Apx Table B.10 Rotavirus numbers in different water types

Reference	Country	Source	Method	Number	Unit
Lodder & Husman (2005)	Netherlands	Raw sewage	RNA extraction and RT-PCR	2.0E+04	PDU/l
Oragui et al. (1989)	Brazil	Raw sewage	indirect immunoflorescence	9.0E+04	FF/l
Lodder & Husman (2005)	Netherlands	Maas River	RNA extraction and RT-PCR	2.0E+02	PDU/l
Lodder & Husman (2005)	Netherlands	Waal River	RNA extraction and RT-PCR	2.0E+03	PDU/l

Apx Table B.11 Calculated rotavirus concentration in sewage and source water

	Discharge m^3/d	Rotavirus n/l
Total treated sewage	24,300	6.69E04[3)]
Total untreated sewage	102,100	1.06E05[1)]
Ganga (non-monsoon)	17,280,000 ($200 m^3/s$)[2)]	720→ 1E03
Ganga (monsoon)	129,600,000 ($1,500 m^3/s$)[2)]	96→ 1E02

[1)] Lodder & de Husman et al. (2005) * 5.3 (prevalence factor for India compared to the Netherlands), [2)]DasGupta (1975),[3)] 0.2 log unit removal (Lodder & de Husman 2005) applied to [1)]

Apx Table B.12 Level and case level of risk for rotavirus in IW 18 per person per year

		Calculated terms	Non-mon	mon
Rotavirus organisms per liter in sewage	n	See Apx Table B.8	1.06E05	1.06E05
Estimated rotavirus organisms per liter in Ganga water		See Apx Table B.8	1.0E03	1.0E02
Log reduction provided by RBF	PT_{RBF}		5**	2***
Log reduction provided by Disinfection	PT_{CL}		3[1)]	3[1)]
Drinking water quality	C_D	C_R x (1-PT)	1.00E-05	1.00E-03
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	4.0E-05	4.0E-03
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.253[2)]	0.253[2)]
	β	$ß = N_{50}/ (2^{1/\alpha}–1)$	0.426[2)]	0.426[2)]
	N_{50}	N_{50}=ß x$(2^{1/\alpha}–1)$	6.2	6.2
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	2.4E-05	2.4E-03
Risk of infection per year	$P_{infs,yr}$	*	2.5E-01	
Ratio of illness/infection	$P_{ill/inf}$		0.88[3)]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	2.2E-01	
Disease burden per case	db		0.13	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db x sfr	**1.3E-02**	

* $1-(1-P_{infs,d,nm})^n$ x $(1-P_{infs,d,m})^k$
** reported removal at test field site in central Delhi (see section 5.3.3)
*** solely decay due to river bed scour (see section 5.3.3)
[1)] NRMMC (2011), [2)] Haas et al. (1999), [3)] Havelaar & Melse (2003)

Apx Table B.13 Level and case level of risk for rotavirus in IW 40 per person per year

		Calculated terms	Non-mon	mon
Rotavirus organisms per liter in sewage	n	See Apx Table B.8	1.06E05	1.06E05
Estimated rotavirus organisms per liter in Ganga water		See Apx Table B.8	1.0E03	1.0E02
Log reduction provided by RBF	PT_{RBF}		4**	0.1***
Log reduction provided by Disinfection	PT_{CL}		3[1]	3[1]
Drinking water quality	C_D	C_R x (1-PT)	1.00E-04	7.94E-02
Exposure per event in liters	V		4	4
Dose per event	d	C_D x V	4.0E-04	3.2E-01
Number of events per year	n		243	122
Dose repsonse constants	Beta-Poisson			
	α		0.253[2]	0.253[2]
	β	$ß = N_{50}/ (2^{1/\alpha}-1)$	0.426[2]	0.426[2]
	N_{50}	$N_{50}=ß \times (2^{1/\alpha}-1)$	6.2	6.2
Risk of infection per event (day)	$P_{infs,d}$	$P_{infs} = 1-(1+d/ß)^{-\alpha}$	2.4E-04	1.3E-01
Risk of infection per year	$P_{infs,yr}$	*	1.0E+00	
Ratio of illness/infection	$P_{ill/inf}$		0.88[3]	
Risk of illness per year	$P_{ills,yr}$	P_{infs} x $P_{ill/inf}$	8.8E-01	
Disease burden per case	db		0.13	
Susceptile fraction	sfr		1	
DALY's	DB	Pills x db x sfr	**5.2E-02**	

*$1-(1-P_{infs,d,nm})^{n} \times (1-P_{infs,d,m})^{k}$
**reported removal at test field site in central Delhi (see section 5.3.3)
***solely decay due to river bed scour (see section 5.3.3)
[1]NRMMC (2011), [2]Haas et al. (1999), [3]Havelaar & Melse (2003)

References

Australian bureau of statistics (ABS) (2011) Infant mortality rates. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/3302.0main+features52011. Accessed 22 Jan. 2013.

AIHW (2006) Authoritative information and statistics to promote better health and wellbeing. http://www.aihw.gov.au/life-expectancy/. Accessed 12 Feb. 2013.

Arvind Techno (2013) ARVIND TECHNO ENGINEERS PVT. LTD. http://www.arvindtechno.com/past_projects.html. Accessed 06 Mar. 2013.

Bordalo A.A. (1994) Faecal coliform recovery in two standart media along an estuarine gradient. Wat.Res. 28(11):2331-2334.

Central Ground Water Board (CGWB) (2009). Groundwater brochure of Hardwar district, Uttarakhand. Government of India, Ministry of Water Resources.

Central Pollution Control Board (CPCB) (2006) River quality status of river Yamuna (1999-2005). Government of India, Ministry of Environment and Forests.

Central Pollution Control Board (CPCB) (2007) Development of national emission standards for pesticides manufacturing industry. Government of India, Ministry of Environment and Forests. CWC (2010) River stage gauge and flood forecasting station Haridwar. Central Water Commission (CWC), Ministry of Water Resources, Government of India.

Das Gupta S.P. (1975) The flood plain of Ganga. In: Dasgupta S.P. (eds.) Upper gangetic flood plain Calcutta. 1-7, Dept. Of Sci and Technol., National Atlas Organization.

Dash R.R., Bhanu Prakash E.V.P., Kumar P., Mehrotra I., Sandhu C., Grischek T. (2010) River bank filtration in Haridwar, India: removal of turbidity, organics and bacteria. Hydrogeol J., 18(4), 973-983.

Deepali & Namita Joshi (2012) Study of ground water quality in and around Sidcul industrial area, Haridwar, Uttarakhand, Inda. Journal of Applied Technology in Environmental Sanitation 2 (2): 129-134.

Fischer M. & Milde E. (2007) Leakage detection in water distribution networks in Uttarakhand. Internship report, University of Applied Sciences Dresden. Faculty of Civil Engineering & Architecture, Division of Water Sciences.

Garcia-Armisen T., Prats J. and Servais P. (2007) Comparison of culturable fecal coliforms and Escherichia Coli enumeration in freshwaters. Can. J. Microbiology 53: 798-801.

Government of India (2010), Department of AIDS Control National AIDS Control Organisation: HIV declining in India; New infections reduced by 50% from 2000-2009; Sustained focus on prevention required. Ministry of Health & Family Welfare, Press release.

Government of India (2011a) Annual Health Survey Bulletin 2010-11-Uttarakhand. Census of India, Registrar General India.

Government of India (2011b) Family welfare statistics in India. Ministry of Health & Family Welfare, National Rural Health Mission, New Dheli.

Government of India (2011c) Census of India website: Office of the Registrar General & Census Commissioner, India. Accessed 22 Jan. 2013, http://www.censusindia.gov.in.

Grischek T. (2011)

Grossmann M. & Rother R. (2008) Leakage detection of urban drinking water supply networks in Uttarakhand, India. Internship report, University of Applied Sciences Dresden. Faculty of Civil Engineering & Architecture, Division of Water Sciences.

Haas C.N., Rose J.B. and Gerba C.P. (1999) Quantitative microbial risk assessment, Wiley, New York, USA.

Haas C.N., Thayyar-Madabusi A., Rose J.B. and Gerba C.P. (2000) Development of a dose-response relationship for Escherichia coli O157:H7. International Journal of Food Microbiology 1748: 153–159.

Hachich E.M., Di Bari M., Christ A.P.G., Lamparelli C.C., Ramos S.S. and Sato M.I.Z. (2012) Comparison of thermotolerant coliforms and Escherichia Coli densities in freshwater bodies. Brazilian J. Of Microbiology 43(2):675-681.

Hamilton W.P., Moonil K. And Edward L. Thackston (2005) Comparison of commercially available Escherichia coli enumeration test: Implications for attaining water quality standards. Wat. Res. 39(20): 4869-4878.

Hamner S., Broadway S.C., Mishra V.B., Tripathi A., Mishra R.K., Pulcini E., Pyle B.H. and Ford T.E. (2007) Isolation of potentially pathogenic Escherichia coli O157:H7 from the Ganges River. Appl. Environ. Microbiol. 73(7): 2369-2372.

Havelaar A.H., Van Olphen M., and Schijven J.F. (1995) Removal and inactivation of viruses by drinking-water treatment processes under full-scale conditions. Water Science and Technology 31: 55-62.

Havelaar A.H. and Melse J.M. (2003) Quantifying public health risks in the WHO Guidelines for Drinking-Water Quality: a burden of disease approach, Report 734301022/2003, RIVM, Bilthoven, Netherlands.

Havelaar A.H., Van Duynhoven Y.T.H.P., Nauta M.J., Bouwknegt M., Heuvelink A.E., De Wit G.A., Nieuwenhuizen M.G.M., Van de Kar N.C.A.J. (2004) Disease burden in the Netherlands due to infections with Shiga-toxin producing Escherichia Coli. Epidemiol. Infect. 132: 467-484.

Hijnen W.A.M., Brouwer-Hanzens A.J., Charles K. and Medema G.J. (2005) Transport of MS2 phage, Escherichia coli, Clostridium perfringens, Cryptosporidium parvum and Giardia intestinalis in a gravel and a sandy soil. Environmental Science and Technology 39: 7860-7868.

HIV monitoring (2012) Netherlands HIV/AIDS statistics (2011). http://www.hiv-monitoring.nl/english/patients-and-public/hivaids-epidemic-update/the-netherlands/. Accessed 12 Feb. 2013.

Haridwar Guide map (HGM) (2004)

Haridwar Master Plan (HMP) (2001)In: JNNURN (2006) City development plan: Haridwar – Revised. Jawaharlal Nehru National Urban Renewal Mission. Urban Development Department Government of Uttarakhand.

Hossain M.A., Rahman M.M., Murrill M., Das B., Roy B., Dey S., Maity D. And Chakraborti D. (2012) Water consumption patterns and factors contributing to water consumption in arsenic affected population of rural West Bengal, India. Science of the Total Environment. *in press.*

Howard G, Pedley S. , Barrett M., Nalubega M.and Johal K. (2003) Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. Wat Res 37(14):3421-3429.

Howard G, Pedley S. and Tibatemwa S. (2006) Quantitative microbial risk assessment to estimate health risks attributable to water supply: Can the technique be applied in developing countries with limited data? Journal of Water and Health 4(1):49-65.

Howard G., Ahmed M.F., Teunis P., Mahmud S.G., Davison A. and Dan Deere (2007) Disease burden estimation to support policy decision-making and research prioritization for arsenic mitigation. Journal of Water and Health 5(1): 67-81.

Hunter P.R. (2003) Drinking water and diarrhoeal disease due to Escherichia coli, Journal of Water and Health, 1(2): 65-72.

Indian Drinking Water Guidelines (IDWG) (2004) Indian drinking water guidelines. IS 10500.

International Programme on Chemical Safety (IPCS) (1981). Manganese. Environmental Health Criteria,

17. World Health Organization, IPCS.

Jawaharlal Nehru National Urban Renewal Mission (JNNURM) (2006) City development plan: Haridwar – Revised. Urban Development Department, Government of Uttarakhand.

Kotloff K.L., Winickoff J.P., Ivanoff B., Clemens J.D., Swerdlow D.L., Sansonetti P.J., Adak G.K. and Levine M.M. (1999) Global burden of sigella infections: implications for vaccine development and implementation of control strategies, Bulletin of the World Health Organization, 77(8): 651-666.

Kumar A., Usha N., Sawant P.D., Tripathi R.M., Raj S., Mishra M. Rout S., Supreeta, P., Singh J., Kumar S. and Kushwaha H. S. (2011) Risk assessment for natural uranium in subsurface water of punjab state, India. Human and Ecological Risk Assessment 17(2):381-393.

Lodder W.J. & de Roda Husman A.M. (2005) Presence of noroviruses and other enteric viruses in sewage and surface waters in the Netherlands. Applied and Environmental Microbiology 71(3): 1453–1461.

Mara D., Hamilton A., Sleigh A. and Karavarsamis N. (2010) Options for uodating the 2006 WHO Guidelines: More appropriate tolerable additional burden of disease Improved determination of annual risks Norovirus and Ascaris infection risks Extended health-protection control measures Treatment and non-treatment options. World health organization, Geneva.

Mara D. (2011) Water and waterwater-related disease and infection risks: what is an appropriate value for the maximum tolerable additional burden of disease? Journal of Water and Health 9(2):217-224.

Medema G.J., Juhasz-Hoterman M.H.A. and Luitjen J.A. (2000) Removal of microorganisms by bank filtration in a gravelsand soil. Proceedings, International Riverbank Filtration Conference, Internationale Arbeitsgemeinschaft der Wasserwerke im Rheineinzugsgebiet (IAWR), Amsterdam, The Netherlands.

Mangen M-J. J., van Duynhoven Y.T.H.P., Vennema H., van Pelt W., Havelaar A.H. and de Melker H.E. (2010) Is it cost-effective to introduce rotavirus vaccination in the Dutch national immunization program? Vaccine 28(14): 2624-2635.

Morris S.K., Awasthi S., Khera A., Bassani D.G., Kang G., Parashar U.D., Kumar R., Shet A., Glass R.I., Jha R. & for the million death study collaborators (2012) Rotavirus mortality in India: estimates based on a nationally representative survey of diarrhoeal deaths. Bulletin of the World Health organization 90(10): 720-727.

National Ministry on Macroeconomics and Health (NCMH) (2005) Background Papers—Burden of Disease in India. Ministry of Health & Family Welfare, New Delhi, India.

NRMMC–EPHC–AHMC (2006) Australian guidelines for water recycling (Phase 1): Managing Health and Environmental Risks, Natural Resources Ministerial Management Council, Environment Protection and Heritage Council and Australian Health Ministers' Conference, Canberra.

NRMMC–EPHC–NHMRC (2009) Australian guidelines for water recycling: Managed health and environment risk (Phase 2): Stormwater Harvesting and Reuse, Natural Resource Ministerial Management Council, Environment Protection and Heritage Council and National Health and Medical Research Council, Canberra.

NRMMC (2011) Australian drinking water wuidelines Paper 6 National Water Quality Management Strategy. National Health and Medical Research Council, National Resource Management Ministerial Council, Commonwealth of Australia, Canberra.

Parashar U.D., Hummelman E.G., Bresee J.S., Miller M.A. and Glass R.I. (2003) Global illness and deaths caused by rotavirus disease in children. Emerg Infect Dis 3(9):565-572.

Parashar U.D., Gibson C.J., Bresee J.S. and Glass R.I. (2006) Rotavirus and severe childhood diarrhoea. Emerging Infectious Diseases 12(2): 304-306.

Parashar U.D., Burton A., Lanata C., Boschi-Pinto C., Shibuya K. and Steele D. (2009) Global mortality associated with rotavirus disease among children in 2004. J Infect Dis 200(1):9-15. doi:10.1086/605025 PMID:19817620

Planning Commission Government of India (PCGI) (2003) Pilot study on water efficiency for upper Ganga canal (Uttar Pradesh). Water and Power Consultancy Services (India), A government of India undertaking, New Delhi.

Pokkamthanam A.S., Riederer A.M. and Anchala R. (2011) Risk assessment of ingestion of arsenic contaminated water among adults in Bandlaguda, India. Journal of Health and Pollution 1(1):8-15.

Rasmussen P.P. & Ziegler A.C. (2002) Comparison and continuous estimates of fecal coliform and escherichia coli bacteria in selected kansas streams, May 1999 Through April 2002. U.S. Geological Survey, Water-Resources Investigations Report 03-4056.

Registrar General of India (RGI) (-) In: National Ganga River Basin Authority (2011) Environmental and social management framework (ESMF): Volume I - Environmental and Social Analysis. The Energy and Resources Institute, New Delhi.

Riley L.W., Remis R.S., Helgerson S.D., McGee H.B., Wells J.G., Davis B.R., Hebert R.J., Olcott E.S., Johnson L.M., Hargrett N.T., Blake P.A. and Cohen M.L. (1983) Hemorrhagic colitis associated with a rare Escherichia coli serotype. New Engl. J. Med. 308: 681–685.

Rimhanen-Finne R., Vuorinen A., Marmo S., Malmberg S. And Haenninen M.-L. (2004) Comparative analysis of Cryptosporidium, Giardia and indicator bacteria during sewage sludge hygienization in various composting processes. Applied Microbiology 38(4):301-305.

Oragui J. I., Mara D. D., Silva S. A. and Konig A. M. (1989) A new technique for the enumeration of rotaviruses in wastewater samples. Water Sci. Technol. 21: 99-104.

Saadoun I., Schijven J., Shawaqfah M., Al-Ghazawi Z., Al-Rashdan J., Blandford W., Boving T., Ababneh Q. and Berg H. V. D. (2008) Removal of fecal indicator coliforms and bacteriophages by riverbank filtration (RBF) in Jordan. In Proc. Int. Conf. on Construction and Building Technologies, 16.–20.06.08, Kuala Lumpur, pp. 191–198.

Saini B. (2011) Water quality improvement during riverbank filtration at Haridwar. Master thesis, Environmental Engineering Section, Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667.

Sandhu C. (2008) Simulation of groundwater flow and transport for Haridwar. Report, Cooperation Centre for River Bank Filtration, Haridwar, India.

Sandhu C., Schoenheinz D., Grischek T. (2010) The impact of regulated river-flow on the travel-time and flow-path of bank filtrate in Haridwar, India. In: Zuber A., Kania J., Kmiecik E. (eds) Extended abstracts, 38. IAH Congress Krakow, 12-17 Sept. 2010, 2299-2305.

Sandhu C., Grischek T., Kumar P., Ray C. (2011a) Potential for riverbank filtration in India. Clean Techn Environ Policy, 13(2), 295-316.

Sandhu C., Grischek T., Schoenheinz D., Prasad T., Thakur A.K. (2011b) Evaluation of bank filtration for drinking water supply in Patna by the Ganga River, India. In: Ray C., Shamrukh M. (eds.) Riverbank filtration for water security in desert countries. NATO Science for peace and security series, Springer, 203-222.

Sandhu C., Grischek T., Kumar P., Ray C. (2012a) Promise of bank filtration in India. J Indian Water Works Association, Special Issue Dec. 2012, 5-12.

Sandhu C. & Grischek T. (2012b) Riverbank filtration in India – using ecosystem services to safeguard human health. Water Sc. Techn, 12(6), 783-790.

Sandhu C., Voltz T., Grischek T. (2012c) Nutzung von Aufenthaltszeiten für die Erarbeitung eines Hochwasserschutzkonzeptes für Uferfiltratfassungen in Indien [Use of residence times to develop flood safety concepts for bank filtration sites in India]. FHDGG conference, 16-20 May 2012.

Sandhu C. (2013) Ph. D. Thesis*. in preparation*, Dresden University of Technology, Institute of Waste Management and Contaminated Site Treatment, and Dresden University of Applied Sciences, Division of Water Sciences

State Bureau of Health Intelligence (SBHI) (2002) Government of West Bengal.

Schijven J.F., Hoogenboezem W., Hassanizadeh S.M. and Peters J.H. (1999). Modelling removal of bacteriophages MS2 and PRD1 by dune infiltration at Castricum, the Netherlands. Water Resourc. Res. 35: 1101–1111.

Schijven J.F. and Hassanizadeh S.M. (2000) Removal of viruses by soil passage: overview of modeling, processes and parameters. Crit. Rev. Environ. Sci.Technol.: 30, 49–127.

Schijven J.F. (2001) Virus removal from groundwater by soil passage: Modeling, field and laboratory experiments. Ph.D. thesis, Delft University of Technology, Delft, The Netherlands.

Schubert J. (2002) Water quality improvements with riverbank filtration at Duesseldorf Waterworks in Germany. In: Ray, C., Melin, G. and Linsky, R. B. (eds) Riverbank Filtration-Improving Source-water Quality. Kluwer Academic Publishers, Dordrecht, 267–277.

Sing M., Singh I.B., Mueller G. (2007) Sediment characteristics and transportation dynamics of the Ganga River. Geomorphology, 86(1-2), 144-175.

Singh L., Choudhary S.K. and Singh P.K. (2012) Pesticide concentration in water and sediment of River Ganga at selected sites in middle Ganga plain. International Journal of Environmental Sciences 3(1): 260-274.

Singhal D.C., Israil M., Sharma V.K. and Kumar B. (2010) Evaluation of groundwater resource and estimation of its potential in Pathri Rao watershed, district Haridwar (Uttarakhand). Current Science 98(2): 162-170.

Smeets P.W.M.H., van Gelder P.H.A.J.M., van Dijk J.C., and G.J. Medema (2011) On the variability and uncertainty in quantitative microbial risk assessment of drinking water. In: Smeets P.W.M.H. (eds.) Stochastic modelling of drinking water treatment in quantitative microbial risk assessment. IWA Publishing London, New York.

Sprenger C., Lorenzen G. and Pegdeker A. (2006) Occurrence and fate of microbial pathogens and organic trace compounds at riverbank filtration sites in Delhi, India. D 5.2.6 Techneau.

Tate J.E., Chitambar S., Esposito D.H., Sarkar R., Gladstone B., Ramani S., Raghava M.V., Sowmyanarayanan T.V., Gandhe S., Arora R., Parashar U.D. and Kang G. (2009) Disease and economic burden of rotavirus diarrhoea in India. Vaccine (27(5): F18-F24.

The Kirby Institute (2011) HIV, viral hepatitis and sexually transmissible infections in Australia Annual Surveillance Report 2011. The Kirby Institute, the University of New South Wales, Sydney, NSW

United States Environmental Protection Agency (USEPA) (2002) Implementation guidance for ambien water quality criteria for bacteria. Report EPA-823-B-003. Office of water, Washington, DC.

Uttaranchal Pey Jal Nigam (2006) Water Supply Plan. In: JNNURN (2006) City Development Plan: Haridwar – Revised. Jawaharlal Nehru National Urban Renewal Mission. Urban Development Department Government of Uttarakhand.

van Pelt W., Friesema I., Doorduyn Y., de Jager C. and van Duynhoven Y.T.H.P. (2008) Bilthoven: National Institute of Public Health and the Environment; 2008. Report No.: Internal report.

Weiss W. J., Bouwer E. J., Aboytes R., LeChevallier M. W., ÓMelia C. R., Le, B. T. and Schwab K. J. (2005) Riverbank filtration for control of microorganisms: results from field monitoring. Water Research 39 (10): 1990–2001.

World Health Organization (WHO) (2008) The global burden of disease: 2004 update. World Health Organization, Geneva.

World Health Organization (WHO) (2009) Risk Assessment of Cryptosporidium in Drinking Water. World Health Organization, Geneva.

World Health Organization (WHO) (2011) Guidelines for drinking-water quality: Volume 1 Recommendations 3rd edn. World Health Organization, Geneva.

World Health Organization (WHO) (2012) World health statistics. World Health Organization, Geneva.

World Bank (2012a) Life expectancy at birth, total (years). http://data.worldbank.org/indicator/SP.DYN.LE00.IN. Accessed 12 Feb. 2013.

World Bank (2012b) Mortality rate, infant (per 1,000 live births). http://data.worldbank.org/indicator/SP.DYN.IMRT.IN. Accessed 12 Feb. 2013.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

YOUR CSIRO

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation.

FOR FURTHER INFORMATION

CSIRO Water for a Healthy Country Declan Page
t +61 8 83038748
e declan.page@csiro.au
w www.csiro.au