Saph Pani

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

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Post-treatment Requirements of Different Natural Treatment Systems

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AP	Anaerobic Pond
ARR	Artificial Recharge and Recovery
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage Transfer and Recovery
BF	Bank Filtration
BOD_5	Biochemical Oxygen Demand (5 day basis)
CFU	Colony Forming Units
CWs	Constructed Wetlands
DOC	Dissolved Organic Carbon
DP	Duckweed Pond
FC	Faecal Coliform
FTIR	Fourier Transform Infrared Spectroscopy
GAC	Granular Activated Carbon
HLR	Hydraulic Loading Rate
KI	Kelly's Index
KLD	Kilolitres per Day
KT	Karnal Technology
MAR	Managed Aquifer Recharge
MR	Magnesium Ratio
MLD	Millions Liters per Day
MPN	Most Probable Number
MR	Magnesium Ratio
NTS	Natural Treatment System
OP	Oxidation Pond
OMP	Organic Micropollutant
O&M	Operation and Maintenance
PI	Permeability Index
PP	Polishing Pond
RSBC	Residual Sodium Bicarbonate
RSF	Rapid Sand Filter
RCW	Radial Collector Wells
RO	Reverse Osmosis
RWH	Rainwater Harvesting
SAR	Sodium Absorption Ratio

SAT	Soil Aquifer Treatment
SFA	Sewage Feed Aquaculture
SS	Suspended Solids
SSF	Slow Sand Filter
STP	Sewage Treatment Plant
TC	Total Coliform
TDS	Total Dissolved Solids
TN	Total Nitrogen
TP	Total Phosphorus
UF	Ultrafiltration
WHP	Water Hyacinth Pond
WSP	Waste Stabilization Pond
UASB	Up-flow Anaerobic Sludge Blanket

1 Introduction

1.1 Background and scope of the report

Work package 4 of EU Saph Pani Project deals with the post-treatment aspects of natural treatment systems (namely bank filtration BF, managed aquifer recharge MAR, constructed wetlands CWs and other natural systems for wastewater treatment). One of the objectives under this work package is to assess the pre- and post-treatment requirements of different types of natural treatment systems (NTSs) used in India for water and wastewater treatment and reuse. Analysis of the efficiencies and effectiveness of pre-treatment and post-treatment systems is important for the proper design and functioning of the NTSs and to ensure that the treated water from the NTSs meet the local water quality guidelines and standards for intended use.

This deliverable provides a general overview of the pre- and post treatment requirements for different NTSs namely BF, MAR (which includes artificial recharge and recovery ARR and soil aquifer treatment SAT), CWs and other NTSs for wastewater treatment and reuse. It presents some examples of pre- and post-treatments of NTSs based on case studies. Additionally, it elaborates on the pre- and post-treatment requirements at different Saph Pani case study sites in India based on field water quality sampling and analysis. Furthermore, it analyses the potential impact of different future scenarios and climate change factors on the performance of different NTSs and additional pre- and post-treatment requirements in future.

1.2 Pre- and post-treatment requirements for NTSs

Pre- and post-treatment systems are integral components of natural systems employed for water and wastewater treatment. These systems not only enhance the performance of NTSs but also help to meet the water quality requirements for different applications. The type of pre- and post-treatment systems required depend on the type of NTS employed, source type and water quality (rain water, urban runoff, river or lake water, wastewater treatment plant effluent), local hydrogeological conditions, process conditions (hydraulic loading rate, travel time/distance, abstraction rate) applied and intended use of the water after the NTSs (Figure 1). Furthermore, it is influenced by national and local regulations regarding groundwater recharge, wastewater reuse and water quality standards and guidelines in place (Sharma and Amy, 2010). Inadequate pre-treatment may clog the NTSs, reduce their runtime and removal capability and consequently make additional post-treatment necessary. On the other hand, a well-designed NTS with proper pre-treatment will require minimal post-treatment. Sometimes, pre- or post-treatment is required to ensure that there is no detrimental effect on aquifers or other receiving water bodies.

Therefore, the design and implementation of NTSs should focus on providing the appropriate combinations of pre- and post-treatment systems for a given NTS so that it is process-efficient (in terms of removal of contaminants), cost-effective and environment-friendly.

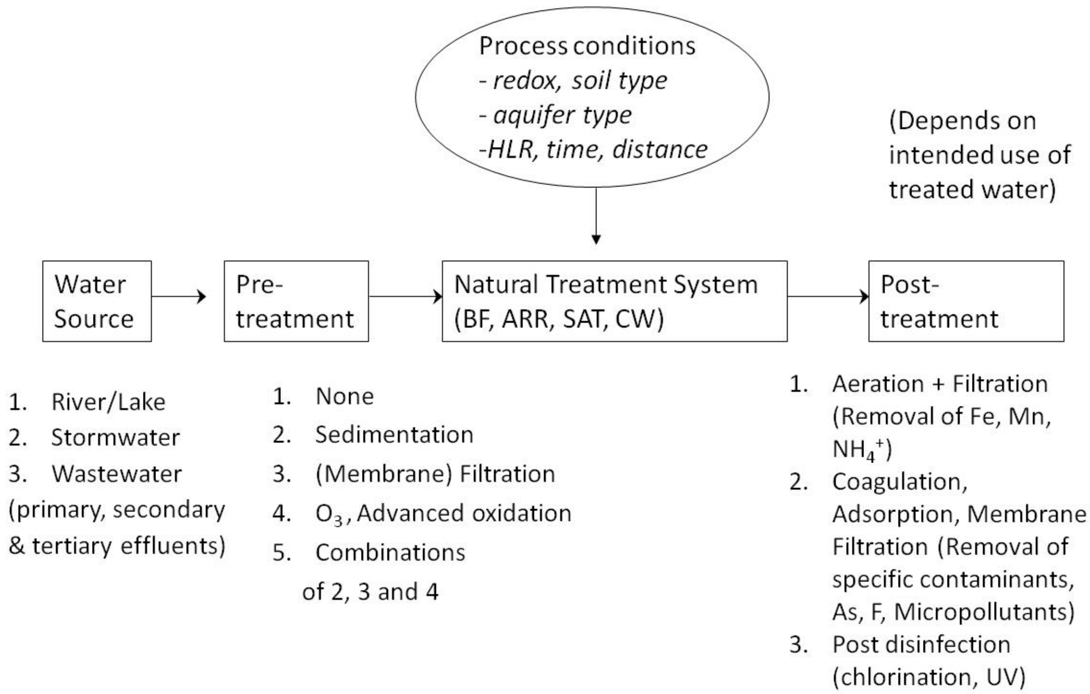

Figure 1 Natural treatment system components

Pre-treatment is relevant for MAR (ARR and SAT) systems, CWs and other NTSs for wastewater treatment and reuse. Sedimentation (using detention tanks, reservoirs, settling basin), filtration (roughing or rapid sand), are some of the common pre-treatment applied for ARR systems (CGWB, 2007; Holländer *et al*., 2009). Sometimes coagulation, adsorption, membrane filtration, advanced oxidation, disinfection and their combinations have been applied as pre-treatment in some NTSs (van der Hoek, 2000; van Houtte and Verbauwhede, 2005; Tielemans, 2007; Sharma *et al*., 2011) to reduce clogging and contamination of the aquifers. Screen, sedimentation and sand filtration are also commonly applied pre-treatments for CWs and other pond based NTSs, if any.

Commonly, used post-treatment methods include (i) disinfection/chlorination to ensure microbial safety and disinfectant residual in the water distribution system, (ii) aeration/chemical oxidation-rapid sand filtration to remove common groundwater contaminants like iron, manganese and ammonium, (ii) ozonation for oxidation of bulk organics and organic micropollutants (OMPs), (iv) activated carbon filtration (with or without pre-ozonation) to remove the OMPs and colour/taste and odour present in the water, (v) softening and pH correction to remove the hardness and to ensure that there is no scaling or corrosion of water distribution system.

Disinfection (by chlorination) is the most common post-treatment applied to bank filtrates in India while few systems also use aeration followed by rapid sand filtration before chlorination (e.g. Mathura, Ahmedabad). Suspended solids removal by sedimentation in settling basins, detention tanks/chambers or ponds followed by sand filtration is the most common pre-treatment applied to rainwater or stormwater or riverwater used for MAR in India. Sometimes both of these two pre-treatment processes (sedimentation and filtration) are achieved in a combined unit which forms a part of recharge structure. Screens, septic tanks (with or without baffles), grit chambers, settling basins and UASB reactors and their combinations have been used as the primary or pre-treatment before various CWs and other NTSs for wastewater treatment in India. Post-treatment of effluents from CWs and other NTSs for wastewater is nearly absent in India. Effluents from these NTSs are generally used for irrigation and discharged to nearby water bodies without further treatment. In the context of escalating water demand, increasing pollution of water sources, growing environmental awareness and need for wastewater reclamation and reuse, it is expected that NTSs in use in India will require appropriate pre- and post-treatment systems (Saph Pani D4.2, 2013).

1.3 Examples of typical pre- and post-treatment systems worldwide

Bank filtration systems are in use in Europe for more than 100 years. Earlier BF systems along the rivers with low turbidity required no or minimal treatment (generally to remove iron and manganese present in well water) (Schubert, 2002; Hiemstra *et al.*, 2003; Eckert and Irmscher, 2006). With the increasing pollution of surface water sources, extensive post-treatment systems are now being employed for polishing bank filtrates. Post-treatment of bank filtrates vary significantly from only disinfection to elaborate systems with advanced oxidation, activated carbon adsorption, membrane filtration, disinfection and their combinations. Table 1 presents some examples of post-treatment systems applied to bank filtrates.

ARR and SAT generally have both pre- and post-treatment systems as the source water may not be of good quality for direct infiltration and recharge and the abstracted water may not meet water quality requirements for intended use. Literature review and field studies in India in the context of Saph Pani project revealed that India has a long tradition in water harvesting and the artificial recharge (using wells, check dams, recharge basins), which is mainly focused on water conservation and groundwater replenishment. Planned recharge of aquifers (with surface water or wastewater effluents) followed by subsequent abstraction (of recharged water) for municipal use is not a common practice in India (Saph Pani D2.1, 2013). Therefore, pre-treatment systems for MAR in India is mainly limited to reducing the sediment load (by sedimentation and filtration systems) in order to facilitate infiltration and reduce clogging. Some typical examples of pre- and post-treatment systems to ARR are presented in Table 2.

Table 1 Selected examples of post-treatment applied to bank filtrates

BF site	Source	Post-treatment applied	Objective of post-treatment	References
Haridwar, Uttarakhad (India)	Ganga River and Upper Ganga Canal	Chlorination only	Disinfection	Sandhu *et al*. (2011, 2012);
Mathura, Uttar Pradesh (India)		Aeration + RSF + chlorination	Removal of organic matter, pathogens;	Singh *et al*. (2010); Kumar *et al*. (2012)
Berlin (Germany)	Lake Tegel	Aeration + RSF	Removal of iron and manganese	Grunheid *et al*. (2005)
Dusseldorf (Germany)	Rhine River	Ozonation + activated carbon filtration + ClO_2 disinfection + phosphate + silicate	Removal of organic micropollutants, disinfection and corrosion control	Schubert (2002); Eckert and Irmscher (2006)
Maribor (Slovenia)	Drava River	Sedimentation + aeration + RSF	Removal of fines, iron and manganese	Rismal and Kopac (2008)
Reijerwaard, (Netherlands)	River Nieuwe Maas	Aeration + RSF + aeration + RSF	Removal of methane, iron, manganese and ammonium	de Vet (2011)
Englese werk, Zwolle (Netherlands)	River Ijssel	a) Aeration + RSF + aeration + RSF + GAC + aeration b) Cartridge filtration + nanofiltration + RSF + GAC + aeration	Removal of methane, iron and manganese, hardness, organic micropollutants	Hiemstra *et al*. (2003)
Louisville, Kentucky (USA)	Ohio River	Coagulation + sedimentation + RSF +disinfection	Removal of iron and manganese	Wang (2002); Hubbs *et al*. (2006)
Lincoln, Nebraska (USA)	Platte River	Aeration + chlorination + filtration + chloramination	Removal of iron, manganese and Pathogens	Gullick *et al*., (2006)

RSF = Rapid sand filtration; GAC = Granular activated carbon

Table 2 Selected examples of pre- and post-treatment applied to MAR system

MAR site	Source water	Pre-treatment	MAR technology	Post-treatment	References
Graz (Austria)	Local streams	Sedimentation + Horizontal gravel filtration	Infiltration via basins and ditches	None (directly supplied as DW)	Tischendorf (2007)
Basel (Switzerland)	River Rhine	Screening + RSF	Infiltration in natural forest area	Activated carbon filtration + UV disinfection	Schütz (2008)
Mulheim-Dohne (Germany)	Ruhr River	Pre-ozonation + coagulation + sedimentation + ozonation + double layer filtration + biological ACF	Infiltration through horizontal gallery and vertical wells	Chlorination + pH correction	Bundermann (2006)
PWN Andijk (Netherlands)	Lake Ijssel	Micro-sieves + coagulation + sedimentation + RSF + ACF + AOP	Dune infiltration	Aeration + RSF + Softening + RSF	de Roda Husman *et al.* (2005)
Amsterdam (Netherlands)	Lek canal (Rhine River)	Coagulation + sedimentation + RSF + pH correction	Dune infiltration	Aeration + RSF + Ozonation + Softening + BACF + SSF	van der Hoek (2000) Tielemans (2007)
Prairie Waters Project Aurora, Colorado (USA)	South Platte River	Riverbank filtration	Infiltration basins	Softening + UV - H_2O2 + RSF + ACF	Ingvoldstad (2007)

ACF = activated carbon filtration, AOP = advanced oxidation process, SSF = slow sand filtration

In the framework of the EU RECLAIM WATER project, eight international pilot or full-scale test sites treating municipal wastewater effluents and/or stormwater for aquifer recharge were investigated in order to assess the overall performance of these sites. These case studies covered a range of pre- and post-treatment technologies aimed at different types of reuse. The characteristics of each site are summarized in Table 3. The level and type of treatment prior to recharge determined the contaminant load that needed polishing by the aquifer. It was observed that the aquifers preceded by lower levels of pre-treatment (i.e. secondary effluent, or raw wastewater) seem to be able to buffer high contaminant concentrations and achieve an abstracted water quality comparable to sites using high pre-treatment technologies. This clearly demonstrates that selection of proper pre- and post-treatment is vital to make NTSs robust and reliable water reclamation systems.

Table 3 Pre- and post-treatments at eight RECLAIM WATER case study sites (Le Corre *et. al.*, 2012)

Case study Site	Source water	Pre-treatment	Recharge rate	Retention time (days)	Post treatment	Reuse purpose
Sabadell, Barcelona region (Spain)	Secondary effluent (activated sludge with nutrient removal)	None	6.9 Mm^3/y (2006)	-	UV and chlorination	Public park irrigation Street cleaning
Nardò, Salento region (Italy)	Secondary effluent (activated sludge with nutrient removal + chlorination)	None	4.4 Mm^3/y (average)	~60	None	Salt intrusion barrier + drinking water source
Shafdan, Tel Aviv region (Israel)	Secondary effluent (activated sludge with nutrient removal)	None	120 Mm^3/y (full site)	180-360	Intermediate chlorination	Irrigation
	Tertiary effluent	Sec effluent + UF	~120 m^3/d (pilot site)	30-60		
Gaobeidian, Beijing (China)	Tertiary effluent	Secondary effluent + coagulation + sand filtration + ozonation + slow sand filter	350 - 500 m^3/d (pilot site)	30	None	None*
Torreele/ Wulpen (Belgium)	Tertiary effluents	Secondary effluent + UF + chlorination + RO	2.5 Mm^3/y	~35	Chlorination, aeration, rapid sand filtration and UV prior to distribution	Sustainable groundwater management, drinking water production
Salisbury, Adelaide (Australia)	Wetland treated urban stormwater	in-stream basins + holding storage	0.2 Mm^3/y (ASTR)	~200	None	Intended irrigation, industrial use and

Case study Site	Source water	Pre-treatment	Recharge rate	Retention time (days)	Post treatment	Reuse purpose
		basins + cleansing wetland				drinking water production
Atlantis (South Africa)	Secondary effluent mixed with urban stormwater runoffs	None	2.7 Mm^3/y	150-210	Ion exchange + Chlorination	Potable water supply
The Mezquital Valley (Mexico) (Uninten-tional aquifer recharge)	Untreated wastewater mixed with stormwater and natural surface water	None	800 Mm^3/y	-	Chlorination	Industrial use, domestic use, Potable water production, Irrigation

2. Pre- and post-treatment requirements for Saph Pani case study sites

2.1 Post-treatment requirements for BF sites in India

2.1.1 Case study site Haridwar

2.1.1.1 Overview of RBF system and existing post-treatment

Twenty two RBF caisson wells (Figure 2) abstract a mixture of bank filtrate and groundwater from the upper unconfined aquifer within the main city of Haridwar (Saph Pani D1.1, 2012; Saph Pani D1.2, 2013).

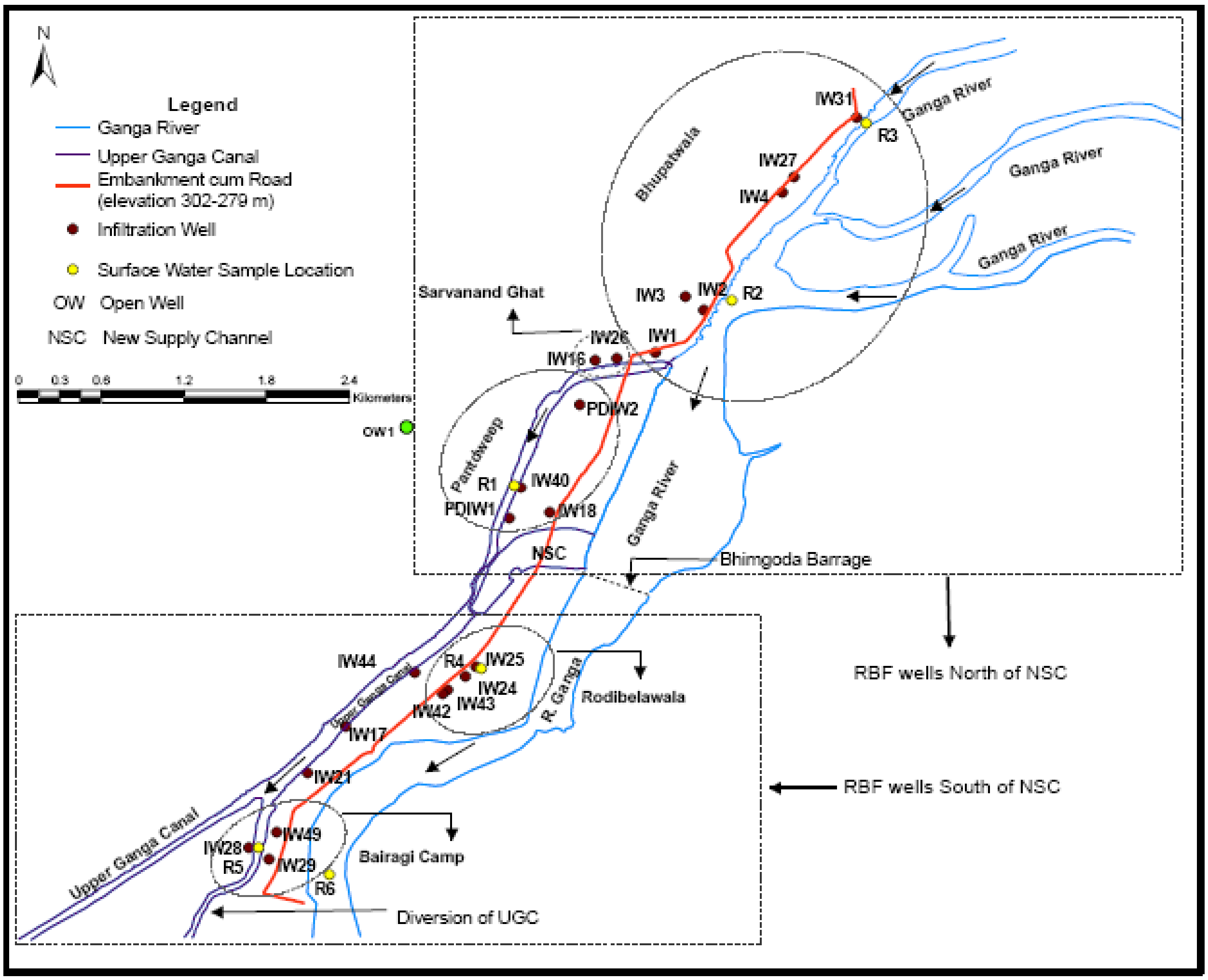

Figure 2 Location of RBF wells and surface water sampling points in Haridwar (Saph Pani D1.2, 2013)

The caissons have a diameter of 10 m and are relatively shallow (7 – 10 m below ground level). The water is abstracted by vertical turbine pumps using an impeller. The only post-treatment applied to the water abstracted from these wells is disinfection by chlorination using sodium hypochlorite (NaClO). As per the design and construction of the existing disinfection system on-site at the RBF well, NaClO is injected (using a dosing pump) directly into the distribution pipeline immediately after the abstraction pump. However, when the disinfectant dosing pumps are defunct or non-existent, NaClO is directly poured manually into the well caisson (as is the case of some wells in July 2013).

2.1.1.2 Objective and sampling of post-treated water

The objective of this particular study was to analyse the current quality of post-treated water (after disinfection) of the Haridwar RBF system in order to determine future post-treatment requirements. Consequently, the status of the disinfection system installed at the RBF wells was investigated by HTWD and UJS in July 2013 (HTWD and UJS, 2013). Furthermore one water sample was analysed from nearly each RBF well in June, July and August 2013 by NIH (NIH, 2013).

Most wells have a tap installed in the main supply-pipe a few metres after the abstraction pump of the well but before the disinfection-point to take water samples. There are thus two options to sample **post-treated** water:

- When the disinfection equipment works for each well, then the post-treated water sample has to be collected at the consumer-end or from a drinking water reservoir (clear-water reservoir) in the city (not necessarily in close proximity to the wells).
- Or, in the event when the disinfection equipment is defunct and NaClO is directly poured into the well caisson, the water sample can directly be taken from the sampling tap.

For this particular study, the second option was exercised because the disinfection apparatus in the period June – August 2013 was non-functional in around 90% of the RBF wells (Table 1). The samples were analysed in the water quality laboratory of NIH Roorkee for physico-chemical parameters, major ions, total coliforms and *E. coli* (Annex 1).

2.1.1.3 Results

The relevant parameters for post-treatment identified in Haridwar are microbiological pathogen indicators, especially Total Coliforms (TC) and *E. coli*. The status of disinfection equipment to post-treat the abstracted water (HTWD and UJS, 2013), and the TC and *E. coli* counts (in MPN/100 mL) determined for the RBF wells in June and July 2013 (NIH 2013), are presented in Table 4. The TC and *E. coli* counts for August 2013 are provided separately in **Annex 1** because counts in Colony Forming Units (CFU/100 mL) and Most Probable Number (MPN/100 mL) are not comparable. The detailed water quality results for all parameters for June, July and August is presented in Annex 1 (NIH, 2013).

From Table 4 it is apparent that despite the fact that disinfection dosage pumps exist and were operational (albeit for two wells only), Total Coliforms (TC) and *E. Coli* were detected (up to counts of 93 and 9 MPN/100 mL respectively) in the post-treated water in the distribution pipeline immediately after the point of disinfection at the RBF well in June – July 2013. In August 2013, 4 – 150 CFU/100 mL of TC were detected in all the wells after disinfection, but some wells located considerably close to the Ganga river and Upper Ganga Canal (UGC) showed no detection of CFU for *E. coli* (**Annex 1**). It is however worth noting that in August 2013, CFU of *E. coli* were also detected in some wells which receive a high portion of groundwater (mainly IW18, IW26, IW1, BWIW1, BWIW4; Saph Pani D1.2). This could imply the flow of contaminated landward-side ambient groundwater to the RBF wells. However, this presumption is based on only one single data set (August 2013, **Annex 1**), but nevertheless it is an important aspect to be considered. The risk from contaminated land-side groundwater has also been highlighted in a recent health risk-assessment conducted for the RBF wells in Haridwar (Bartak *et al*., 2013).

Table 4 Status of disinfection equipment and Total Coliform and *E. coli* counts of water from RBF wells after post-treatment in June and July 2013 (HTWD and UJS, 2013; NIH, 2013)

Well	Status of disinfection equipment (dosage pumps)	Coliform counts in water from RBF wells after post-treatment (n = 2; June & July 2013)		Remarks
		Total Coliform [MPN/100 mL]	*E. coli* [MPN/100 mL]	
IW18	Disinfectant dosing pumps **exist** and are **operational**	4 – 43	<3 – 9	Coliform counts of abstracted water before disinfection
BWIW2		75 – 93	<3 – 9	
BWIW4	Disinfectant dosing pumps **exist** but are **defective**	150 – 240	43 – 93	5 – 10 L of NaClO is directly poured into the well caisson 2 – 3 times per day (sometimes, for some wells, the dose is increased or applied more frequently).
BWIW1		43 – 240	4 – 93	
IW43		<3 1)	<3 1)	
IW42		4	<3	
IW49		28 – 460	15 – 23	
IW21		93 – 150	15 – 93	
IW28		<3 – 9	<3	
IW29		<3 – 23	<3	
PDIW1		43 – 93	9 – 15	
IW31	Disinfectant dosing pumps either	93 1)	23 1)	

IW27	**non-existent** or **defective**	43 – 93	7 – 9	
IW25		<3 – 9	<3	
IW44		9	<3 [1)]	
BWIW3	Disinfectant dosing pumps **non-existent**	93 – 120	23 – 43	
IW40		93	21 – 28	
IW17		<3 – 4	<3	
IW26	No information available	23	<3 [1)]	-
IW24		93 [1)]	15 [1)]	
[1)] only 1 sample taken in June 2013 (n = 1)				

For the remaining 18 wells (90%) that are disinfected by directly pouring NaClO into the well caisson). TC were detected at highly variable counts ranging from the detection limit of <3 MPN/100 mL to as high as 460 MPN/100 mL. In 8 out of these 18 wells, E. coli were either not detected or were found to be below the detection limit.

All other parameters (**Annex 1**) were within the limits of the Indian Standards for Drinking Water (IS 10500 – 1991).

2.1.1.4 Post-treatment requirements for RBF case study site Haridwar

It is evident that irrespective of whether the disinfection equipment is functional or not, or if the disinfectant is simply poured into the caisson of the well, the water after post-treatment at the RBF well-end is insufficiently disinfected (Annex 1). Generally, in order to boost the level of residual chlorine in the distribution network, the operational practise of UJS is to pour NaClO into the various drinking water reservoirs located at various points in the city. Nevertheless, when considering RBF in the context of a multiple-barrier approach to prevent contamination of drinking water, RBF offers the first important barrier between the source of the water and point of abstraction in terms of a significant removal of pathogens and turbidity in India (Sandhu and Grischek, 2012; Saph Pani D1.2, 2013). Thus, in order to prevent an eventual contamination of the water supply distribution network, the provision and continuous maintenance of a robust disinfection system must be made on-site at each RBF well in Haridwar. Such measures will also supplement the flood-proofing of RBF wells (Saph Pani D1.2, 2013).

2.1.2 Case study site Srinagar

The RBF well constructed in Srinagar in 2010 with DST support (PW-DST) has been consistently delivering water with most parameters within the desirable limits as per the Indian Standards 10500 (1991), except two parameters — total coliform (TC) and nitrate (Saph Pani D1.1, 2012). A TC count of ~3000 MPN/100 mL was detected once in the monsoon of 2012. At other times of the year, no coliforms were detected in the well water. The abstracted water is disinfected on-site at the RBF well using NaClO before being distributed, in order to address such occasional breakthrough of pathogens in the abstracted water.

The nitrate concentration in the RBF well water has been consistently above the permissible limit of 45 mg/L for drinking water (IS 10500 -1991). The possible source of this nitrate seems to be some of the bedrock in the region, which is leaching nitrate in the groundwater. There are three approaches (Jensen *et al*., 2012) to deal with this problem:

a. Change the operational design and/or pumping conditions of the RBF system to increase the portion of bank filtrate and thereby reduce the nitrate concentration,
b. Mix the RBF well water with another water source having lower nitrate concentration,
c. Or constructing post-treatment units for nitrate removal.

These three options should be considered in decreasing order of priority. The most robust, easy to maintain and probably most inexpensive method is if the nitrate level can be reduced by changing the operational conditions of the RBF well (option “a”). If thereby the nitrate concentration is not lowered below the 45 mg/L limit, then the option to mix should be explored (option “b”). The construction of post-treatment units (option “c”) should only be resorted to if the first two options do not yield the desired results.

For Srinagar, these three options can be implemented with the following possibilities:

a) Changing operational design and pumping conditions: It is possible to lower the nitrate concentration to within the permissible limits by increasing the pumping rate which will increase the portion of young bank filtrate and decrease the proportion of groundwater and old bank filtrate originating from upstream part of the town (Saph Pani D1.2, 2013). But as the pumping rate cannot be increased beyond a certain limit for the PW-DST, the portion of young bank filtrate flowing to the PW-DST well can further be increased by installing more wells nearby. The RBF wells at a well-field in Dresden-Tolkewitz, Germany, also had a high nitrate concentration because of high nitrate in the land-side groundwater (Grischek *et al*., 1996). Defining a certain pumping rate to optimize the portion of bank filtrate helped in reducing the nitrate level in the abstracted water at that particular site.

b) Mixing with other water: Srinagar currently also has conventional water treatment plant which directly uses the river water and treats it by coagulation-flocculation, rapid sand filtration and disinfection before distributing it. Mixing RBF well water with this water from the conventional treatment plant can bring down the nitrate concentration in the water supply.

c) Nitrate treatment units can be installed based on the following options: Post-treatment systems using technologies such as anion exchange, reverse osmosis, electrodialysis, biological denitrification and chemical denitrification can also installed. However these are comparatively disadvantageous (to options a and b), especially in the mountainous state of Uttarakhand because they are expensive, require significant amount of maintenance and operational know-how and generate large volumes of residues. Furthermore they require significant amounts of uninterrupted power supply which is extremely difficult to provide year-round in Uttarakhand particularly when the hydropower generation decreases during monsoon (June – September, due to very high suspended sediment load in surface water) and low-flow periods (December – February).

2.1.3 Case study site Nainital

In Nainital, all RBF wells except one (PW3-old) have been consistently giving good quality water. Well 3 old gives water with high turbidity. Therefore, it is not used for abstracting water for supply. In other wells, total as well as fecal coliform counts are below the detection limit of 2 MPN/100 mL. Sometimes during monsoon, total coliform count in one or two wells is ~7 MPN/100 mL. This level of pathogens is easily treated with the chlorination of water that is being currently done on-site at the waterworks before distribution.

Occasionally, Ca^{2+} concentration in some of wells farther away from the lake increases above the desirable limit of 75 mg/L (IS 10500 – 1991), but remain lower that the permissible limit of 200 mg/L in absence of alternate source of water. Concentration of Mg^{2+} is often above the desirable limit of 30 mg/L, but is also below the permissible limit of 100 mg/L. Since the water abstracted from several wells is mixed in two reservoirs at the waterworks before distribution, the ions concentrations also get averaged.

Therefore, other than chlorination which is currently being done, no other post-treatment is necessary at present.

2.2 Pre- and post-treatment needs for MAR case study sites

2.2.1 Raipur

Raipur, the capital of Chhattisgarh, is subject to investigations within Saph Pani project on possible interactions between the city's lakes (mainly collecting stormwater) and the underlying aquifer, partially used for local drinking water abstraction. A summary of the geology and hydrogeology of the site are given in Saph Pani D2.2 (2013).

The results presented in the following paragraphs are taken from a study that was carried out by the Freie Universität Berlin (Gröschke, 2012) in Raipur city around the Narayia Talab, the Budha Talab and the Maharajbandh Talab to assess the hydrogeological and hydrochemical characteristics. The pre- and post-treatment needs were identified in Saph Pani D4.1 (2013) and can be summarized as follows:

In general and also for the parameters investigated, groundwater quality is suitable for drinking purposes except for a few samples which showed concentrations of Na^{+}, Cl^{-}, NO_3^{-}, Fe and Mn exceeding the guideline values (Figure 3). The study of Gröschke (2012) showed that the parameters NO_3^{-}, Fe and Mn probably need post-treatment before distributing water for the public water supply. Based on the experience at other sites in India, pre-treatment is required to remove suspended solids for improving the efficiency of infiltration. Also disinfection of the recovered water will most probably be necessary before distribution as drinking water.

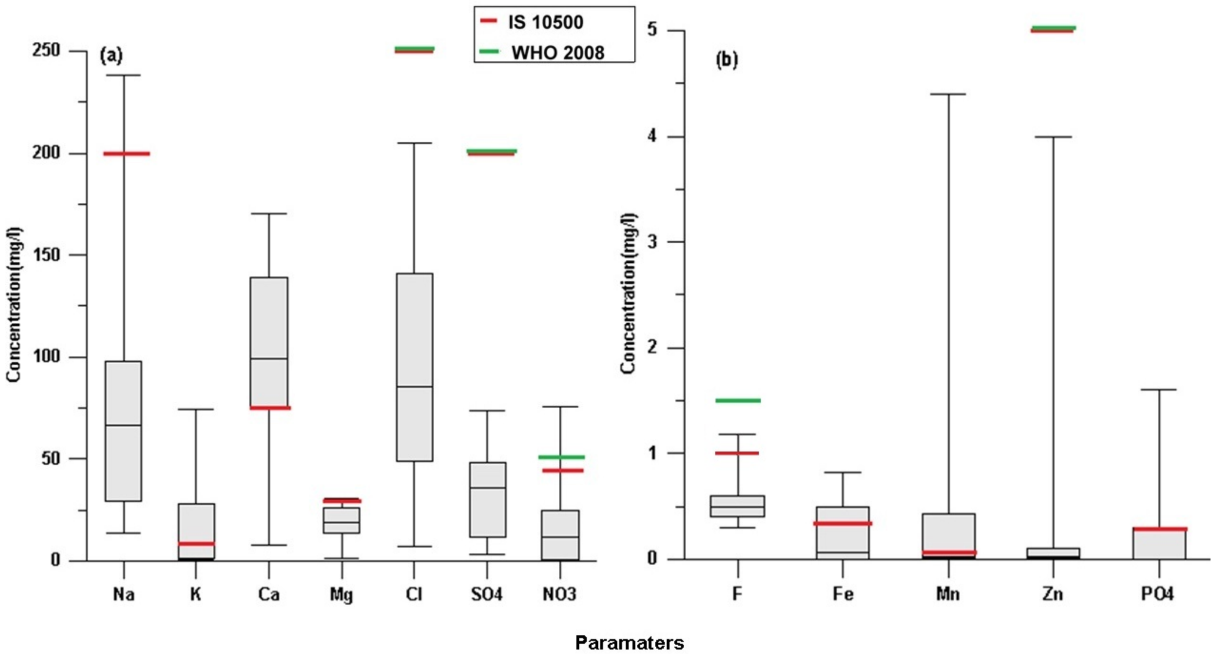

Figure 3 Distribution of groundwater quality in Raipur (a) Major ions (b) Minor ions and trace metals (data source: Gröschke, 2012)

2.2.2 Chennai

Chennai, located in Tamil Nadu on the south-eastern coast of India, is subject to investigations within Saph Pani project on the potential of MAR to counteract seawater intrusion into the alluvial aquifer of the A-K river basin, partially used for drinking water abstraction and irrigation. As summary of the geology and hydrogeology are given in Saph Pani D2.2 (2013). The pre- and post-treatment needs were identified in Saph Pani D4.1 and can be summarized as follows:

Salinity and the high magnesium concentration are the major quality problems when using Chennai groundwater for drinking purposes. Concentrations of SO_4^{2-} and NO_3^- exceeded the guideline value in 20% of the wells, raising problems for use as drinking water. This suggests that the groundwater needs post-treatment in terms of these parameters prior to the distribution. However treatment methods for removing ions like SO_4^{2-} and NO_3 are relatively costly and required higher level skills for operation and maintenance. It is suggested that widespread implementation of MAR structures to reduce salinity in the aquifer is likely to reduce this water quality problem. As in Raipur, the microbial quality of the water has not been monitored. If needed, chlorination is a cheap and effective post-treatment option to eliminate microbial contamination.

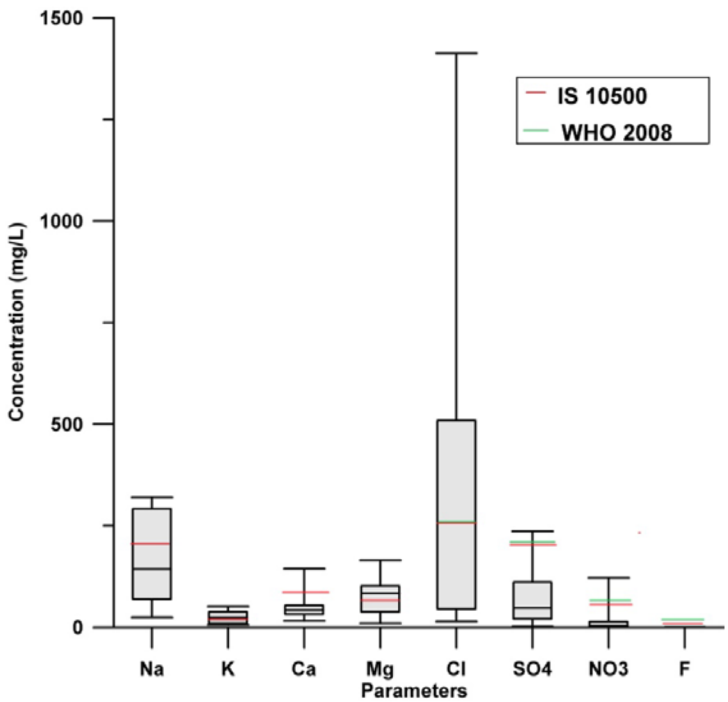

Figure 4 Selected drinking water quality parameters of the groundwater in Chennai

Table 5 Groundwater quality for irrigation in Chennai

Parameter	Min	Max	Mean	Max. Permissible limit	No of samples exceeded the permissible limit	Percentage of samples exceeded the permissible limit
TDS (mg/L)				2100	2	20
Salinity (mg/L)	456	6214	1338	2250	2	20
Cl (mg/L)	15	1412	264.8	500	3	30
SO_4 (mg/L)	1.56	236.3	27.1	1000	0	0
SAR	0.97	6.19	3.16	<10 or 10–18	0	0
RSBC (mg/L)	-1.60	9.20	2.92	<5	2	20
Na%	25.4	55.7	38.9	<20 or 20–40	4	40
PI	38.37	67.16	57.0	Class 1 or 2	0	0
KI	0.36	1.38	0.75	<1.0	3	30
MR	32.89	89.29	67.15	Below 50%	8	80

In the case of irrigation suitability, salinity and TDS are relatively high in a few samples. High Mg levels is observed in majority of the samples (80%) in terms of MR. Although data on turbidity in the source water is lacking, experience from Anna University shows that reduction of suspended solids improves infiltration rates. A pilot study conducted in Anna University Chennai using SAT showed high removal efficiency for nitrate (up to 98%) after 15 cycles (Deepa and Krishnaveni, 2012) under reducing conditions. Under these conditions SAT can be a cost-efficient treatment method for the removal of nitrate, which is encountered in few locations in the study area.

2.2.2.1 Periapalayam Check Dam Area, Tamil Nadu

The Arani River is a seasonal river and carries water only during the monsoon period. The village next to the check dam is called Periapalayam and is located about 40 km north of Chennai. It is a rural area with intensive agriculture activities. In addition, several big industrial companies are also located in the region. As there is a famous temple close to the river, many devotees are visiting each year. In 2010 a check dam was constructed across the Arani river to augment the groundwater resources. The check dam has a length of 260 m and is 3.5 m high.

Selected groundwater parameters as well as hydrological conditions in the check dam area have been investigated regularly by the Geology Department of Anna University since July 2010. In April 2013 a joint sampling campaign with FHNW was carried out and continued every three months until now by Anna University in order to investigate the influence of the check dam on groundwater quality. Groundwater samples were taken from two dug-cum bore wells and four deep bore wells in the area. Water quality parameters including chlorinated pesticides and insecticides, biological parameters as well as organic and inorganic parameters have been measured in these samples. All sample locations are listed in Table 6.

Table 6 Investigated bore wells in the Periapalayam check dam area

Sample	Location	Type	Depth [m]	Distance to check dam [m]
1	Watch tower	Deep bore well	30	150
2	Field / HW 1	Deep bore well	40	85
3	Rose field	Deep bore well	40	275
4	Hotel	Deep bore well	26	1000
5	Jasmine field	Dug-cum bore well	36	650
6	Friend house / HW3	Dug-cum bore well	19	85
7	Check dam	Surface water	-	-

Parameters including dissolved oxygen (DO), temperature, pH, conductivity (EC) and salinity are measured in field right after sample collection. Atrazine is extracted from the groundwater samples by solid phase extraction (SPE) and measured by GC-MS in FHNW. Content of selected microbiological parameters, mainly water borne pathogens (*E. coli*, *Enterobacter aerogenes*, Enterobacter species, *Salmonella typhirmurum* and Vibrio species) were measured by the microbiology department in the Anna University. All other parameters were measured by the external laboratory in Chennai. Five sampling campaign have been conducted until August 2013. All obtained results are listed in Annex 2 and Annex 3.

Based on available results, it can be concluded that the groundwater in the investigated region has fairly high quality compared to the WHO guidelines in terms of physical/chemical parameters (WHO, 2008). A relatively high fluoride concentration was detected in all sample locations in March 2013. On the other hand, various types of water borne pathogens were detected in nearly all sample locations except Sample Nr. 6 friend house despite it is the shallowest well. This is mainly due to the fact that the surface of this well is protected with stone and sealed with tiles by the owner of the house.

Since chlorinated pesticides and herbicides could be sorbed and degraded in the soil, among all screened chemicals only atrazine was detected in sample Nr. 2 and 3 in ng/L concentrations. Therefore, the screening for these compounds was no longer continued.

2.2.2.2 Post treatment requirements for the Periapalayam Check Dam Area

As bacterial contamination was identified in nearly every sample locations, it is obvious that microbiological parameter is most critical for the portable use of groundwater in the check dam area. The easiest and most relevant method of disinfection (to avoid bacteria) is to boil the groundwater before drinking. Another possibility is chlorination. Chlorination tablets are available in the Periyapalayam area at relatively low price. Regular dose of chlorination tablets into the household water storage tanks can provide long term disinfection effect in daily water usage. However neither regular chlorination nor boiling is applied commonly in the area.

Natural disinfection techniques like solar water disinfection (SODIS) could be an alternative. This technique has been known for more than 30 years. Water is disinfected by placing the water in transparent PET bottles in a sun-exposed place for about 6 to 48 hours. The exposure time is depending on the intensity of sunlight and the sensitivity of the pathogens that are expected to be found in the water.

Another natural disinfection method that combines the SODIS treatment with pasteurization is SOLVATTEN®. SOLVATTEN ® is a specially designed container that uses heat, UV and a built-in filter (35 µm) to clean contaminated water. 11 liters of water can be treated in 2-6 hours, depending on the sunlight intensity. An indicator signals the end of the treatment process by turning a red face to green. With this tool the safe use of the water can be ensured. Because the method also uses heat to kill the bacteria the process is faster than the SODIS method where only UV radiation is used.

Another method to produce safe drinking water at household-scale is with a ceramic filter. Ceramic filters remove bacteria from water by size exclusion. To prevent the growth of bacteria in the holes of the filter and to increase the effectiveness, the ceramic pot is painted with a silver compound (IFRC, 2008; UNICEF, 2008).

2.2.3 Maheswaram

The experimental watershed being monitored for MAR studies in the Saph Pani project is located around the town of Maheshwaram, 40 km from Hyderabad, Andhra Pradesh. As a part of MAR system implementation at Maheswaram watershed, Tummulur percolation tank (near Tummulur village) has been selected for investigations within the Saph Pani project. An overview of the geological and hydrogeological situation is given in Saph Pani D2.2 (2013). The pre- and post-treatment needs were identified in Saph Pani D4.1 and can be summarized as follows:

The available data shows that, in general, most of the water quality parameters of the groundwater are suitable for drinking purposes. However, a few parameters like Ca and Mg were high at certain times. The major health hazard is due to the high F concentration in almost all seasons. So these 3 contaminants need to be treated after recovery.

There is no information on the microbial quality of the well water used for small-scale (household level) applications and irrigation. Microbial quality of these well water must be monitored and sufficient disinfection need to be provided if necessary.

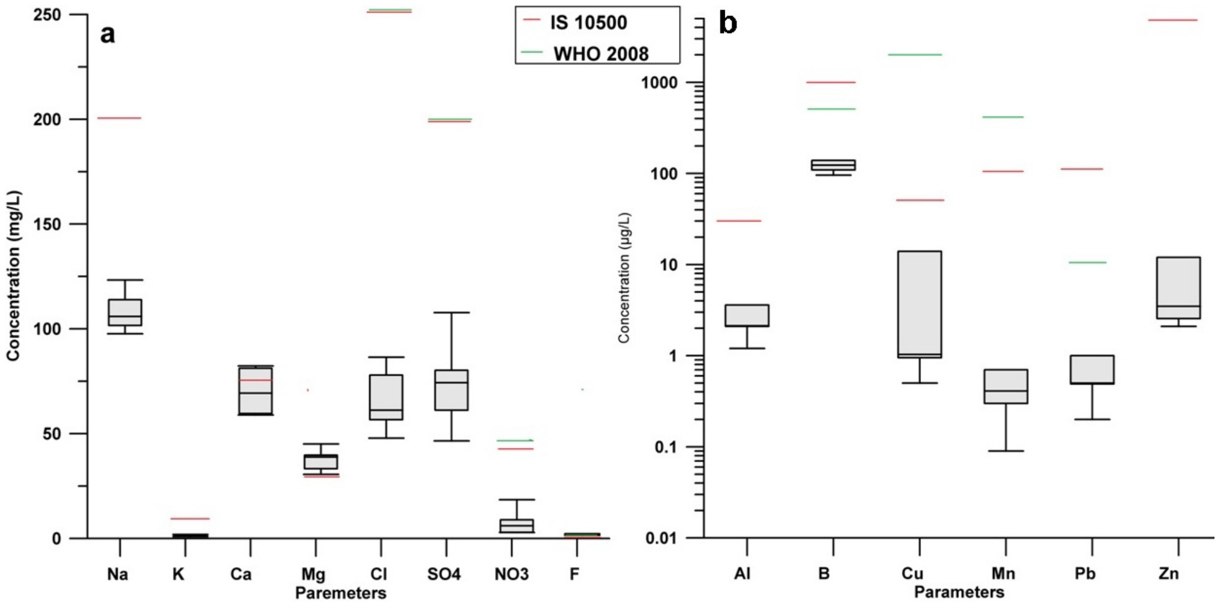

Figure 5 Groundwater quality in Maheswaram (a) major ions (b) trace metals. The seasonal variation (2006-2009) of a well (M35) is presented in this figure

With respect to irrigation, the low salinity values show that the high KI and Na% can be discarded and no post-treatment is needed. Furthermore, as clay deposits in the tanks used for irrigation are reported, it is recommended to remove suspended solids present in the source water by applying some pre-treatment.

Table 7 Groundwater quality for irrigation in Maheswaram (7 seasons from 2006- 2009)

Parameter	Min	Max	Mean	Max. Permissible limit	No of seasons exceeded the permissible limit	Percentage of seasons exceeded the permissible limit
TDS (mg/L)	753	1024	860	2100	0	0
Salinity (mg/L)	878	1198	887	2250	0	0
Cl (mg/L)	47.8	86.4	66	500	0	0
SO_4 (mg/L)	46.5	107.4	77	1000	0	0
B (mg/L)	0.1	0.14	0.12	2	0	
SAR	13.6	15.5	14.74	<10 or 10–18	0	0
Na%	46.5	52.8	49.6	<20 or 20–40	7	100
KI	0.9	1.1	1	<1.0	4	57
MR	29.1	36.2	34.16	<50%	0	0

2.3 Pre-and post-treatment requirements for CWs and other natural wastewater treatment systems in India

NTSs have been employed in India for more than four decades as the low-cost, less resource intensive and more ecologically sustainable form of wastewater treatment. There are different types of NTSs available and the most practiced systems include: Constructed Wetlands (CWs), Hyacinth and Duckweed Ponds, Karnal Technology (KT) for on-land disposal of wastewater, Fish Ponds (FPs), Waste Stabilization Ponds (WSPs), Polishing Ponds (PPs), Oxidation Ponds and Lagoons and, Algal-bacterial Ponds. All wastewater treatment systems based on NTSs have been designed and operated to meet the regulatory standards prescribed by Central Pollution Control Board, New Delhi (CPCB) for reuse and discharge into the water body. In most of the cases, the treated effluents from NTSs are directly reused in agriculture or disposed into an adjoining river. Treated domestic wastewaters from NTSs in India are mainly reused in irrigation of agricultural fields and gardens. Another substantial reuse is sewage-fed aquaculture ponds.

IIT Bombay conducted an India-wide survey for assessment of the most practiced NTSs for wastewater treatment and reuse (Saph Pani D3.1 Report). During this study, a total of 108 sites using NTSs for wastewater treatment were identified. 41 engineered NTSs were visited and secondary data were collected by interviewing the operating staff of the respective STPs as well as by utilizing the literature, log books, and progress reports supplied by the respective personnel.

In most cases, properly operating NTSs are able to achieve up to 3 – 4 log reduction of pathogenic bacteria. More importantly, compared to physical/chemical treatment the natural die-off of pathogenic bacteria in NTSs is a more efficient and effective way of treatment, specifically in the Indian context, as no chemicals are used and by-products are formed.

2.3.1 Pre-treatments and their applications for NTSs

The aim of the pre-treatment is to ensure proper functioning and improve the performance of secondary treatment units installed in the treatment train. During pre-treatment, potential clogging due to suspended solids (SS) and removal of SS are tackled simultaneously. Although the foremost objective of the pre-treatment is the reduction of SS in wastewater, this may also reduce organic content. In some cases the hydrolysis and stabilization of the generated sludge is part of the pre-treatment. Some pre-treatment technologies can reach up to 30 to 50% COD or BOD removal.

During the India-wide survey of NTSs, it was observed that the pre-treatment of wastewater has a special significance or crucial role to ensure the successful operation of CW based NTSs. However, the information on the operation and efficiency of pre-treatment systems combined with CW is scarce. Dahab and Surampalli (2001) found clogging in a subsurface flow CW

(SSFCW) system after 3.5 years of treating wastewater with a load of 1.44 g of TSS/m^2 d which indicate total suspended solids (TSS) as the cause of clogging in the CW bed. Winter and Goetz (2003) showed that in order to avoid clogging in a vertical flow CW the average concentration of TSS in the inflow should not exceed 100 mg/L, while the TSS load should not exceed 5 g of TSS/m^2 d.

A properly operating septic tank installed before a CW gives excellent removal efficiency of TSS at a particular organic load and temperature. Septic tanks show poor efficiency in removal of TSS only due to poor maintenance (Neralla *et al*., 2000; Vymazal, 2002). Anaerobic digesters, as a primary treatment technology for CW, are systems with a very small energy input, low operational cost, and low surplus sludge generation (Hoffmann *et al.,* 2002).

Pre-treatment systems can achieve a TSS removal of 50–70%, generating primary effluent TSS concentrations in the range of 50–90 mg TSS/L, when well-operated (Metcalf and Eddy, 2003). Furthermore, septic and imhoff tanks stabilize the sludge by anaerobic digestion, reducing the amount of sludge generated. Another classical pre-treatment alternative, which is being used mainly for larger installations, is the primary decanter. Primary decanters offer TSS removal of 50–70%, but also produce a high amount of primary sludge (Metcalf and Eddy, 2003). The modified options of septic tank and other modern pre-treatment units and their TSS removal efficiencies are given in Table 8.

Table 8 Pre-treatment technologies for wastewater treatment and TSS removal

SN	Types of Pre-treatment	% TSS Removal	Reference
1	Septic tank	47	Philippi *et al*. (1999); Viet *et al* (2007)
2	Septic tank with anaerobic filter	70	Viet *et al.* (2007)
3	Baffled septic tank	85	Viet *et al.* (2007)
4	Baffled septic tank with anaerobic filter	91	Viet *et al.* (2007
5	Two-step upflow anaerobic reactor	NA	Hamouri *et al.* (2007)
6	Hydrolytic upflow digester	60	Ligero *et al*. (2001)
7	Pre-composting tanks	NA	Gajurel *et al.* (2004)
8	Imhoff tank	NA	Hoffmann *et al*. (2011)
9	Primary decanters	50-70	Metcalf and Eddy (2003)

Physico-chemical treatment (coagulation and flocculation followed by clarification) is an advanced pre-treatment for domestic sewage, reaching up to 90% TSS removal and 80% COD removal (Metcalf and Eddy, 2003). However, advanced pre-treatment may not be suitable in the context of CW technology due to the additional cost of the coagulants and energy for adding and mixing coagulants, and increased sludge handling (Caselles-Osorio and Garcia, 2007).

2.3.2 Pre-treatment requirements for successful operation of NTSs: the Indian experiences

As a part of the assessment of NTSs for wastewater treatment practiced in India, some case studies were selected for in-depth evaluations in assessing the potential benefits of pre-treatment in successful operation and maintenance (O&M). During this assessment, two types of NTSs were compared; (i) NTSs which are being installed and maintained with pre-treatment units and (ii) NTSs with poor maintenance or absence of pre-treatment units. The comparison focused on the following aspects:

1. Role of pre-treatment in reducing the overall O&M of NTSs,
2. Role of pre-treatment in improving the life span of secondary treatment units,
3. Role of pre-treatment in reducing pollutant removal load on secondary treatment process,
4. Social benefits associated with installation of improved pre-treatment units,
5. Health benefits associated with installation of improved pre-treatment units, and
6. Effect of pre-treatment on overall physico-chemical and biological removal of pollutants

Some details of the case studies on assessment of pre-treatment of NTSs are presented in Table 9.

Table 9 Pre-treatment of selected NTSs in India

SN	Name and Location of NTSs	Status of Pre-treatment	Performance
1.A	Constructed Wetland, Kachpura, Agra, Utter Pradesh	Well designed and maintained	Satisfactory
1.B	Constructed Wetland, Ujjain, Madhya Pradesh	Absent	Not satisfactory
2.A	Waste stabilization pond at Peela Khar, Agra, Utter Pradesh	Well designed and maintained	Satisfactory
2.B	Waste stabilization pond, Vrindavan, Mathura, Utter Pradesh	Not maintained	Not satisfactory
3.A	Duckweed pond at Saidpur, Roop Nagar, Punjab	Well designed and maintained	Satisfactory
3.B	Duckweed pond, Uncha, Roop Nagar, Punjab	Absent	Not satisfactory
4	Karnal Technology, Ujjain, Madhya Pradesh	Absent	Suffers from clogging

Source: Saph Pani D3.1 (2013)

2.3.2.1. Assessment of the role of pre-treatment in successful O&M of CW systems

The assessment of two CW based NTSs (depicted in Plate 1) are presented below:

(A) Constructed Wetland, Kachpura, Agra, Utter Pradesh

The decentralised wastewater treatment system at Kachpura slum was constructed as a part of Cross-cutting Agra Program (CAP) for low-income communities. The system was installed in 2002 with the financial assistance from Water Trust UK and London Metropolitan University through technical support of Vijay Vigyan Foundation. The capital cost for the system was INR 1 million and annual operation and maintenance (O&M) cost was around INR 70'000. The aim of the programme was to improve the sanitation conditions in the slum areas. The system is treating approximately 50 kilolitres per day (KLD) of wastewater received from 5 clusters of slums through a common drain. The remaining untreated wastewater flows through the parallel drain into the major drain that connects to the River Yamuna.

The treatment system comprises a screen chamber which prevents the solid waste entering into the system. The wastewater then enters into a three-chambered septic tank. After primary treatment, it flows to nine-chambered baffled anaerobic reactor filled with gravel and then to CW. The CW bed is filled with three different types of filter media (white river pebbles, red stones and gravels) and planted with *Canna indica*. The performance of the system is satisfactory in terms of pollutants removal. The treatment system is being properly operated and maintained by local people. The local community of Kachpura reuse the treated wastewater for horticulture and irrigation, without any disinfection.

In the treatment train the pre-treatment units have been adequately designed and installed and have also been well maintained since the start of treatment plant. The proper pre-treatment units are giving several benefits to the CW bed which are described as follows:

- The pre-treatment units, installed for removal of grit, reduce the overall day-to-day O&M activities – consequently one person is able to take care of STP.
- The removal of grit in the primary settling tank has reduced the clogging of septic tank and CW bed.
- The pre-treatment units are able to remove 45% of organic load as well as daily shock load on CW bed.
- As a result of reduction of shock load in pre-treatment units, the CW beds have a uniform performance all year around. The uniform quality of treated effluent from the NTS has enhanced the acceptance of treated effluent as well as confidence in the treatment technology in the community owning the system.

- Proper O&M of pre-treatment units has made proper utilization of the sludge generated likely and hence reduced the potential health impacts.
- The treatment system is achieving satisfactory removal of physico-chemical pollutants.

(B) Constructed Wetland, Ujjain, Madhya Pradesh

A horizontal flow CW system of capacity 80 KLD (size: 17 m × 85 m × 0.7 m) was constructed and commissioned in 2002 for treating the domestic wastewater of an urban community. The capital cost for establishing this treatment plant was provided by UNDP. The CW was constructed in a wastewater carrying drain (nallah). Wastewater without any primary treatment is being passed through the CW. During construction, river sand was used as construction material for CW bed and *Phragmites karka* was planted. The treatment plant is greatly suffering from lack of maintenance which has resulted in clogging of the bed as well as development of a dwelling for domestic animals (*e.g.,* Pig). The clogging of the bed is also due to lack of pre-treatment of domestic wastewater before entering into the CW bed. During the rainy season, the CW bed is also flooded which is the main cause of the decrease in performance and the clogging of the bed. The clogging in the CW bed has caused short-circuiting of water flows leading to incomplete utilization of system resulting in poorly treated effluent. The absence of pre-treatment of the incoming flow in the CW bed causes the accumulation of floating matter in between the vegetation which has resulted in odour and mosquito problems in the nearby surrounding. The treatment system is beyond recovery, produces a partially treated effluent and hence fails to achieve its objectives.

(A) Underground pre-treatment units installed at CW based NTSs, Kachpura, Agra

(B) Successfully operated CW system at CW based NTSs, Kachpura, Agra

(C) Absence of pre-treatment unit resulted in clogging of CW bed

(D) Poor quality of treated effluents coming out from CW bed

Plate 1: Comparison of impacts of pre-treatment units on overall performance of CW systems (Source: Saph Pani D3.1, 2013)

2.3.2.2. Assessment of the role of pre-treatment in successful O&M of WSP

For assessment of the role of pre-treatment in successful O&M of WSP based NTS, the two systems were selected (depicted in Plate 2) which are described below:

(A) Waste stabilization pond, Peela Khar, Agra, Utter Pradesh

The WSP of capacity 10 MLD at Peela Khar, Agra was established under Yamuna Action Plan for treating domestic wastewater of Agra city. The Jal Nigam Agra, Utter Pradesh is responsible for O&M of the STP since it was established. The STP is performing satisfactorily in achieving design norms of treated effluent. Some amount of treated wastewater is being reused for irrigation and remaining is discharged into the Yamuna River. There are no means available for microbial decontamination or post-treatment at the treatment site.

The pre-treatment units (screen chambers and grit chambers) were properly designed, properly installed and well maintained since the start of treatment plant operation. The properly operated and maintained pre-treatment units are giving several benefits (depicted in Plate 2) to the WSP units, which are described as follows:

- The grit chamber installed for removal of grit are functioning well and remove the readily settable particles from the influent wastewater.
- The removal of coarse floating matter in the screen chamber reduces the possibility of these floating objects reaching into subsequent treatment units. The removal of floating coarse matter including polythene and straw improves the overall appearance of the

system. Moreover, it also reduces the possibility of formation algal mats on the floating matter which creates odour in the absence of sunlight.

- The grit chamber reduces the frequency of clearing of anaerobic pond as compared with systems where there are no pre-treatment units available or not functioning adequately.
- Proper O&M of pre-treatment units increases the likelihood of proper utilization of grit removed during day-to-day cleaning operations.
- The treatment system achieves satisfactory removal of physico-chemical pollutants.

(B) Waste stabilization pond, Vrindavan, Mathura, Utter Pradesh

The WSP of capacity 14.5 MLD at Vrindavan, Mathura, was established under NRCD, Govt. of India, for treating domestic wastewater of Vrindavan Township. The Jal Nigam Mathura, Utter Pradesh, is the agency responsible for O&M of this STP. The WSP does not achieve design norms of treated effluent. The system performance suffers from the lack O&M since a long time. Some treated wastewater is being reused in agricultural fields for irrigation and the remaining portion is discharged into the Yamuna River. There is no microbial decontamination system or post-treatment available at the site.

The pre-treatment units (screen chambers and grit chambers) were installed at the commissioning of treatment plant. These units got spoiled in the course of time due to lack of maintenance and are totally dysfunctional now. The observed impacts (depicted in Plate 2) of inadequately functioning pre-treatment units on the overall performance of treatment plant are as follows:

- The grit and floating matter from the influent wastewater cannot be removed leads to clogging of the anaerobic ponds. Furthermore, the accumulation of grit and floating matter in the anaerobic ponds has led to reduction of hydraulic retention time which is affecting further treatment units. It was observed that the facultative pond 1 is behaving almost like an anaerobic pond. Therefore, the four ponds in series are not serving their purpose adequately.
- The accumulation of floating matter in the treatment units causes a dreadful appearance, which lowers the acceptance of the system by the nearby community.
- The system produces partially treated effluent and hence failed to achieve its objectives.

(A) Pre-treatment units installed at WSP based NTSs, Agra, Utter Pradesh

(B) Successfully operated WSP based NTSs, Agra, Utter Pradesh

(C) Inadequately maintained pre-treatment unit at WSP based NTSs, Mathura, Utter Pradesh

(D) Accumulation of coarse floating matter in WSP based NTSs, Mathura, Utter Pradesh

Plate 2: Comparison of impacts of pre-treatment units on overall performance of WSP systems (Source: Saph Pani D3.1, 2013)

2.3.2.3. Assessment of role of pre-treatment in successful O&M of duckweed pond

For assessment of the role of pre-treatment in duckweed pond based NTS, the two systems were selected (depicted in Plate 3) which are described as follows:

(A) Duckweed pond at Saidpur, Roop Nagar, Punjab

The duckweed pond of capacity 0.5 MLD was established in 1998 for treating the domestic wastewater of the village community. The wastewater is first primarily treated by a screen and grit chamber before entering into the DP. The treated wastewater from the DP flows into a fishpond. Presently, the pisciculture are discontinued because of some Village Council disputes. The system is performing well in terms of reuse standard for disposal on land and irrigation.

Previously, pisciculture activities during sewage treatment were generating a revenue of about INR 50'000-70'000 per year which was utilized for O&M of the treatment plant by the Village Council. The treated effluent is directly being reused for irrigation without any disinfection process, as there are no means available for microbial decontamination at the treatment site.

The presence of pre-treatment units is giving several benefits for successful O&M of the treatment plant (depicted in Plate 3) as described below:

- The pre-treatment units are effectively removing the coarse floating matter and grit from the raw wastewater. The removal of coarse floating matter in the screen chamber reduces the possibility of these materials reaching the DPs which may hinder the duckweed harvesting activities. The removal of floating coarse matter including polythene and straw improves the overall appearance of the system.
- The removal of grit in the grit chamber reduces the frequency of clearing of duckweed as compared with systems where pre-treatment units are absent or not functioning adequately.
- Proper O&M of the pre-treatment units increases the likelihood of proper utilization of the grit removed during day-to-day cleaning operations.
- The treatment system is performing well in removal of physico-chemical pollutants.

(B) Duckweed pond, Uncha, Roop Nagar, Punjab

The duckweed pond with a capacity 1 MLD was established in 2008 for treating the domestic wastewater of a village community. In the treatment train, the grit chamber was installed for removal of readily settable particles from the influent. The wastewater treated by DP was originally overflowing into the fishpond. The system is not being operated and maintained properly and hence effluent is not meeting standards of disposal on land or irrigation. The treated effluent is being directly used for irrigation without any disinfection, as there are no means available for microbial decontamination at the treatment site.

Although some pre-treatment units were installed during the commissioning of treatment plant, these units are not functional due to lack of proper O&M. The observed consequences of failure of the pre-treatment units on the overall performance of the treatment plant (depicted in Plate 3**)** are described below:

- Due to the dysfunctional pre-treatment units, the raw influent along with grit and floating objects enter the DP which leads to rapid siltation. Also, due to the floating objects in the pond, the duckweed species are unevenly distributed and hence a relatively low production of duckweed in the system results. The low production of duckweed as well as a reduced hydraulic retention time in the DP leads to lack of food and a high BOD in the fish pond (due to reduced treatment efficiency of DP). Consequently, the fish disappear and the purpose of installing a duckweed pond along with a fish pond is not being fulfilled.

- The village community has started complaints regarding the bad appearance of DP pond due to the floating objects like polythene and straw and which lowers the acceptance of treatment system.
- The treatment system is not removing physico-chemical pollutants satisfactorily.

(A) Pre-treated discharge of influent into duckweed pond at Sandhuan, Roop Nagar, Punjab

(B) Successful production of duckweed in the pond at Saidpur, Roop Nagar, Punjab

(C) Inadequately maintained pre-treatment unit at duckweed pond at Uncha, Roop Nagar, Punjab

(D) Accumulation of coarse floating matter in duckweed pond at Uncha, Roop Nagar, Punjab

Plate 3: Comparison of impacts of pre-treatment units on overall performance of duckweed pond systems (Source: Saph Pani D3.1, 2013)

2.3.2.4. Assessment of the role of pre-treatment in successful O&M of Karnal Technology

In order to assess the role of pre-treatment in Karnal Technology (KT) based NTS, two systems were selected (depicted in Plate 4) which are described as follows.

Karnal Technology, Ujjain, Madhya Pradesh

The KT-based 1.79 MLD STP at Barogarh, Ujjain, Madhya Pradesh, is situated at the bank of Shipra River. The treatment plant was established in 2002 through funding provided by National River Conservation Directorate (NRCD) for saving the Shipra River. The treatment plant receives only domestic wastewater which is applied to absorb completely into the soil-plant-bed. The treatment system is performing well in terms of absorption of wastewater that is being applied daily. The planted trees grow well as no death of any tree was reported. The trees look matured and regulatory body is planning for harvesting.

Pre-treatments are lacking since the start of the STP. Due to the absence of pre-treatment units the grit and floating objects are not removed which hinders the proper distribution of wastewater in the furrows. In many places, floating objects like polythene and other non-readily degradable materials accumulate and cause an uneven absorption of wastewater by the ground.

(A) Pre-treatment units installed at WSP based NTSs, Agra, Utter Pradesh

(B) Successfully operated WSP based NTSs, Agra, Utter Pradesh

Plate 4: Comparison of impacts of pre-treatment units on overall performance of KT-based systems (Source: Saph Pani D3.1, 2013)

2.3.3 Post-treatment requirements for CWs and other natural systems for wastewater treatment

The India-wide survey of NTSs by IITB showed that out of 108 sites of wastewater treatment based on NTSs, only 3 have a post-treatment facility. In these post-treatment systems, typically 1-2 mg/L of chlorine is dosed at the outlet before the effluent is being reused for irrigation, gardening or discharged into the water body. The treated effluents from 22 out of 108 NTSs are currently being used for irrigation of agricultural fields. In other cases, the effluents from NTSs are directly discharged into the nearby rivers or other water bodies.

To assess the potential of the most practiced NTSs for wastewater treatment and reuse in India, a performance evaluation was made by IITB. The study involved assessment of the quality of treated effluents from various successfully operated NTSs. Five NTSs based on various treatment technologies were selected and wastewater samples were collected to assess the quality of raw and treated effluents (Table 10).

Table 10 Removal of different pollutants in selected NTSs

Parameter	CW Ropar		WSP Mathura		SFA Karnal		PP Karnal		DP Ludhiana	
	In	Out	In	Out	In	Out	In	Out	In	Out
BOD_5 (mg/L)	210	15	235	50	198	10	60	27	190	15
COD (mg/L)	NA	NA	550	110	680	52	215	145	325	125
*p*H	7.5	7.7	7.3	7.5	7.4	8	6.9	7.3	7.1	7.3
TP (mg/L)	8	2.5	NA	NA	7.3	6.24	6.5	6	5.8	2.9
TKN (mg/L)	19.6	2.9	21.01	14.7	15.4	8.6	14.8	12.6	17.2	6.7
DO (mg/L)	NA	NA	NA	NA	0	2.6	0	1.5	0	2.4
TSS (mg/L)	375	30	435	190	524	48	250	80	430	62
TCC/100 mL	10^7	10^3	7×10^7	10^6	18×10^6	10^5	3×10^6	5×10^5	10^7	10^4
FCC/100 mL	1.3×10^6	10^3	6×10^6	10^5	9×10^5	10^4	10^6	10^5	8×10^5	3×10^3

Note: In = Raw effluent, Out = Treated effluent; TP = Total Phosphorus; TKN = Total Kjeldahl Nitrogen; DO = Dissolved Oxygen; TSS = Total Suspended Solids; TCC = Total Coliform Count; FCC = Faecal Coliform Count; NA = Not Available

The NTSs in Table 10 which are operating properly are satisfactorily achieving the regulatory norms prescribed by the CPCB. The CW based NTS is the most effective in removal of microbial pollutants including total coliform and faecal coliform along with physic-chemical pollutants. Also, the CW based NTS is the most effective in removal of nutrients from the wastewater. This is important to reduce the eutrophication on discharge into the natural water bodies. However, it is also clear from the case studies that the treated effluent may cause microbial water contamination if reused directly even for irrigation, due the presence of a high number of faecal bacteria. Therefore, post-treatment is indispensable for such secondary treated wastewater, before any reuse or its disposal into water body.

There is a high potential to use the effluent from NTSs in agriculture because of its low cost and high nutrient content. For that infrastructure must be in place for transfer of the treated effluent from the treatment plants to the agriculture fields. The farmers must also be made aware of the implication of the wastewater reuse in agriculture and potential health effects. Wastewater containing can introduce nutrients into water bodies with resulting eutrophication in affected water bodies. The heavy algal growth can cause difficulties in downstream water treatment (Arceivala and Asolekar, 2006; Asolekar *et al*., 2013).

The accumulation of detergents, pesticides, heavy metals and other non-biodegradable substances in the downstream waters can also adversely affect the beneficial use of water resources. Therefore, even if some of the NTSs are meeting the water quality regulations for disposal on land or in water bodies, it is important that further post-treatment is applied to effluents depending upon the intended reuse options, to ensure that the risk of microbial contamination is minimized and potential effect on public health is not compromised.

Groundwater contamination due to indiscriminate disposal of untreated or partially treated municipal and industrial wastewater is another major concern in India. Less than 50% of the urban population has access to a sewage disposal system. Most of the existing collecting systems discharge without treatment. The sewage pollution accounts for more than 75% of the surface water contamination in India. For the sustainable development, changing the wastewater management practices is necessary – aiming at reduction in wastewater generation and reuse or recycle where possible, which may assist in reducing the severe water crisis foreseen in India in the next two decades. Therefore, through proper wastewater management and with the appropriate use of CW and other NTSs in combination with suitable post-treatment it is expected that issues of water scarcity, environmental pollution, poverty and food insecurity can be addressed in an integrated way.

2.3.4 Post-treatment of CW effluent aimed at reuse: phosphate removal

Phosphorus removal is relatively low and variable in CWs (Yang *et. al,* 2001; Rousseau *et. al*, 2008). As a part of a MSc study at IITB, Srivastav (2013) analyzed the removal of phosphate and nitrogen from the effluent of CWs aiming at further reuse. A literature review was conducted to find appropriate technologies for phosphorus removal from CW effluents and to determine techno-economic constraints of candidate technologies. Different types of magnetic bio-chars were prepared and their effectiveness in nutrient removals was analyzed based on laboratory-scale studies.

The biochar used in the study were prepared from different plants used in CW systems. The magnetic biochar was prepared according to method described by Chen *et al*. (2011). The segregated plant samples were air-dried in sunlight for 4 days to remove the excess moisture. It was followed by drying samples in hot air oven for 24 hours at 105ºC. The biomass was then pyrolysed in muffle furnace at 500ºC for 1 hour. The furnace was initially heated up to 500ºC and then samples were put and were taken out after 1 hour. The samples were left in ambient air to cool down, while keeping the crucible covered to avoid formation of ash by oxidation. The samples were then sieved through a 0.45 mm standard sieve to avoid fine ash particles in the biochar. After pyrolysis, the samples were crushed using mortar and pestle. The crushed materials were then rinsed using distilled water 4-5 times. Finally, the biochar samples were dried and stored for characterization and further experimentation. Details of the preparation of different types of biochar, experimental methods and process conditions applied as well as results obtained are presented in the Thesis of Srivastava (2013).

The highest phosphate removal rates from a standard solution of concentration 50 mg/L PO_4^{3-} were observed in magnetic *Canna indica* (60% phosphate removal after stabilization) followed by magnetic biochar samples of water hyacinth stem and water hyacinth leaf, *Typha latifolia, Colocasia* (stem) with removal in the range of 50–55%. Magnetic biochar samples showed a phosphate removal of 80-90% in first few minutes followed by leaching out and stabilization after 30 – 60 minutes of contact time (Figure 6).

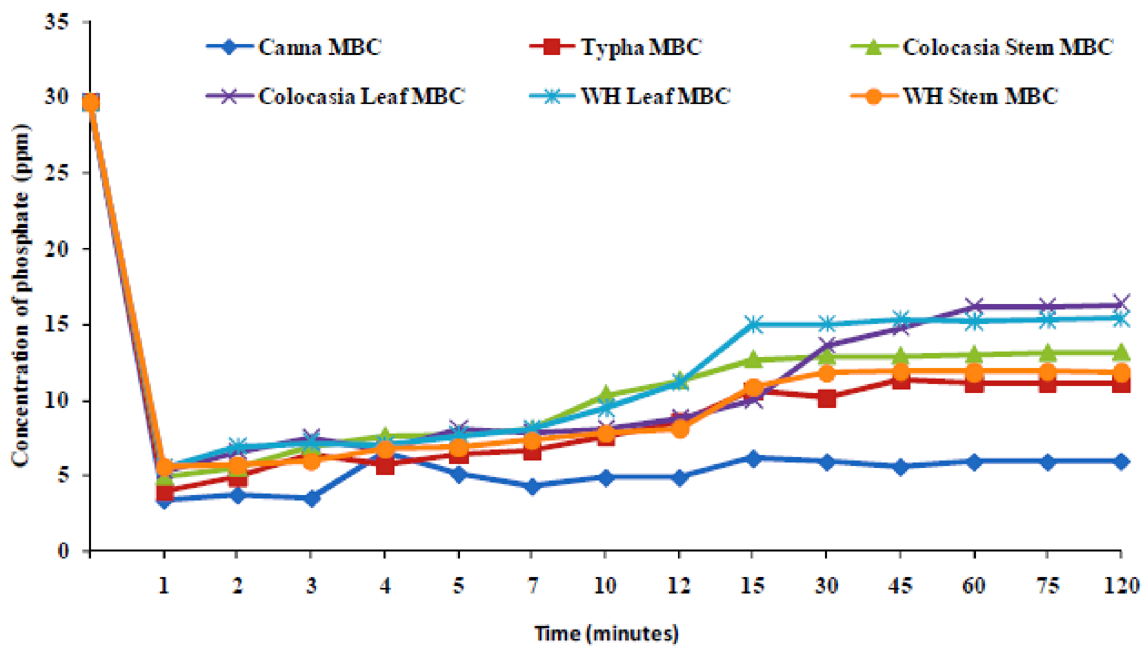

Figure 6 Removal of phosphate by different magnetic biochar with respect to time

(WH = Water hyacinth; MBC = Magnetic Biochar)

All biochar samples showed ammonium removal efficiency of 20–50% from the standard solution of 20 mg/L concentration. Nitrate removals were found negligible (<5%) and a few samples showed negative removal i.e. leaching of nitrate from biochar into the solution. Magnetic biochar pore water showed pH in the acidic range whereas non-magnetic biochar showed pH in the basic range. Nanoparticles in micrometer range were detected in the pores of biochar. FTIR confirms the presence of oxygen carrying functional groups with negative charge on the surface of the biochar which play a crucial role in removal of various pollutants. In sum, this study clearly shows that the biomass generated in CW systems can be used for further removal of pollutants after conversion into biochar and magnetic biochar.

3. Analysis of the potential impact of future scenarios on pre- and post-treatment requirements for different NTSs

3.1 Future scenarios and climate change factors influencing the performance of NTSs

Some of the future scenarios or global change pressures like (i) population increase and urbanization, (ii) climate change, (iii) emerging contaminants, (iv) energy crisis and (v) increasing environmental awareness and stricter regulations are likely to affect the performance of natural systems for water and water treatment as these factors have direct and indirect impact on the quantity and quality of different types of water (TECHNEAU, 2007; Lozan *et al*., 2007; Cooley *et al*., 2013). Effect of these influencing factors on the performance of NTSs and requirements for pre- and post-treatment systems are summarized in the following paragraphs:

3.1.1 Population increase and urbanization

Rapid increase in population and escalating urbanization has increased water demand for different use and increased the production of wastewater. It is likely that this trend will continue in future. The expansion of the existing water supply (treatment and distribution) as well as wastewater treatment systems would therefore be necessary to cope with this situation. In this context, water supply systems relying on BF, ARR and SAT may need to produce more water which may lower the groundwater table and reduce the retention time during soil passage, ultimately resulting in relatively lower quality (reduction of removal efficiency of different contaminants). Secondly, increased pollution of the surface water sources (due to inadequate waste and environmental management) will reduce the efficiency of removal of different contaminants by soil-based NTSs like BF, ARR and SAT. This clearly implies that additional and robust post-treatment systems will be required in the future for BF and ARR systems used for drinking water production.

Furthermore, increased wastewater production implies that additional pre-treatment will be required before the wastewater is treated by CWs and other NTSs. The higher wastewater load will lead to reduction of removal efficiencies of these NTSs and therefore, the post-treatment systems would need upgrading. Moreover, additional land areas would be required for expansion of NTSs (like CWs and Ponds), which is already getting difficult to acquire in many urban areas using such systems. Consequently, robust and efficient pre-treatment and post-treatment systems should be provided in addition to NTSs to meet the future wastewater treatment requirements. Development of hybrids and integrates of NTSs and conventional wastewater treatment systems is another option to reduce land area requirements and to increase removal efficiencies.

3.1.2 Climate change factors

Several studies have reported that the main climate change factors that might affect water and wastewater treatment industry include, (i) increase in average temperature and reduced frost period, (ii) increased flooding, (iii) increased drought, (iv) variable precipitation pattern (changes in frequency and intensity), and (v) sea level rise (IPCC, 2007, Howe *et al*., 2010; Major *et al*., 2011). The climate change factors seriously affects the water balance of the given areas as there are periods of less water availability while water demand is increasing. There is also likely increase in water demand (at least periodically) during droughts and increase demand for agriculture. This also causes conflict of interest with other water use. Furthermore, it affects the performance of NTSs as there are likely changes in raw water quality (increase in water temperature, natural organic matter and nutrients) leading to increasing number of bacteria in raw water and promoting the growth of bacteria in water distribution system. In general, climate change will consequently lead to increase in cost of water treatment both for conventional as well as NTSs.

Climate change effects are likely to introduce higher variability in groundwater levels and influence the amount and rate of groundwater infiltration. There is also likely changes (increase) in groundwater temperature which may influence the physico-chemical reaction rates and water permeability in the aquifer (IPCC, 2007). Study of climate change effect on BF system in Dusseldorf (Germany) revealed that required capacity of the production wells could be ensured even during extremely low water periods. However, low water periods accompanied by high water temperatures have a serious impact on river water quality and on hydrogeochemical processes during RBF (Eckert *et al.*, 2008). There is also likelihood of increasing concentrations of substances coming from agricultural land and surface overflows (e.g. nitrate, pesticides, heavy metals). All these affects will ultimately influence the quality of abstracted water and increase the need for comprehensive post-treatment systems for any water use.
In general, climate change effects will likely lead to increase in chemical use (in coagulation and oxidation processes, disinfectants), increase in backwash water use and sludge production, and decrease in filter run time for post-treatment systems. This will increase the overall cost of post-treatment (capital as well as O&M).

3.1.3 Emerging contaminants

With the increasing use of synthetic chemicals in industry and increasing pollution of surface water sources, several new inorganic, organic or microbial pollutants (which were not known or identified before) have now been detected in water sources (Xagoraraki and Kuo, 2008). Many of these contaminants are not completely removed during water and wastewater treatment processes (Wintgens *et al*., 2008). It has been reported that majority of these emerging contaminants are reduced considerably during soil passage but some of them are partially removed or simply pass through. In this context again, the post-treatment systems after NTSs should be robust enough to remove the micropollutants that are present in bank filtrates, water abstracted from ARR/SAT wells as well as in the effluents of CWs and pond systems before any use.

On the other hand, regulations may not allow the ARR or SAT of water containing higher concentrations of sediments, organic matter, nutrients and micropollutants. For those cases, extensive pre-treatment systems will be required to ensure that the regulations are met and the performances of NTSs are not affected by the presence of these emerging contaminants.

3.1.4 Energy crisis

Water supply (treatment and distribution) and wastewater (treatment and reuse) management is directly linked to energy consumption. A considerable amount of energy is used in water and wastewater treatment, contributing up to 50% of operational expenditures (ABB, 2012). Rapid rise in energy price worldwide has pointed out to the need of energy efficiency in water and wastewater treatment. In this context it is expected that there will be likely shift to environment-friendly and energy-efficient NTSs for water and wastewater treatment and reuse wherever feasible. Secondly, energy production and conversion depend on water availability. As a consequence, all water supply and wastewater management and reuse planning in future should to take both water and energy into consideration and aim for optimum utilization of these scare resources (Olsson, 2012; Lazarova *et al*., 2012). This implies that in future pre- and post-treatment systems should be designed and implemented together with the NTSs for water and wastewater treatment to minimize the energy use and to maximize the removal efficiencies.

3.1.5 Environmental awareness and stricter regulations

There is increasing environmental awareness and concern as well as stricter regulations over (i) the use of chemicals in water and wastewater treatment, (ii) presence of organic micropollutants in water and their impact on human health, (iii) impact of wastewater discharge to land and water bodies. This would mean that in future more efficient water and wastewater treatment systems will be legally required to meet the health and environmental regulations and standards. On one hand, this might lead of improvement in the quality of surface water sources used for BF and ARR and wastewater effluents used for SAT. Secondly, this would also require that comprehensive post-treatment systems are provided for each NTSs (as a backup or ultimate treatment barrier) to ensure that water quality guidelines and regulations are met at all times.

3.2 Post-treatment requirements for BF sites in India in future

Inferences on the potential impact of future scenarios on pre- and post-treatment systems for BF systems in India can be drawn from various plausible sources / scenarios, but equally importantly also from published literature on BF and climate change (Schoenheinz 2004, Schoenheinz and Grischek 2011, Sprenger *et al*. 2011). The future potential post-treatment requirements for BF sites in India are described in Table 11.

Table 11 Future scenarios and post-treatment requirements for bank filtration in India

Influencing factors (Future scenarios)	**Effect on Water Quality**	**Effect on Water Quantity**	**Impact on bank filtration**	**Coping strategies**
Population increase: - Increased water demand for different uses - Urbanization	May increase pollution in river and wells	May decrease due to lower ground-water level or surface recharge due to increased abstractions	Limit on water abstraction from a single well	- Constructing more wells along the river - Ensuring construction of well head & source protection zones
Climate change factors Increase in average temperature	Increased mineralization, more coliforms	May decrease	Floods (drought) may increase (decrease) the portion of bank filtrate in the well and thus change the amount of groundwater or direct surface infiltration	- Make wells closer to river - Higher chlorine dose
Increased flooding	Coliform breakthrough	Increase		- Flood-proofing of wells
Increased drought	High mineralization	Decrease		- Construct deeper wells
Variable precipitation patterns	Fluctuating water quality	May be variable		- Real-time water quality monitoring. - Installing multiple wells at varying distances and switching operations of the wells as per the conditions
Emerging contaminants; Deteriorating source water quality (increasing pollution)	May become worse	May not change, or increase or decrease due to change in clogging layer or hydraulic conductivity of the aquifer	It would still be effective in reducing pollutant load but would not be fully dependable without further water treatment	- Increase travel time/distance of well - Put additional layers of suitable aquifer material around the well - Additional post-treatment units according to the pollutant

3.3 Pre- and Post-treatment requirements for MAR sites in India in future

Environmental and socioeconomic developments such as increasing population, rapid urbanization and industrialization, along with climate change are important issues in the developing and newly industrialized countries of the world. It is expected that these factors affect the water resources quality and quantity, thus directly or indirectly affecting MAR systems.

Population growth in India is one of the major concerns in the economic and environmental context (Nair, 2009). Already now, both sufficient quantity and quality drinking of water cannot be supplied to the existing population. Therefore the predicted increase of 0.3 billion people in 2050 (PRB, 2007) is demanding additional drinking water storage, treatment and supply options to meet the increasing demand. Increasing sewage generation and agricultural activities are further results of population growth. In addition, growing urbanization and industrialization are important future developments that may lead to further increasing water demand and the release of industrial chemicals and emerging contaminants. In the past 100 years the share of urban population in India has increased from 10.8% (1901) to 27.8% (2001) of the total population (RGI, 2001). In the past three decades it has increased at a rate of 2% per decade (IUSSP, 2009). Industries are contributing to 20.2% of the total Gross Domestic Production (UNDP, 2011), an average growth rate of 8% maintained for the past few years clearly indicate growing importance. Already now the concentration of pesticides, pharmaceuticals and personal care products are increasing in both surface and groundwater of India (Agarwal *et al*. 2010; GRBMP, 2011).

Increasing frequency and severity of the extreme hydrological events are mostly attributed to the impacts of already ongoing climate change. Mall *et al*. (2006) summarized that, the beginning of the 21st century has witnessed drastic changes in the surface temperature, rainfall, evaporation and extreme events in India. However, the ultimate results of extreme climatic events are floods and droughts. The potential impacts of climate change scenarios are on MAR are discussed in the later part of this report.

It is clear that the effects of above mentioned scenarios can bring drastic effects on both groundwater and surface water. The reduction in availability and poor water quality expected under the above-mentioned conditions will have long term impacts on the performance of MAR systems. Recharge with poor quality water may result in frequent clogging and subsequent maintenance, which may reduce the efficiency of MAR system. In order to cope with this predicted condition, additional pre- and post-treatment may become necessary to meet the respective water quality guideline values. In this report different future scenarios are critically evaluated in terms of (i) influencing factors (ii) effects on water quality and quantity (iii) possible impact on MAR and (iv) coping strategies.

3.3.1 Effects of increasing population and water demand on MAR and coping strategies

Population increase is the leading factor that may affect both quality and quantity of water supply in the coming decades. It is projected that the population in India will reach 1.6 billion in 2050 against a current population 1.3 billion (PRB 2007). The predicted increase in population for the years 2000 to 2030 show that the share of rural population will reduce from 72% to 54%. On the other hand the urban population will have a share of 46% in 2030 compared to 29% in 2000. This shows that the urban population will increase comparatively at a higher rate than rural population in future (Brockerhoff, 2000).

Amarasinghe *et al.* (2007) predicted an overall increase in water demand from 680 billion cubic meter (bcm) in 2000 to 900 bcm in 2050. India is an agrarian country and its economy largely depends on agricultural production. Subsequently the agricultural sector is the largest consumers of water in India. Figure 6 shows the increasing water demand for 3 major sectors (domestic, agricultural and industries) that is forecasted from 2000 to 2050 (Amarasinghe *et al*. 2007). According to this study the domestic water demand will increase from 34 bcm to 101 bcm (up to 197% increase) – not only due to population growth but also a side-effect of urbanization and enhanced living conditions. Demand of water for irrigation, increasing from 605 (2000) to 637 bcm (2050), will exert more pressure on the groundwater resources and it is expected that water table will be lowered, if countermeasures are not taken. Among the three sectors, it is expected that industrial growth will exhibit the highest increase of 283% by increasing the water demand from 42 to 161 bcm. Already now, India is experiencing shortage of water for sufficient supply, so the predicted total increase in 2050 (of 220 bcm) will be a huge problem in the water sector.

Sewage generation

Increased water demand also impacts the water quality. The sewage production is directly proportional to water consumption. Currently open dumping of the sewage or directly mixing it with the surface water is a common practice in many places. Population increase will create the situation that already existing municipal sewage systems will exceed their capacities and this may lead to the contamination of surface water resources. It is predicted that the sewage volume in class I cities and class II towns for whole India will increase from 26,254 million litre per day (MLD) in 2003 to 83,300 MLD in 2051 (Bhardwaj, 2005). Out of 26,254 MLD of wastewater generated in 2003-04, only 7044 MLD (27%) are treated and the remaining 19,210 MLD (73%) was discharged without proper treatment (CPCB, 2005). Pollutants of main concern in wastewaters are nutrients (e.g. nitrate, phosphate), suspended solids and pathogens. High organic carbon content in surface water due to the sewage load results in an anoxic condition.

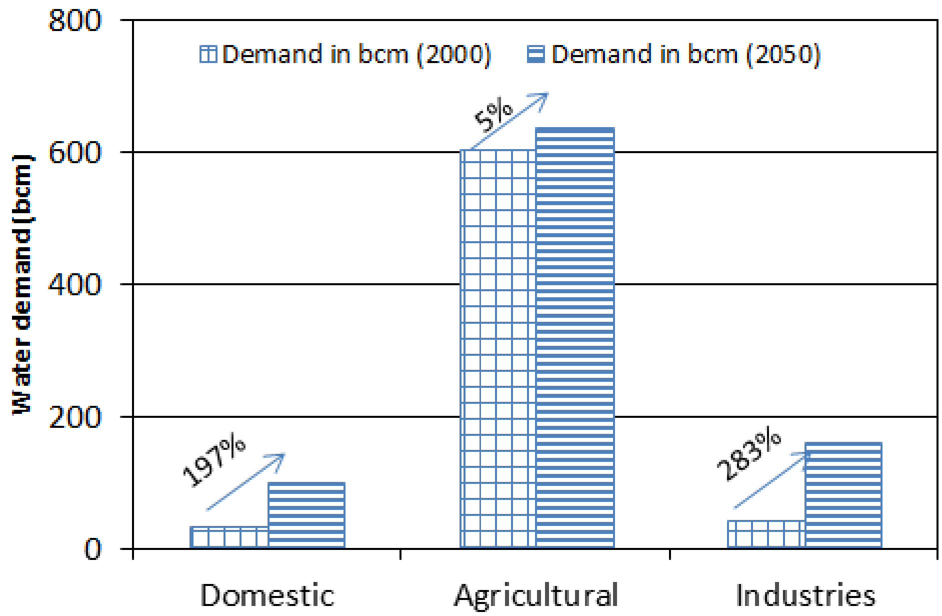

Figure 7 Projected water demand to 2050 for different sectors (Amarasinghe *et al*., 2007).

Agriculture

The need for more food for growing population will also accelerate the agricultural activities. Organic compounds from plant matter and nutrients, fertilizers and pesticides added to the soil in farming practices finally reach the water body (Hemond and Fechner-Levy, 2000). Consequently, this will cause the degradation of water quality through nitrate, phosphate and different pesticides (Moss, 2008). Higher level of nutrients may cause toxic algal blooms as well as taste and odour problems in the surface water resources.

Coastal Areas

Coastal aquifers are often densely populated and environmentally sensitive areas. Drastic changes in the land use are experienced in many of these locations and may result in considerable changes in the net groundwater recharge. Moreover, increased pumping may reduce the groundwater level and results in saline water ingression, making groundwater unfit for irrigation and human consumption.

Coping strategies

MAR systems are designed to operate based on surface water, harvested rainwater or reclaimed water. Therefore, the impacts of population growth on water resources have a definite effect on the performance of MAR systems. These impacts may lead to additional pre- and post-treatment requirements as well as adjusted cleaning and maintenance activities of recharge structures to meet the drinking/irrigation water quality guidelines. Higher concentrations of suspended solids originating from the increased sewage generation or flood events may need sedimentation and sand filtration. Increasing nitrate concentration in the water may be treated using suitable de-nitrification techniques such as RO, Ion exchange, biological de-nitrification etc. High concentration of Fe^{2+} and Mn^{2+} can be precipitated as oxides and which may be removed by sand filtration. In the case of pathogens, chlorination would be sufficient; otherwise ozonation or UV disinfection could be employed. Majority of these water quality impacts on MAR can be minimised by the provision of proper wastewater treatment systems (for municipal and industrial wastes) locally and strict regulations on effluent disposal to maintain water quality of rivers and lakes. An overview of the impacts of population growth on MAR systems is shown in Table 12.

Table 12 Possible impacts of population growth and industries/urbanisation on MAR

Influencing Factors	Effect on water quality	Effect on water quantity	Impacts on MAR	Coping strategies (additional pre- and post-treatment required)
Population growth - Projected population in the year 2050:1.3 to 1.6b.*(PRB 2007)* - Increasing water demand *(680 to 900* bcm)* (Amarasinghe et al. 2007; KPMG 2010) *Forcasted to 2050	- Increasing sewage volume in Class I cities and Class II towns from 2003 to 2051: *26,254 to 83,300 MLD (*Bhardwaj *2005)* - At the coastline groundwater overexploitation and subsequent seawater intrusion - Inadequate sanitation systems cause increase in nutrients and pathogens in water - Algal growth due to nutrients	- Increasing pressure on water resources - Increasing water demand	- Higher sewage load makes surface water unfit for MAR - Higher sewage load may cause clogging and deteriorate the quality of the recovered water in MAR systems. Therefore pre-treatment becomes necessary - Anoxic condition through high organic carbon and rising temperature	- Reducing sewage load on water bodies by providing proper wastewater treatment systems - Sedimentation and sand filtration for TSS removal (pre-treatment) - RO for salinity removal - NO_3: RO, Ion exchange, Biological de-nitrification etc. - Fe and Mn: aeration and sand filtration
Increasing industrialization*, urbanization and intensification of agriculture:** - Increasing pollution; deteriorating source water quality (emerging pollutants). - *Average industrial growth is reported as 8% per annum during 2007-2012 (Kaushal 2012;Planing Commission India 2012) - ** An average of 2% growth during past 3 decades (IUSSP 2009)	- Increased industrial effluents - Pollution from fertilizers and pesticides: (*Pesticides* levels of 13 µg/L against permissible limit of 1 µg/L were reported from the Ganga basin. Major threats were DDT and HCH (GRBMP, 2011), organochlorine pesticides higher than 1 µg/L observed in Delhi (Mutiyar *et al*., 2011)) - Higher CO_2 emission and acidic rainfall - Personal care products, pharmaceuticals, steroids and hormones and plasticizes levels will also be increased in future	- Stressed water resources	- Persistent pollutants (pesticides, PhACs, PCPs) may break through - Increased sulphur and nitrogen dioxides in the atmosphere may result in acidic rainfall. This lead to various hydrogeochemical reactions and subsequent source water contamination.in the aquifer - A higher NH_4 levels (>0.2 mg/L; Rastogi and Sarin, 2005) in rain were reported from Ahmedabad. - Source water rich in Na (from industries) may trigger the release of geogenic contaminants such as fluoride and increase their concentration.	- Strict regulation on effluent disposal to maintain water quality of river and lakes - Along with the conventional treatment methods like activated carbon, oxidation-filtration or membrane process such as NF and RO as post-treatment may be needed to remove the persistent compounds - Apart from the first flush and metallic filters, activated carbon filters and biofilms may be implemented to remove ammonia. - pH regulation using Na_2CO_3,NaOH $CaCO_3$ and $MgCO_3$ - F^-; electrocoagulation, ion exchange or membrane filtration as post-treatment

3.3.2 Effects of urbanization and industrial growth on MAR and coping strategies

As mentioned before the growth of industries may cause water pollution from the untreated organic and inorganic toxic industrial effluents and increased emission of harmful gases into the atmosphere. As a result of increased fossil fuel combustion, the amounts of sulphur and nitrogen oxides emitted to the atmosphere are increasing. These gases react with atmospheric moisture and precipitate as acid rain (mostly in the form of sulphuric acid, ammonium nitrate, and nitric acid). In India many researchers have reported cases of acid rain from the industrial cities like Delhi (Balachandran and Khilare, 2001), Bangalore (Shivashankara *et al*., 1999), Bombay (Khemani *et al*., 1989) and Dhanbad (Singh *et al*., 2007) in recent past. Acidic rainfall may cause undesirable geochemical reactions with the aquifer and that may alter the water quality (Johnson *et al*., 1981). A higher NH_4 level in the rain water reported from Ahmedabad (>0.2 mg/L; Rastogi and Sarin 2005) is also attributed to growing industrialization. This level may increase in future due to increasing air pollution.

As a geogenic contaminant, the mobility of fluoride from source rock is predominantly controlled by ions such as HCO_3^-, Ca^{2+} and Na^+ at an alkaline pH. In groundwater these ions are predominately sourced from the rock weathering. Several researchers reported that higher Na/Ca ratio is favourable for the F^- mobilization in groundwater (Guo *et al*., 2007; Rafiquea *et al*. 2009; Reddy *et al*., 2010; Currell *et al*., 2011; Kim *et al*., 2011). However, in quite a few locations in India, certain industries (e.g., tanneries) are discharging effluents enriched in common salt (NaCl). This uncontrolled anthropogenic increase in Na^+ ions (higher than natural sources) observed as indirectly triggering the F^- mobility from the source rock and increasing its level in groundwater (Sajil Kumar, 2012). This is applicable to other industries as well if Na^+ rich effluent discharge and F^- rich source rocks are present.

Emerging contaminants such as personal care products, antibiotics, prescription and non-prescription drugs, steroids and hormones, pesticides, plasticizers, surfactants and fire retardants are one of the priority concerns in the present water supply schemes (Bhandari *et al*., 2009; GRBMP, 2011). High levels of pesticides in water have been reported from few locations in India. Pesticides levels up to 13 µg/L (permissible limit 1 µg/L) are reported from the Ganga basin where DDT and HCH are the major threats (GRBMP, 2011). In another study at the BF site in Delhi, occurrence of pesticides such as DDT, HCH, Endosulfan and Aldrin was observed (Mutiyar *et al*., 2011). Increasing urbanization, industrialization and general standard of living suggest that the use of personal care products, pharmaceuticals, steroids and hormones and plasticizes levels may also be increasing in the future and emerging contaminants may be a growing concern on water quality.

It is observed that in the rainwater harvesting (RWH) systems in India, the only treatment applied is first flush diverter (a valve to remove the impurities from atmosphere and/or dirty roof top) and metallic/sand filters. In future, acidity and a comparatively less concentration of ammonia may found in rainwater. The existing methods may be sufficient because the subsurface passage of water may be enough to buffer the acidity as well as ammonium. Considering the health impacts of high F^- concentration in drinking water, suitable post-treatment techniques such as electro-coagulation, ion exchange or membrane filtration can be used (Meenakshi and Maheshwari, 2007).

Natural water treatment systems like MAR are successful in removing many organic micropollutants and pharmaceuticals although certain substances may persist in the subsurface (Grünheid *et al*., 2005). Additional treatment may be necessary to meet the drinking water guidelines. This will increase the overall cost of water treatment system. Although, conventional treatment methods will remove some substances still activated carbon, ozonation / biofiltration, NF or RO may still be required in future to remove pharmaceuticals and personal care products.

3.3.3 Effect of climate change on MAR systems and coping strategies

Although climate change is expected to have major impact on water supply (Delpla *et al*., 2009; Howard *et al*., 2010), studies on the vulnerability of MAR systems to climate change are rare. Sprenger *et al*. (2011) studied the impact of climate change on bank filtration (BF) systems. The authors argue that in contrast to mere surface water abstraction, BF holds the possibility, in times of lowered river discharge, that drinking water production may temporarily be switched to abstraction wells with a higher ambient groundwater share.

General projections of impact of climate change on MAR systems are difficult as MAR performance is highly site specific and climate change predictions are prone to uncertainties of climate scenarios and hydrological modelling (IPCC, 2007). Therefore, two climate scenarios (‘drought’ and ‘flood’) were selected in this report (see Table 13) to draw conclusions on how MAR systems may become affected irrespective of other concomitant changes (e.g. land adaptation). In this section climate change factors such as increasing temperature, floods and droughts are discussed according to their impacts on MAR systems as well as potential countermeasures in terms of pre- and post-treatment.

Table 13 Description of possible effects of drought and flood scenarios on water resources

Drought scenario	Flood scenario
- High evapotranspiration - Low precipitation - Low groundwater recharge - High groundwater abstraction - Low run-off and discharge regime	- High precipitation - High groundwater recharge - Low groundwater abstraction - High run-off and discharge regime
Resulting in predominant loosing river conditions, and on the long run intermittent river flow	Resulting in high river stages and occurrence of flood events

3.3.3.1 Change in precipitation pattern and resulting increase in floods and droughts

In India, failure of monsoon and unexpected rains cause droughts and floods every year. This section deals with the potential impact of floods and droughts on MAR systems. The impacts resulting from drought and flood scenarios are provided in Table 11.

Floods

Water availability

Substantial changes in the magnitude and frequency of floods are expected to affect Kolkata and other Indian cities are as a consequence of climate change (Gosain, 2013). Increased riverine and inland flooding, particularly in northern and eastern India where millions of people are currently affected, will last at least three months of the year (Revi, 2008). Many Indian river basins like Godavari and Mahandi are under severe threat from the climate change induced flood events (Gosain *et al*., 2006). Extreme precipitation events are also increasingly causing floods in the west coast of India, especially in Gujarat (Revi, 2008). Mumbai was affected by severe flood in 2005 and thousands of people lost their lives. Heavy floods were witnessed in Andhra Pradesh and Karnataka during October 2009.

Floods will increase the quantity of surface water but also groundwater recharge will be increased if aquifer storage is available and soil conditions are favourable. For the Krishna river basin e.g. the flood prone areas showed an increase of water table 0.5-4 m during 1999-2009 (NRAA, 2011). However, due to the poor management of flood events, available surplus water is not utilized effectively. Few useful countermeasures are suggested below.

Countermeasures

Other option is reducing the surface water supply by developing a groundwater based irrigation program. This will create reduced groundwater table and resulting in increased unsaturated zone/excess storage space (NRAA 2011). Moreover the surface water leftover in the storage structures could be utilized for other purposes. As practiced in Salisbury (Australia), excess water pumped to potential natural storage aquifers and recovery during stress period may be an option to increase the water availability (Page *et al*., 2009).

With regard to the water quality, in some cases dilution of already contaminated water may improve its quality. But in general, interaction with the contaminants oil, gasoline, nitrates and pesticides from agricultural fields and industrial chemicals, faecal matter from sewage systems and septic tanks may degrade the quality considerably (Huelshoff *et al*., 2009). Another important problem is the increase of TSS in water during flood events (Kale and Hire, 2004). These suspended particles may also act as carriers for heavy metals and pathogens. The discharge of water will increase and also cause inundation. Dilution of water is observed in the natural environments such as rural areas, where less contamination is expected. On the other hand in urban areas, water will be contaminated due to the interaction with pollution sources. Groundwater recharge by flood water may introduce contaminants such as nitrates, pesticides, industrial chemicals etc. that may deteriorate groundwater quality (Huelshoff *et al*., 2009).

Excess groundwater recharges in the agricultural fields rise the water table. This can bring salts into the plant root zone from deeper saline aquifers. These salts may accumulate preferably 2 m within the water table (Podmore, 2009). Soil-salinization may cause intensification of salt concentration in surface-water resources and undesirably affects the use of the water for different purposes (Williamson *et al*., 1987; Schofield *et al*., 1988; McFarlane and Williamson, 2002).

In the case of MAR, flooding events may cause physical damage to the structures such as infiltration basins or check dams. Frequent clogging of MAR structures by TSS and subsequent maintenance may increase the O&M cost. As mentioned earlier pre-treatments such as sedimentation tanks and filter systems may be necessary to avoid clogging.

<u>Droughts</u>

Drought is mainly attributed to a reduction of precipitation events, a condition were the discharge of water may be reduced or there will not be any discharge. In India drought is mainly due to failure of monsoon. Overall water quality and quantity will be affected.

Water availability

When surface water availability is limited and drought conditions are ongoing the pressure on groundwater resources will increase and subsequent lowering of the water table is likely. In coastal aquifers the freshwater flow may be reduced due to the drought as well as the over pumping of groundwater. Consequently seawater may intrude to the coastal aquifers and inland lakes.

Water quality

Increase in phosphate, pathogens and organic micropollutants can be observed due to increased evaporation and point source pollution in urban areas (Huelshoff *et al*., 2009; Hrdinka *et al*., 2012). In surface water bodies the low flow rate may accelerate algal blooms (Huelshoff *et al*., 2009). Higher concentrations of phosphates and nitrate also support eutrophication.

Table 14 Possible impacts of climate change scenarios on MAR systems

Influencing Factors	**Possible impacts on source water**		**Impacts on MAR (relies mostly on SW)**	**Coping strategies *(additional pre- and post-treatment required)***
Climate change	**Surface water**	**Ground water**		
Temperature increase IPCC (2007) predicted 6 scenarios to 2090-2099 A1FI : 4°C A1T : 2.4°C A1B : 2.8°C A2 : 3.4°C B1 : 1.8 °C B2 : 2.4°C	- Increased evaporation - Decreased O_2 solubility in water - Increased algal and phytoplankton growth - Increased DOC - Accelerateed microbial regrowth in distribution systems (Zwolsman, 2008)	- Impact of temperature may not be so immediate in GW as SW - Increased vegetation growth → CO_2 in the soil → groundwater may dissolve more $CaCO_3$ - Decreased viscosity and increased flow velocity	- Evaporation loss and concentration of salts - Higher temperature may result anoxic conditions during underground passage which may result in the mobilization of redox sensitive species including Fe, Mn and As	- F :electro-coagulation, ion exchange or membrane filtration - Algal toxins: Activated carbon - Taste and odour: Oxidation, adsorption - Fe, Mn, As: Aeration, SSF - Salinity: RO - Hardness: Ion Exchange
Flooding	- Surface run-off and inundation may mobilize point and non-point contaminants - Increase of TSS in flood water (Kale and Hire, 2004) - Increased river discharge and inundation	- Increased groundwater recharge - Possible introduction of contaminants by increased groundwater recharge	- Physical damage of the MAR structures (Agnese *et al*., 2013) - Frequent clogging of MAR structures by TSS and subsequent maintenance of CD, and CW	- TSS: Sedimentation, Sand filtration - Heavy metals: Chemical precipitation, ion exchange, phytoremediation, biological treatment etc. - Pathogens: Chlorination, UV treatment or ozonation
Drought	- Reduced/no discharge and reduced dilution potential - Algal blooms (Techneau 2009) - Increase in PO4, pathogens and organic micropollutants (Techneau 2009; Hrdinka et al. 2012) - Concentration of salts due to reduced stream flow	- Reduced/no GW recharge → declining water table - Lowering of freshwater table may cause intrusion of saltwater from the sea or inland salt lakes	- Complete/partial failure of the MAR due to lack of surface water - Increasing salinity	- Sulfate: Nanofiltration, ion exchange - Salinity: RO

3.3.3.2 Effect of increasing temperatures on NTSs

The surface temperature of the earth is increasing gradually with a higher rate in the past few decades. Next to pH the temperature is the physical parameter that has the most profound impact on water chemistry, biology and the processes involved in removal of contaminants. Several geochemical processes such as dissolution, complexation, degradation or evaporation will be favoured by increased temperature, whereas the solubility of gases decreases with inclining water temperature. Consequently, the capacity to dissolve oxygen is lowered in warm water. For instance, water of 10°C can dissolve 11.5 mg/L O_2 while with 20°C only 9.4 mg/L oxygen can be dissolved in equilibrium with the atmosphere.

Though it is a global scenario, most of the impacts are more visible in the highly populated and already water stressed regions (Huelshoff *et al*., 2009). IPCC (2007) estimated six major scenarios, namely A1, A1FI, A1T, A2, B1 and B2, of global average surface temperature in 2090-2099 relative to 1980-1999. All the six scenarios are explained in detail in the section below.

A1: represents the future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. A1 scenario is subdivided based on the technological change in the energy system into three groups; fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). The predicted temperature increase for A1FI, A1T and A1B are 4, 2.4, and 2.8°C, respectively.

A2: describes a very heterogeneous world, continuously increasing population. Economic development is regionally oriented and per capita economic growth and technological change more fragmented and slower than other scenarios. The best predicted estimate of temperature increase in 2090-2099 is 3.4°C.

B1: describes same global population, as in the A1 scenario, but accompanied by quick revolution in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The best predicted estimate of temperature increase in 2090-2099 is 1.8.

B2: describes a world that is emphasized on local solutions to economic, social and environmental sustainability, continuously increasing global population as in A2 with a lower rate, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1. The best predicted estimate of temperature increase in 2090-2099 is 2.4°C.

Algal blooms in the surface water

According to Sorokin and Krauss (1962), algae growth is slow at colder temperatures and will keep increasing till reaching the optimum level. The range may be noted as 20-40°C with an optimum value at 30°C (Sanchez *et al*., 2008; Christov *et al*., 2001; Cassidy, 2011). Similar observations were reported by Eppley (1972). Under the predicted climate change the temperature of the surface waters may fall well within this range and may cause severe algal blooms. This may result in water quality problems such as algal toxins (e.g. microcystins and anatoxins), as well as distinctive odour and taste (Ibrik, 2004). Algal toxins can be treated using activated carbon. For the taste and odour conventional treatment techniques such as oxidation and adsorption may be adopted.

Pathogens in the subsurface

The temperature dependencies of microorganisms may vary considerably across different groups. An increase in temperature may enhance the growth rate to a certain temperature (depending up on the type of organism). Beyond that level, structural cell components become denatured and inactivation of heat-sensitive enzymes occurs. In general, the increase in temperature results in higher inactivation, die-off and sorption of micro-organisms (Foppen and Schijven, 2006; Berger, 2002; Dasch et al., 2008). Temperature is the most important factor that influences virus inactivation and the rate increases with temperature. Extreme temperature increase may show a positive effect on the microbial inactivation, so that pre- or post-treatment may not be necessary. However, in case of pathogens present in the recovered water chlorination or UV treatment/ozonation may be adopted.

Evaporation

The water holding capacity of the atmosphere is increased by the increase in temperature, resulting in evaporation. Warmer climate will accelerate the hydrologic cycle, altering rainfall, magnitude and timing of run-off. Increased evaporation may dry out some areas and fall as excess precipitation on other areas (EPA, 2013). The major impact of source water quantity will be the loss of water as evaporation and falling groundwater levels/availability. In MAR systems like basin infiltration or check dams comprise open surface water areas, evaporation of water during high temperature periods may cause a loss of source water and also increasing concentration of salts. High salinity in the recovered water may need pre/post-treatment such as RO, NF and cation exchange.

Change in water viscosity

The hydraulic conductivity (k-value) describes the water movement through porous media. It depends, among other, also on the viscosity of water. As the temperature increases, viscosity of the water will decrease and so as the hydraulic conductivity (Haridasan and Jensen, 1972). Kestin *et al*. (1974) summarized that for a range of temperature 20, 40 and 60°C the viscosity of water is decreasing to 1002, 652 and 466 µPas, respectively. In another study the infiltration rate during pond infiltration was estimated to increase from 0.056 cm/hr (in winter) to 0.127 cm/hr (in summer) (Braga et al. 2007). This results show that increase in temperature will increase infiltration rate in MAR structures, but may result in shorter travel times; i.e., less time for substance degradation.

Redox conditions

In the case of ASR/ASTR and infiltration ponds, increase in temperature may create anoxic conditions during subsurface passage. Increased oxygen consumption due to the organic matter degradation during subsurface passage may create redox zones where electron acceptors such as nitrate, manganese, iron oxide, hydroxide and sulphate may be mobilized (Massmann *et al*., 2008; Gross-Wittke, 2010; Farnsworth and Hering, 2011). Significant changes in the above mentioned species due to increasing temperature were observed during bank filtration at lake Tegel in Berlin (Gross-Wittke, 2010). The ensuing anoxic condition was resulted in the increased use of alternative electron acceptors such as NO_3 microbial catalysed reduction of nitrate/ammonification, denitrification and reduction of Mn^{4+} and Fe^{3+} followed by enrichment of groundwater with manganese and iron (Gross-Wittke, 2010). A slight increase in SO_4 was also reported. High concentration of Fe^{2+} and Mn^{2+} in the recovered water, aeration and Slow Sand Filtration (SSF) may be adopted as post treatment.

3.3.4 Summary and conclusion

The predicted population increase from 1.3 billion (2011) to 1.6 billion (2050) in India is likely to have severe effects on the already stressed water resources. The impacts of population growth on MAR could be increased sewage production, combined with probable GW overexploitation, increased use of fertilizers etc. A total of 32% increase in water use is estimated for 2050. Higher TSS in source water from sewages may result in clogging of MAR. This may be tackled by installing sedimentation and sand filtration as additional pre-treatment. Higher salinity due to overexploitation may be treated with RO. Increased use of fertilizers and improper sanitation facilities may result in elevated nitrogen in surface water. This can be treated by RO, Ion exchange, and biological de-nitrification.

The major impacts of urbanization and industrial growth were identified as increasing industrial effluents, higher SO_2 and NO_2 emission resulting in acid rain, increased use of pesticides and personal care products as well as other organic pollutants. For the emerging pollutants additional pre/post-treatment such as activated carbon, oxidation-filtration or membrane process such as NF and RO were suggested. For higher ammonium concentrations in rainwater, activated carbon filters may be used. In case of higher fluoride concentrations electro-coagulation, ion exchange or membrane filtration may be adopted.

The different climate change scenarios were investigated based on scenarios of increasing average temperatures, floods and droughts. Temperature has a gradual but continuous effect on water quality and quantity in terms of increased rates of algal growth, evaporation and concentration of salts, a change in hydrological cycle and triggering biogeochemical processes.

For MAR, an increase in temperature may result in anoxic conditions during subsurface passage which may result in the mobilization of redox sensitive species like nitrate, manganese, iron oxide, hydroxide and sulphate loss of water by evaporation is an issue for MAR structures with large open surfaces (e.g. check dams and infiltration ponds). The pre-/post-treatment need for water under the increasing temperature are: (i) fluoride with electro-coagulation, ion exchange or membrane filtration; (ii) algal toxins with activated carbon, (iii) taste and odour with oxidation and adsorption, (iv) Fe, Mn and As with aeration + filtration, (v) salinity with reverse osmosis, and (vi) hardness with lime softening or ion exchange.

If conditions are suitable flooding may increase groundwater recharge. However, uncontrolled flooding cause groundwater contamination through the interaction with the contaminant sources like agricultural fields, industrial and urban wastes. Increase in TSS load in the groundwater is the most common problem anticipated. Higher TSS level may cause clogging in natural treatment systems. In groundwater the flow length and/or travel times may be reduced and is may affect the treatment efficiency. Physical damage of the MAR structures is also possible. TSS may also act as carriers for the heavy metals that potentially need treatment. Sedimentation tanks and SSF can be adopted to avoid the higher TSS level.

Drought reduces the discharge and dilution potential of the surface water which may cause more frequent algal blooms. Point source pollution and irrigation return flows are expected. Groundwater recharge will be reduced, decreasing freshwater flow which may end up in saline intrusions. Lowering of water table and subsequent atmospheric exposure may oxidise the sulphate minerals. Drought may result in the failure of MAR structures. The potential coping strategies may be the treatment of sulphate with nanofiltration and ion exchange and salinity with reverse osmosis.

MAR systems are generally robust, and flexible towards the changing conditions, failures in achieving the required water quality objectives can be met by additional pre-or post-treatment.

3.4 Pre- and post-treatment requirements for CW and other natural wastewater treatment systems in India in future

In general, natural wastewater treatment systems like CW and pond systems are relatively robust and flexible in terms of their capability to handle the variation in influent water quality. The future scenarios of population growth, urbanization and industrialization, alteration in the water quality matrix of wastewater generated as well as climatic change conditions are likely to influence the performance of NTSs in terms of removal efficiencies for different contaminants of concern. Table 15 presents the possible impacts of population growth and industrialization/urbanization on CW and other NTSs for wastewater treatment. It is expected that these technologies will continue to be relevant also in future to take care of potential increase in the quantity and change in concentrations of the pollutants. Additionally, pre-treatment will be required in the future to reduce the sediment loads further in order to maximise bulk organic and nutrient removal capabilities of NTSs. It is likely that with urbanization and industrialization higher load of organic micropollutants may end up in the wastewater which may not be properly or completely removed in these NTSs alone. In that context, post-treatment methods like activated carbon, (advanced) oxidation-filtration or membrane process such as NF and RO may be needed to remove the organic micropollutants. The type of post-treatment required for each type of NTSs is mainly dependent on the intended use of the effluents from these systems (irrigation - unrestricted or restricted, non-potable and potable municipal reuse or industrial reuse) and the local regulations and guidelines for effluent reuse and/or regulation and bylaws related to disposal.

Table 16 highlights the possible impact of climatic change on CW systems. Potential increase in average temperature may lead to increased evaporation loss and higher concentration of salts in effluent. On contrary changing precipitation pattern may affect the water requirements (from treatment flow stream) for the growth of the plants. Additionally, higher temperature may result anoxic conditions during underground passage which may result in the mobilization of redox sensitive species including Fe, Mn and As. Increased incidences of flooding may cause physical damage of the CW based treatment systems as well as other NTSs structures. This may also lead to frequent clogging of CW based treatment systems as well as other NTSs. On the other hand some increase in temperature may be beneficial for biodegradation as well biomass growth. Therefore, it is expected that, depending upon the intended use, future CW effluents will likely need some physicochemical post-treatment ranging from disinfection to membrane filtration and advanced oxidation.

Table 15 Possible impacts of population growth and industries/urbanisation on CW-based treatment systems and other NTSs

Influencing Factors	Effect on water quality	Effect on water quantity	Impacts on CW-based treatment systems and other NTSs	Coping strategies (additional pre- and post-treatment required)
Population growth - Projected population in the year 2050:1.3 to 1.6b.*(PRB 2007)* - Increasing water demand *(680 to 900* bcm)* (Amarasinghe *et al*., 2007; KPMG 2010) *Forecasted to 2050	- Increasing sewage volume in Class I cities and Class II towns from 2003 to 2051: *26,254 to 83,300 MLD* (Bhardwaj, *2005)* - At the coastline groundwater overexploitation and subsequent seawater intrusion - Inadequate sanitation systems cause increase in nutrients and pathogens in water - Algal growth due to nutrients	- Increasing pressure on water resources - Increasing water demand	- Higher sewage load makes surface water more contaminated and CW based treatment systems as well as other NTSs will continue to remain relevant. - Higher sewage load will also need serious pre-treatment to prevent clogging. Therefore pre-treatment will continue to remain essential.	- Sedimentation and sand filtration for TSS removal (pre-treatment) - RO for salinity removal - NO_3: RO, Ion exchange, Biological de-nitrification etc - Fe and Mn: aeration and sand filtration
Increasing industrialization*, urbanization and intensification of agriculture:** - Increasing pollution; deteriorating source water quality (emerging pollutants). - *Average industrial growth is reported as 8% per annum during 2007-2012 (Kaushal 2012;Planing Commission India 2012) - ** An average of 2% growth during past 3 decades (IUSSP 2009)	- Increased industrial effluents - Pollution from fertilizers and pesticides: (*Pesticides* levels of 13 µg/L against permissible limit of 1 µg/L were reported from the Ganga basin. Major threats were DDT and HCH (GRBMP, 2011), organochlorine pesticides higher than 1 µg/L observed in Delhi (Mutiyar *et al*. 2011)) - Higher CO_2 emission and acidic rainfall - Personal care products, pharmaceuticals, steroids and hormones and plasticizes levels will also be increased in future	- Stressed water resources	- Persistent pollutants (pesticides, PhACs, PCPs) may break through - Increased sulphur and nitrogen dioxides in the atmosphere may result in acidic rainfall. This lead to various hydrogeochemical reactions and subsequently may affect the bio-geo-chemical cycling of base metal cations in CW based treatment systems as well as other NTSs. - A higher NH_4 levels (>0.2 mg/L; Rastogi and Sarin 2005) in rain were reported from Ahmedabad. - Source water rich in Na (from industries) may trigger the release of geogenic contaminants such as fluoride and increase their concentrations.	- Along with the conventional treatment methods like activated carbon, oxidation-filtration or membrane process such as NF and RO as post-treatment may be needed to remove the persistent compounds. - Apart from the first flush and metallic filters, activated carbon filters and biofilms may be implemented to remove ammonia. - pH regulation using Na_2CO_3,NaOH $CaCO_3$ and $MgCO_3$ - F^-; electro-coagulation, ion exchange or membrane filtration as post-treatment

Table 16 Possible impacts of climate change scenarios on CW systems

Influencing Factors	**Possible impacts on source water**		**Impacts on CW based treatment systems as well as other NTSs**	**Coping strategies** ***(additional pre- and post-treatment required)***
Climate change	**Surface water**	**Ground water**		
Temperature increase IPCC (2007) predicted 6 scenarios to 2090-2099 A1FI : 4°C A1T : 2.4°C A1B : 2.8°C A2 : 3.4°C B1 : 1.8 °C B2 : 2.4°C	- Increased evaporation - Decreased O_2 solubility in water - Increased algal and phytoplankton growth - Increased DOC - Accelerateed microbial regrowth in distribution systems (Zwolsman, 2008)	- Impact of temperature may not be so immediate in GW as SW - Increased vegetation growth → CO_2 in the soil → groundwater may dissolve more $CaCO_3$ - Decreased viscosity and increased flow velocity	- Evaporation loss and concentration of salts - Higher temperature may result anoxic conditions during underground passage which may result in the mobilization of redox sensitive species including Fe, Mn and As	- <u>F</u> :electrocoagulation, ion exchange or membrane filtration - <u>Algal toxins:</u> Activated carbon - <u>Taste and odour:</u> Oxidation, adsorption - <u>Fe, Mn, As</u>: Aeration, SSF - <u>Salinity:</u> RO - <u>Hardness:</u> Ion Exchange
Flooding	- Surface run-off and inundation may mobilize point and non-point contaminants - Increase of TSS in flood water (Kale and Hire, 2004) - Increased river discharge and inundation	- Increased groundwater recharge - Possible introdcution of contaminats by increased groundwater recharge	- Physical damage of the CW based treatment systems as well as other NTSs structures - Frequent clogging of CW based treatment systems as well as other NTSs	- <u>TSS:</u> Sedimentation, Sand filtration - <u>Heavy metals:</u> Chemical precipitation, ion exchange, phytoremediation, biological treatment etc. - <u>Pathogens</u>: Chlorination, UV treatment or ozonation
Drought	- Reduced/no discharge and reduced dilution potential - Algal blooms (Techneau 2009) - Increase in PO4, pathogens and organic micropollutants (Techneau, 2009; Hrdinka *et al.* 2012) - Concentration of salts due to reduced stream flow	- Reduced/no GW recharge → declining water table - Lowering of freshwater table may cause intrusion of saltwater from the sea or inland salt lakes	- Complete/partial failure of the CW based treatment systems as well as other NTSs due to lack of sewage - Increasing salinity	- <u>Sulfate:</u> Nanofiltration, ion exchange - <u>Salinity:</u> RO

4. Summary and Conclusions

Typical pre- and post-treatment systems used for different types of NTSs worldwide were reviewed and pre- and post-treatment of NTSs in India was analyzed based on literature review and field data collection. Furthermore, key future scenarios or global change drivers which are likely to influence the performance of NTSs were identified and their effect on quantity and quality of water obtained from NTSs as well as coping strategies were outlined.

It was found that BF systems in northern part of India, specifically Saph Pani project case study sites in Uttarakhand, with relatively clean rivers and lakes, are effective in treating water nearly to the quality requirements for drinking water supply. Chlorination is the only treatment necessary and applied to maintain residual chlorine in the distribution system. Some additional chlorination may be required for control of pathogenic organisms during flooding periods. However, BF systems along relatively polluted stretches of river like Yamuna (in Delhi and Mathura) will require extensive post-treatment to remove bulk organic matter as well as organic micropollutants. It is expected that post-treatment of BF with advanced treatment processes like ozonation, activated carbon filtration and membrane filtration will be required for such BF systems to meet the water quality guidelines. The post-treatment requirements for BF systems are likely to increase in the future unless comprehensive programmes are implemented for control of indiscriminate wastewater disposal to water bodies. Construction of wells at proper distance from the river, increasing depth of abstraction wells, increasing the number of wells as well as flood proofing of the wells are some of the coping strategies for the design of BF systems to meet future challenges with respect to quantity and quality of water.

To date majority of the MAR systems in India are designed and constructed aiming at use of rainwater or flood water for groundwater augmentation and therefore pre-treatment is mostly limited to sedimentation basins and sand filters to avoid clogging and to maintain the infiltration rate. Pre-treatment requirements will be more critical in the future if the quality of the rain or storm water changes significantly and if wastewater treatment plant effluents are used for MAR. Secondly, the direct and planned abstraction of recharged water after MAR for municipal and industrial is not practiced. Therefore, post-treatment requirements for MAR systems are not well known or documented. Post-treatment of "ground water" in India is mainly limited either to disinfection to remove pathogens (in case of shallow and contaminated aquifers) or to removal of geogenic contaminants like Fe, Mn, As and F.

The impacts of population growth on MAR could be due to increased sewage production, combined with probable groundwater overexploitation, increased use of fertilizers and pesticides etc. Post-treatment methods like aeration followed by rapid sand filtration, coagulation or adsorption-based processes would be relevant for removal of geogenic contaminants (Fe, Mn, As and F) now and in future due to several potential water quality impacts of global change pressures. Additional advanced post-treatment options would be required in future to deal with organics, nutrients and micropollutants in water from sewage pollution, fertilizers and pesticides. A potential increase in the incidences of floods and droughts in parts of India would further demand the increased use of MAR as an integrated water resource management option which would need suitable pre- and post-treatment systems.

The field survey of NTSs in India showed that CW and other natural systems for wastewater treatment, when operating properly, are meeting the CPCB standards for disposal and hence do not require additional post-treatment. However, the majority of the NTSs installed are not functioning properly or not meeting the water quality requirements due to poor O&M maintenance. Furthermore, some of the NTSs systems do not have proper pre-treatment systems. Therefore, proper design, implementation and O&M of pre-treatment systems require serious attention to improve overall performance of NTSs in India.

As there is water scarcity in different parts of India for municipal, industrial as well as agricultural use, appropriate post-treatment of CWs and other NTS effluents to meet different quality requirements for various intended use should be promoted. Research at IIT Bombay clearly showed low cost biochar prepared from CW plant systems would be effective in further polishing of the effluent from CWs, specifically phosphate. The field survey has also clearly shown that the concentration of microbial organisms is relatively high in the effluents of NTSs even for agricultural reuse. This can be addressed either by proper design of pre-treatment and NTSs or with the introduction of a range of post-treatment systems (e.g. disinfection) depending upon water quality requirements. In general, post-treatment of effluents from NTSs is expected to become more and more essential in future, firstly to compensate the influence of increased incidences of precipitation, floods or droughts on performance of NTSs and secondly to provide multiple barrier treatment system for high end re-use in order to reduce water scarcity in municipal (potable and non-potable) and industrial sector.

5. References

ABB (2012) Wastewater Treatment - Brochure. www.abb.com/water

Agarwal, A., Pandey, R.S. and Sharma, B. (2010) Water Pollution with Special Reference to Pesticide Contamination in India. *J. Water Resource and Protection*, 2:432-448

Amarasinghe, U.A., Shah, T., Turral, H, and Anand B.K. (2007) India's water future to 2025 - 2050: Business-as-usual scenario and deviations. Colombo, Sri Lanka: International Water Management Institute. 47p. (IWMI Research Report 123).

Arceivala, S.J. and Asolekar, S.R. (2006) Wastewater Treatment for Pollution Control (3rd Edition, 8th Reprint) Tata McGraw Hill Education (India) Pvt. Ltd., New Delhi.

Asolekar, S.R., Kalbar, P.P., Chaturvedi, M.K.M. and Maillacheruvu, K. (2013) Rejuvenation of Rivers and Lake in India: Balancing Societal Priorities with Technological Possibilities. In Volume 4 - Sustainability of Water Quality Ed. Jerald Schnoor, In Comprehensive Water Quality and Purification Edited by Satinder Ahuja [Accepted, Elsevier Publication].

Bartak, R., Page, D., Sandhu, C., Dillon, P. and Grischek, T. (2013) Haridwar risk assessment: Managed Aquifer Recharge and Water Safety plan. CSIRO, Australia.

Brockerhoff, M.P. (2000) An Urbanizing World. Population Bulletin, Washington, DC: Population Reference Bureau. 55 (3): 1- 48.

Balachandran, S. and Khilare, P.S. (2001). Occurrence of Acid rain over Delhi. *Environmental Monitoring and Assessment*, 71:165–176

Bhandari, A., Surampalli, R.Y., Adams, C.D., Champagne, P., Ong, S.K., Tyagi, R.D, and Zhang, T.C. (2009) Contaminants of emerging environmental concern. American Society of Civil Engineers, USA.

Bhardwaj, R.M. (2005) Status of Wastewater Generation and Treatment in India. IWG-Env, International Work Session on Water Statistics, Vienna, June 20-22 20. Pp 1-9

Braga, A., Horst, M, and Traver, R.G. (2007) Temperature Effects on the Infiltration Rate through an Infiltration Basin BMP. *J. Irrig. Drain Eng.,* 133:593-601.

Caselles-Osorio, A. and Garcia, J. (2007) Effect of physico-chemical pretreatment on the removal efficiency of horizontal subsurface-flow constructed wetlands. *Environ. Pollut*. 146, 55–63.

Cassidy, K.O. (2011) Evaluating Algal Growth At Different Temperatures. Theses and Dissertations, Biosystems and Agricultural Engineering. Paper 3.

Chen, B., Chen, Z. and Lv, S. (2011). A novel magnetic biochar efficiently sorbs organic pollutants and phosphate, *Bioresource Technology*, 102, 716-723.

Christov, C., Pouneva, I., Bozhkova, M., Toncheva, T., Fournadzieva, S, and Zafirova, T. (2001) Influence of temperature and methyl jasmonate on Scenedesmus incrassulatus. *Biologia Plantarum* 44(3):367-371.

Cooley, H., Ajami, N., Ha, M.-L., Srinivasan, V., Morrison, J., Donnelly, K. and Christian-Smith, J. (2013). Global Water Governance in the 21st Century. Pacific Institute, USA.

CGWB (2007) *Manual on Artificial Recharge of Groundwater*. Central Ground Water Board, Government of India.

CPCB (2005) *Status of Sewage Treatment in India*. Central Pollution Control Board, p.101.

Currell, M., Cartwright, I., Raveggi, M. and Han, D. (2011) Controls on elevated fluoride and arsenic concentrations in groundwater from the Yuncheng Basin, China. *Applied Geochemistry* 26:540–552.

Dahab, M.F. and Surampalli, R.Y. (2001) Subsurface-flow constructed wetlands treatment in the plains: five years of experience. *Water Science & Technology*, 44 (11-12), 375–380.

Dash, N., AL-Zarouni, M., Al-Kous, N., Al- Shehhi, F., Al-Najjar, J., Senok, A. and Panigrahi D (2008) Distribution and Resistance Trends of Community Associated Urinary Tract Pathogens in Sharjah, UAE. *Microbiology Insights*, 1:41–45.

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

Eckert, P., and Irmscher, R. (2006) Over 130 years of experience with riverbank filtration in Düsseldorf, Germany. *Journal of Water Supply: Research and Technology- AQUA,* 55(4), 283–291.

Eckert, P., Lamberts, R. and Wagner, C. (2006). The impact of climate change on drinking water supply by riverbank filtration. *Water Science and Technology - Water Supply,* 8(3), 319-324.

Eppley, R.W. (1972) Temperature and Phytoplankton Growth in the Sea. Fishery Bulletin 7:1063-1085

Farnsworth, C.E. and Hering, J.G. (2011) Inorganic Geochemistry and Redox Dynamics in Bank Filtration Settings. *Envi Sci and Tech,* 45:5079–5087.

Foppen, J.W.A and Schijven, J.F. (2006) Evaluation of data from the literature on the transport and survival of Escherichia coli and thermotolerant coliforms in aquifers under saturated conditions. *Water Research*, 40:401 – 426.

Gajurel, D. R., Benn, O., Li, Z., Behrendt, J. and Otterpohl, R. (2004) Pre-treatment of domestic wastewater with pre-composting tanks: evaluation of existing systems. *Water Science and Technology*, 48(11), 133-138

Gosain, A.K., Rao, S. and Basuray, D. (2006) Climate change impact assessment on hydrology of Indian river basins. *Current Science*, 90:346–353

GRBMP (2011) Emerging contaminants in Ganga River Basin with special emphasis on pesticides. GBP_IIT_EQP_SOA_02_report _ver 01. Pages 33.

Gröschke, M. (2012) *Hydrogeological characterization of Raipur Urban Area, Chhattisgarh, India - Hydrochemistry and isotope investigations* Hydrogeology Group, Department of Earth Sciences. Berlin, Freie Universität Berlin. Masters: 63

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

Grünheid, S., Amy, G. and Jekel, M. (2005) Removal of bulk dissolved organic carbon (DOC) and trace organic compounds by bank filtration and artificial recharge. *Water Research*, 39 (14): 3219-28

Guo, Q., Wang, Y., Ma, T. and Ma, R. (2007) Geochemical processes controlling the elevated fluoride concentrations in groundwaters of the Taiyuan Basin, Northern China. *J. Geochem. Explor*., 93:1–12.

Hamouri, B. El., Nazih, J. and Lahjouj, J. (2007) Subsurface-horizontal flow constructed wetland for sewage treatment under Moroccan climate conditions, *Desalination*, 215: 153–158.

Haridasan, M. and Jensen, R.D. (1972) Effect of temperature on pressure head-water content relationship and conductivity of two soils. *Soil Sci. Soc. Am. J*., 36:703-708.

Holländer, H. M., Mull, R. and Panda, S. N. (2009) A concept for managed aquifer recharge using ASR-wells for sustainable use of groundwater resources in an alluvial coastal aquifer in Eastern India. *Physics and Chemistry of the Earth,* 34: 270-78.

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

Howe, C., Smith, J.B. and Henderson, J. (2010) *Climate Change and Water: International Perspectives on Mitigation and Adaptation*. American Water Works Association, IWA Publishing.

Hemond, H.R. and Fechner-Levy, E.J. (2000) *Chemical Fate and Transport in the Environment*. Academic San Dieago, CA, USA.

Hoffmann, H., Platzer, C., Heppeler, D., Barjenbrunch, MTr., ¨Anckner, J. and Belli P (2002) Combination of anaerobic treatment and nutrient removal of wastewater in Brazil. In: *Proceedings of the 3rd Water World Congress*, April, Melbourne, Australia, 9–12.

Hrdinka, T., Novicky, O. Hanslık, E. and Rieder, M. (2012) Possible impacts of floods and droughts on water quality. *Journal of Hydro-environment Research*, 6:145-150.

HTWD and UJS (2013) Report on investigation of post-treatment of riverbank filtration case study site Haridwar for Saph Pani project. Report prepared by Division of Water Sciences, Faculty of Civil Engineering & Architecture, Dresden University of Applied Sciences (HTW Dresden), Dresden, Germany and Uttarakhand State Water Supply and Sewerage Organisation – Uttarakhand Jal Sansthan (UJS), Riverbank Filtration Cell, Jal Bhawan, Dehradun, India.

Huelshoff, I. Greskowiak, J. and Gruetzmacher, G. (2009) TECHNEAU Deliverable 5.2.3 Analysis of the vulnerability of bank filtration systems to climate change by comparing their effectiveness under varying environmental conditions. pp 38.

Indian Standard IS 10500 (1991) Indian Standard Specifications for Drinking Water (reaffirmed 1993). Bureau of Indian Standards, New Delhi, India.

IFRC (2008) Household Water Treatment and Safe Storage in Emergencies. International Federation of Red Cross and Red Crescent Societies. Geneva, Switzerland.

IPCC (2007) Fourth Assessment Report: Climate Change Impacts, Adaptation and Vulnerability Summary for Policy-Makers. Intergovernmental Panel on Climate Change.

IPCC (2007) Climate Change: Synthesis Report 2007. An Assessment of the Intergovernmental Panel on Climate Change. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

Ibrik, Z. (2004) Potential effect of climate change on algal growth. Master thesis. Concordia University, Montreal, Quebec, Canada, pp. 151

IUSSP (2009) Urbanization in India: Dynamics & Consequences. http://iussp2009.princeton.edu/papers/91026

Jensen, V.B., Darby, J.L., Seidel, C. and Gorman, C. (2012) Drinking water treatment for nitrate. Technical Report 6. In: Addressing Nitrate in California's drinking water with a focus on Tulare lake basin and Salinas valley groundwater. Report for the State Water Resources Control Board to the Legislature. Center for Watershed Sciences, University of California, Davis.

Johnson, N.M., Driscoll, C.T., Eaton, J.S., Likens, G.E. and McDowell, W.H. (1981) Acid rain', dissolved aluminum and chemical weathering at the Hubbard Brook Experimental Forest, New Hampshire. *Geochimica et Cosmochimica Acta*, 45: 1421-1437

Kale, V.S. and Hire, P.S. (2004) Effectiveness of monsoon floods on the Tapi River, India: Role of channel geometry and hydrologic regime: *Geomorphology*, 57: 275–291

Kaushala, R. (2012) Industrial growth during five year plans. http://www.slideshare.net/crazykudi/industrial-growth-in-in

Khemani, L.T., Momin, G.A., Rao, P.S.P., Safai, P.D., Singh, G. and Kapoor, R.K. (1989) Spread of acid rain in India. *Atmospheric Environment*, 23:757–762

Kestin, J., Sokolov, M. and Wakeham, W.A. (1978). Viscoicty of liquid water in the range 8°C- 150°C. *J. Phys.Chem. Ref. Data,* 7:941-948

Kim, Y., Kim, J. and Kim, K. (2011. Geochemical characteristics of fluoride in groundwater of Gimcheon, Korea: lithogenic and agricultural origins. *Environ Earth Sci*., 63:1139–1148

KPMG (2010) Water sector in India: Overview and focus areas for the future. kpmg.com/in

Kumar, P., Mehrotra, I., Boernick, H., Schmalz, V., Worch, E., Schmidt, W. and Grischek, T. (2012) Riverbank Filtration: An Alternative to Pre-chlorination. *J. Indian Water Works Association*, Special Issue on River Bank Filtration, 50-58.

Lazarova, V. Choo, K.-H. and Cornel, P. (2012) Water-Energy Interactions in Water Reuse. IWA Publishing.

Le Corre, K., A. Aharoni, J. Cauwenberghs, A. Chavez, H. Cikurel, M. Neus Ayuso Gabella, B. Genthe, R. Gibson, B. Jefferson, P. Jeffrey, B. Jimenez, C. Kazner, C. Masciopinto, D. Page, R. Regel, S. Rinck-Pfeiffer, M. Salgot, M. Steyn, E. van Houtte, G. Tredoux, T. Wintgens, C. Xuzhou, L. Yu and X. Zhao (2012). Water Reclamation for Aquifer Recharge at the Eight Case Study Sites: A Cross Case Analysis. *Water reclamation technologies for safe managed aquifer recharge.* C. Kazner, T. Wintgens and P. Dillon (eds.), IWA Publishing.

Lentz, R.D. and Bjorneberg, D.L. (2001) Influence of Irrigation Water Properties on Furrow Infiltration: Temperature Effects. In: D.E. Stott, R.H. Mohtar and G.C. Steinhardt (eds). 2001. Sustaining the Global Farm. Selected papers from the 10th International Soil Conservation Organization Meeting held May 24-29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory. p.705-709.

Ligero, P., Vega, A. and Soto, M. (2001) Pre-treatment of urban wastewaters in a hydrolytic up flow digester. *Water SA*, 27(3), 1–6.

Lozán, J.L., Graßl, H., Hupfer, P., Menzel, L. and Schönwiese, Ch.-D. (2007) Global Chnage: Enough Water for All? University of Hamburg, Germany

Major, D. C., Omojola, A., Dettinger, M., Hanson, R.T. and Sanchez-Rodriguez, R. (2011) Climate change, water, and wastewater in cities. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network, C. Rosenzweig, W. D. Solecki, S. A. Hammer, S. Mehrotra, Eds., Cambridge University Press, Cambridge, UK, 113–143.

Mall, R.K., Gupta, A., Singh, R., Singh, R.S. and Rathore, L.S. (2006) Water resources and climate change: An Indian Perspective. *Current Science*, 90 (12) 25.

McFarlane, D.J. and Williamson, D.R. (2002) An overview of water logging and salinity in southwestern Australia as related to the “Ucarro” experimental catchment. *Agricultural Water Management*, 53:5-29

Meenakshi, Maheshwari R.C. (2006). Fluoride in drinking water and its removal. *Journal of Hazardous Materials*, 137: 456-463

Metcalf and Eddy (2003) Wastewater Engineering: Treatment and Reuse. Fourth Edition. McGraw-Hill, Boston, USA.

Moss, B. (2008) Water pollution by agriculture. *Phil. Trans. R. Soc. B*, 363:659–666.

Mutiyar, P. K., Mittal, A.K. and Pekdeger, A. (2011) Status of organochlorine pesticides in the drinking water well-field located in the Delhi region of the flood plains of river Yamuna. *Drink. Water Eng. Sci*., 4:51–60.

Nair, S. (2009) Impact of population expansion on environment and climate in India. http://iussp2009.princeton.edu/papers/91535

Neralla, S., Weaver, R.W., Lesikar, B.J. and Persyn, R.A. (2000) Improvement of domestic wastewater quality by subsurface flow constructed wetlands. *Bioresour. Technol.* 75, 19–25.

NIH (2013) Water quality report of riverbank filtration case study site Haridwar for the months June, July and August 2013 for Saph Pani project. National Institute of Hydrology (NIH) Roorkee, Ground Water Hydrology Division, Roorkee 247 667, Uttarakhand, India.

NRAA (2011) Impact of High Rainfall/Floods on Ground Water Resources in the Krishna River Basin (during 1999-2009). Study Report 2. National Rain-fed Area Authority, New Delhi, India: 92 p.

Olsson, G. (2012) *Water and Energy*: *Threat and Opportunities*. IWA Publishing.

Page et al. (2009) Operational residual risk assessment for the Salisbury stormwater ASTR project. CSIRO: Water for a Healthy Country National Research Flagship. pp 106.

Philippi, L.R., Da Costa, R.H.R. and Sezerino, P.H. (1999) Domestic effluent treatment through integrated system of septic tank and root zone. *Water Science and Technology*, 40, 125–131.

Planning Commission India (2012) Report of the Working Group on "Effectively Integrating Industrial Growth and Environment Sustainability", Twelfth Five Year Plan (2012-2017). pp 72

Podmore, C. (2009) Irrigation salinity – causes and impacts. Prime facts, pp 4.

PRB (2007) The future population of India. Population Foundation of India, pp 20.

Rafique, T. Naseem, S., Usmania, T.H., Bashir, E., Khan, F.A. and Bhanger, M.I. (2009) Geochemical factors controlling the occurrence of high fluoride groundwater in the Nagar Parkar area, Sindh, Pakistan. *Journal of Hazardous Materials*, 171:424–430

Rastogi, N. and Sarin, M.M. (2005) Chemical characteristics of individual rain events from a semi-arid region in India: Three-year study. *Atmospheric Environment*, 39:3313-3323

Reddy, A.G.S., Reddy, D.V., Rao, P.N. and Prasad, K.M. (2010) Hydrogeochemical characterization of fluoride rich groundwater of Wailpalli watershed, Nalgonda District, Andhra Pradesh, India. *Environ Monit Assess*, 171:561–577.

Revi, A. (2008) Climate change risk: an adaptation and mitigation agenda for Indian cities. *Environment and Urbanization*, 20: 207-22.

RGI (2001) Census of India, 2001, India, 2A, Mansingh Road, New Delhi 110011.

Rousseau, D.P.L., Lesage, E., Story, A., Vanrolleghem, P.A. and Pauw, N.D. (2008) Constructed Wetland for Water Reclamation, *Desalination*, 218, 181-189.

Sajil Kumar, P.J. (2012) Impact of Tanning Industries on Fluoride Dynamics in Groundwater around a Tannery Cluster in South India", Bull Environ Contam Toxicol., 90:338-43.

Sanchez, J.F., Fernandez-Sevilla, J. M., Acien, F.G., Ceron, M.C., Perez-Parra, J. and Molina-Grima, E. (2008) Biomass and lutein productivity of Scenedesmus almeriensis: influence of irradiance, dilution rate and temperature. *Applied Microbiology and Biotechnology,* 79(5):719-729.

Sandhu, C, Grischek, T., Kumar, P. and Ray, C. (2011) Potential for Riverbank filtration in India. *Clean Techn Environ Policy*, 13: 295-316.

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

Saph Pani D1.1 (2012) Database of relevant pollutants in urban areas and their attenuation at RBF sites. EU Saph Pani Project Deliverable. www.saphpani.eu.

Saph Pani D1.2 (2013) Guidelines for flood-risk management of bank filtration schemes during monsoon in India. EU Saph Pani Project Deliverable D1.2. www.saphpani.eu.

Saph Pani D2.2 (2013) Documentation of acquired data and conceptual model of MAR impact as input for WP5 modelling. EU Saph Pani Project Deliverable D2.2. www.saphpani.eu.

Saph Pani D3.1 (2013) Report on experiences with constructed wetlands and techno-economic evaluation, EU Saph Pani Project Deliverable D3.1. www.saphpani.eu

Saph Pani D4.1 (2013) Review of the Post-treatment Applied to Natural Treatment Systems in India and Critical Water Quality Parameters. EU Saph Pani Project Deliverable. www.saphpani.eu.

Schoenheinz, D. (2004) DOC as Control Parameter for the Evaluation of Management of Aquifers with Anthropogenic Influenced Infiltration. PhD Thesis, Dresden University of Technology. Dresden, Germany.

Schoenheinz, D. and Grischek, T. (2011) Behavior of Dissolved Organic Carbon During Bank Filtration Under Extreme Conditions. In: Ray, C., Shamrukh, M. (eds.) Riverbank Filtration for Water security in Desert Countries. Springer Science+Business Media B.V., 51-67. DOI 10.1007/978-94-007-0026-0_4.

Schubert, J. (2002) German experience with riverbank filtration systems. In: *Riverbank Filtration: Improving Source-Water Quality*, C. Ray, G. Melin, and R. B. Linsky, eds. Dodrecht, The Netherlands: Kluwer Academic Publishers.

Sharma, S.K. and Amy, G. (2010) Chapter 15: Natural Treatment Systems. In: *Water Quality and Treatment: Handbook of Community Water Supply*. Sixth Edition, Publisher: American Water Works Association and McGraw Hill Inc., USA.

Sharma, S.K., Hussen, M. and Amy, G. (2011) Soil Aquifer Treatment using Advanced Primary Effluent. *Water Science and Technology*, 64 (3), 640-646.

Shivashankara, G.P., Ranga, K., Ramalingaiah and Manmohan, Rao N. (1999) Characterisation of bulk precipitation in industrial areas of Bangalore city. *Indian Journal of Environmental Health*, 41:229–238.

Singh, A., Mondal, G. C., Kumar, S., Singh, K. K. and Kamal, K.P. and Sinha, A. (2007) Precipitation chemistry and occurrence of acid rain over Dhanbad, coal city of India. *Environ. Monit. Assess.*, 125:99–110.

Singh, P., Kumar, P., Mehrotra, I. and Grischek, T., (2010) Impact of riverbank filtration on treatment of polluted river water. *Journal of Environmental Management*, 91(5): 1055-1062.

Sorokin, C. and Krauss, R.W. (1962) Effect of temperature and illuminannce on Chlorella Growth Uncoupled from Cell Divison. *Plant Physiol.,* 37:37-42.

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

Srivastava, A. (2013) Tertiary treatment of output from constructed wetlands aimed at reuse of treated wastewater. M. Tech Project Report, Centre for Environmental Science and Engineering, Indian Institute of Technology Bombay, India.

Tropper, P. and Manning, C.E. (2007) The solubility of fluorite in H_2O and H_2O–NaCl at high pressure and temperature. *Chemical Geology*, 242:299–306.

TECHNEAU (2007) Global Trends affecting the water cycle. Wind of change in the world of water. D1.1.7. EU Sixth Framework Programme - TECHNEAU Project.

UNDP (2011) India Fact sheet: Economic and Human Development Indicators. http://www.undp.org/content/dam/india/docs/india_factsheet_economic_n_hdi.pdf

UNICEF (2008) *Promotion of Household Water Treatment and Storage in UNICEF WASH Programmes*.

Viet A. N., Pham N. T., Nguyen T. H., Morel A., and Tonderski K., (2007) Decentralized Wastewater Treatment Alternative in Vietnam. *Nowra 16th Annual Technical Education Conference & Exposition Paper*, XI RCS-07.

Vymazal, J. (2002) The use of sub-surface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. *Ecol Eng.,* 18: 633–46.

WHO (2008) Guidelines for Drinking-water Quality. Third Edition Incorporating the First and Second Addenda. Volume 1 Recommendations. Geneva.

Williamson, D.R., Stokes, R.A. and Ruprecht, J.K. (1987) Response of input and output of water and chloride to clearing for agriculture. *J. Hydrology,* 94:1–28.

Winter, K.J. and Goetz, D. (2003) The impact of sewage composition on the soil clogging phenomena of vertical flow constructed wetlands. Water Science and Technology, 48 (5), 9-14.

Wintgens, T., Salehi, F., Hochstrat, R. and Melin, T. (2008) Emerging contaminants and treatment options in water recycling for indirect potable use. *Water Science and Technology*, 57(1), 99-107.

Xagoraraki, I and Kuo, D. (2008) Water Pollution: Emerging Contaminants Associated with Drinking Water. *International Encyclopaedia of Public Health*, First Edition, 6, 539-550.

Yang, L., Chang, H.T. and Huang, M.N.L (2001) Nutrient removal in gravel and soil based wetland microcosms with and without vegetation. *Ecological Engineering*, 18 (1), 91-105.

Zwolsman, J.J.G. (2008) Impacts of climate change on river water quality and drinking water production in the Netherlands *KWR Watercycle Research Institute.* Retrieved Feb 10th, 2009 from http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html

Annex 1.1 Water quality data of RBF wells and surface water in Haridwar on 26 June 2013 (NIH 2013)

Location	Temp. °C	pH	EC µS/cm	TDS mg/L	Turbidity NTU	Alkalinity mg/L	Hardness mg/L	Na^+ mg/L	K^+ mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	HCO_3^- mg/L	Cl^- mg/L	SO_4^{2-} mg/L	NO_3^- mg/L	BOD mg/L	Total Coliform MPN / 100 mL	Fecal Coliform MPN / 100 mL
IW -18	32.4	7.3	435	278	10.0	182	184	9.6	4.9	36.1	22.8	222	10	22.4	4.0	0.5	4	<3
IW -40	32.3	6.9	428	274	2.0	168	180	8.1	3.9	52.1	12.2	205	12	21.2	2.6	0.5	93	21
IW -26	32.4	6.8	498	319	2.0	202	198	11.3	4.5	57.7	13.1	246	18	21.4	4.8	0.5	23	<3
BWIW- 2	32.5	6.9	372	238	1.0	156	160	3.9	5.1	45.7	11.2	190	10	18.3	3.5	1.3	75	<3
BWIW- 3	32.3	6.9	458	293	4.0	186	190	7.4	4.3	36.9	23.8	227	16	26.7	4.4	1.3	120	43
IW- 31	32.4	7.2	492	315	1.0	204	202	12.9	2.7	54.5	16.0	249	16	13.6	7.9	0.5	93	23
IW-25	32.4	7.4	311	199	3.0	116	134	5.2	3.7	36.9	10.2	142	12	22.8	6.6	1.8	9	<3
IW-44	32.4	7.9	236	151	1.0	86	104	4.0	2.2	24.1	10.7	105	14	16.5	4.0	2.7	9	<3
IW- 21	32.5	7.7	236	151	1.0	96	96	2.4	2.3	28.1	6.3	117	10	16.2	2.6	0.5	93	15
IW -29	32.6	7.4	304	195	0.84	122	128	4.7	4.0	34.5	10.2	149	18	17.3	4.4	2.1	23	<3
IW -23	32.5	7.7	316	202	0.44	118	134	2.2	2.9	34.5	11.7	144	14	24.6	4.4	0.5	9	<3
IW -17	32.4	7.7	261	167	0.39	100	102	2.7	2.5	29.7	6.8	122	12	17.8	4.0	0.5	4	<3
IW- 27	32.4	7.3	600	384	1.19	234	242	13.8	4.0	65.8	19.0	286	20	23.5	8.8	2.7	43	9
IW- 4	32.5	7.3	622	398	8.67	248	262	13.7	3.9	69.0	21.9	307	22	28.3	8.8	0.5	150	43
IW- 1	32.4	7.4	459	294	0.77	186	198	7	4.1	56.1	14.1	227	16	19.9	3.5	1.5	43	4
IW -1	32.4	7.4	412	264	0.67	166	180	7.3	4.3	39.3	19.9	203	22	18.3	2.6	1.3	43	15
IW-24	32.5	7.6	294	188	0.8	104	134	2.9	3	37.7	9.7	127	16	22.3	6.2	1.9	93	15
IW -43	32.6	7.6	312	200	ND[1)]	114	142	3.2	3.8	39.3	10.7	139	12	24.4	10.1	1.7	<3	<3
IW -42	32.3	7.6	283	181	1	104	124	3.3	2.8	36.1	8.3	127	16	21.0	4.8	1.9	4	<3
IW -49	32.4	7.6	325	208	0.82	132	148	4.5	2.9	40.9	11.2	161	14	21.5	4.8	1.4	28	15
IW -15	32.6	7.4	682	437	2	204	244	18.7	6.2	41.7	34.0	249	36	28.8	20.2	1.7	93	23
Well IW Jwalapur	32.4	7.5	650	416	0.6	232	268	17.5	2.0	77.8	18.0	283	28	22.5	16.3	1.5	150	75
UGC near IW- 40	32.5	7.9	183	117	30	80	90	0.7	5.0	21.7	8.8	98	4	27.7	13.6	4.7	≥2400	150
Ganga River Near IW- 31	32.5	7.7	231	148	44	86	106	0.8	4.2	32.1	6.3	105	10	28.8	32.1	5.5	1100	93
UGC escape Channel Near IW -28	32.4	7.8	180	115	48	60	60	0.5	4.3	20.1	2.4	81	4	18.3	9.7	5.2	≥2400	210
UGC escape Channe near IW -29	32.4	7.7	178	114	94	74	90	1.0	5.0	24.9	6.8	90	8	21.0	11	4.2	1100	75
Open groundwater well at Kabir Asharam	32.5	7.0	1245	797	1	424	360	35.7	6.7	69.0	45.7	605	48	45.7	15	1.3	1100	75

ND[1)] As IW-43 is extremely close to the UGC escape channel, the bank between the channel and the well was completely eroded during the June 2013 flood such that the surface water was in direct contact with the well-water. Hence the turbidity in the well was equivalent to that of the surface water.

Annex 1.2 Water quality data of RBF wells and surface water in Haridwar on 9 July 2013 (NIH 2013)

Location	Temp.	pH	EC	TDS	Turbidity	Alkalinity	Hardness	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	BOD	Total Coliform	Fecal Coliform
	°C		µS/cm	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	MPN / 100 mL	MPN / 100 mL
IW -18	29.2	6.5	479	307	1.1	194	240	9.6	5.8	62.2	20.6	237	16.0	24.6	0.5	43	9
IW -40	29.2	7.0	433	277	0.3	196	197	10.1	4.3	60.2	11.3	239	17.4	24.4	0.5	93	28
IW- 2	29.5	7.1	331	212	1.6	146	167	4.9	5.4	47.3	11.9	179	11.4	22.0	0.9	93	9
IW- 3	29.6	7.1	522	334	0.9	230	255	12.9	5.0	71.3	18.8	280	16.6	30.4	0.7	93	23
IW- 31	29.9	7.0	463	296	1.1	198	210	14.1	3.2	53.0	19.0	241	17.6	16.2	0.2	Not determined	Not determined
IW-25	29.6	7.3	294	188	0.6	112	131	6.9	4.1	38.7	8.5	137	13.4	22.0	1.1	<3	<3
IW- 21	29.6	7.9	241	154	0.6	100	116	4.6	3.0	34.9	6.9	122	12.2	17.5	0.7	150	93
IW -29	29.9	7.7	263	168	0.8	104	107	5.6	3.1	34.2	5.2	127	8.8	20.4	1.7	<3	<3
IW -23	29.6	7.6	294	188	0.8	117	133	5.3	4.3	38.6	8.9	143	8.2	18.9	0.3	<3	<3
IW -17	29.3	7.8	274	175	0.8	106	117	6.1	3.0	35.9	6.7	130	11.2	19.4	0.3	<3	<3
IW- 27	29.4	7.2	491	314	0.7	246	265	15.8	4.2	55.1	30.9	300	15.8	22.0	1.0	93	7
IW- 4	29.4	7.1	631	404	1.5	252	289	15.8	4.1	69.2	28.3	307	16.4	30.9	0.3	240	93
IW- 1	30.1	7.3	430	275	1.2	190	207	8.7	4.6	31.5	31.2	232	10.8	20.7	1.2	240	93
IW -1	29.8	7.3	421	269	0.6	172	188	10.4	5.0	53.6	13.3	210	12.6	23.1	2.3	93	9
IW-24	29.7	7.6	287	184	1.0	113	136	4.0	3.5	38.7	9.5	138	9.6	21.7	1.9	Not determined	Not determined
IW -42	29.6	7.9	278	178	0.9	109	126	4.4	3.4	35.4	9.2	133	9.0	22.0	1.2	4	<3
IW -49	29.7	7.8	321	205	0.7	129	145	5.8	3.3	39.5	11.4	157	10.6	21.2	1.7	460	23
UGC near IW- 40	29.3	8.1	146	93	840	70	87	4.0	16.2	24.6	6.2	85	7.4	44.4	5.1	≥2400	240
Ganga river near IW- 31	29.8	8.0	180	115	142	74	83	4.6	16.3	22.4	6.6	90	11.8	41.8	5.9	≥2400	460

23.1.1 UGC escape Channel Near IW -28	29.3	8.0	147	94	198	72	67	4.1	16.7	19.8	4.3	88	4.8	36.5	5.4	≥2400	150
23.1.2 Open groundwater well at Kabir Asharam, Bhupatwala	29.5	6.9	1191	762	2.5	492	417	66.3	7.3	107.9	36.0	601	51.6	58.8	1.1	Not determined	Not determined

Annex 1.3 Water quality data of RBF wells and surface water in Haridwar on 6 August 2013 (NIH 2013)

Location	Temp.	pH	EC	TDS	Turbidity	Alkalinity	Hardness	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}	BOD	Total Coliform	Fecal Coliform
	°C		µS/cm	mg/L	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 mL	CFU/100 mL
IW -18	29.6	7.6	487	312	1.3	192	220	9.9	5.8	57.7	18.5	234	18	19.9	3.2	19	6
IW -40	29.6	7.6	485	310	1.7	190	224	10.4	4.7	61.8	17.0	232	16	22.7	0.4	16	Not detected
IW -26	29.5	7.6	636	407	1.5	256	290	18.3	5.4	77.8	23.3	312	26	21.5	0.4	58	9
IW- 2	29.7	7.8	402	257	2.4	170	182	5.0	5.8	45.7	16.5	207	12	21.9	0.8	56	Not detected
IW- 31	29.6	7.7	517	331	0.9	216	222	13.3	2.9	61.0	17.0	264	14	12.4	0.4	36	Not detected
IW-25	29.6	7.9	327	209	0.7	128	158	5.2	3.7	32.9	18.5	156	14	21.5	1.6	4	Not detected
IW-44	29.6	7.9	334	214	1.0	124	146	5.4	3.8	40.9	10.7	151	12	22.9	1.6	2	Not detected
IW- 21	29.7	8.0	269	172	1.0	110	132	3.2	2.5	34.5	11.2	134	10	15.9	0.0	26	10
IW -29	29.7	7.8	223	143	2.2	90	94	5.0	2.7	28.1	5.8	110	18	15.1	2.8	1	Not detected
IW -23	29.5	7.6	336	215	1.5	130	144	8.7	3.6	36.9	12.6	159	16	19.2	0.4	ND	Not detected
IW -17	29.5	7.0	299	191	0.9	120	132	4.0	2.7	36.1	10.2	146	14	19.8	0.8	19	Not detected
IW- 27	29.6	7.2	602	385	11.5	252	258	13.1	3.5	74.6	17.5	307	18	22.3	2.8	Not determined	Not determined
IW- 4	29.6	7.1	658	421	3.6	264	290	12.6	3.1	82.6	20.4	322	18	23.5	2.4	30	9
IW- 1	29.5	7.4	467	299	1.0	206	216	6.0	3.8	62.6	14.6	251	12	17.5	2.0	61	17
IW -1	29.4	6.9	452	289	1.6	182	182	9.1	4.7	58.5	8.7	222	20	21.6	0.4	15	1
IW-24	29.6	7.5	326	209	1.7	140	164	3.8	3.7	48.9	10.2	171	14	24.3	1.2	Not determined	Not determined
IW -43	29.6	7.4	343	220	ND[1)]	144	156	2.8	3.5	41.7	12.6	176	20	21.3	0.4	36	5
IW -42	29.5	7.1	298	191	1.8	122	132	3.1	3.1	42.5	6.3	149	18	20.5	0.8	8	2
IW -49	29.4	7.2	335	214	1.9	140	150	3.4	2.9	50.5	5.8	171	18	19.6	1.2	11	Not detected
UGC near IW- 40	29.5	6.6	183	117	62	80	94	2.1	3.8	29.7	4.9	98	8	12.9	2.4	1000	100
Ganga River near IW- 31	29.7	6.7	249	159	115	98	118	2.1	3.1	33.7	8.3	120	10	26.5	3.2	1000	100
UGC escape Channel Near IW -28	29.5	6.5	189	121	165	80	92	1.4	2.8	25.7	6.8	98	6	14.5	1.6	2000	100

ND[1)] As IW-43 is extremely close to the UGC escape channel, the bank between the channel and the well was completely eroded during the June 2013 flood such that the surface water was in direct contact with the well-water. Hence the turbidity in the well was equivalent to that of the surface water.

Annex 2 Physical/chemical parameters in groundwater samples in the check dam area between April and August 2013

Sample	1	2	3	4	5	6
	Watch tower	Field/HW1	Rose field	Hotel	Jasmine field	Friend house/HW3
Sample number (n)	4	3	4	4	4	2
BOD [mg/L]	< 2	< 2	< 2	< 2	< 2	< 2
COD [mg/L]	4-24	4-16	< 4-34	8-28	0-27	< 4
Atrazine [ng/L]	BDL	43	566	BDL	BDL	BDL
TN [mg/L]	0.9-1.4	1.2-5	0.6-13	1.2-24	0.6-6	0.6-0.8
TP [mg/L]	BDL-1.1	BDL-0.4	BDL-2.7	0.4-1.7	BDL-3	BDL-0.04
F [mg/L]	0.7-1.4	0.4-1.9	0.2-1.7	0.1-2.29	0.2-4.9	0.38-2.1
Fe [mg/L]	BDL-0.03	BDL	BDL-0.1	BDL-0.6	0.1-0.6	BDL
Cl [mg/L]	BDL	BDL	BDL	BDL	BDL	BDL
Mn [mg/L]	BDL-0.002	BDL	BDL	BDL-0.01	BDL-0.3	BDL
Br [mg/L]	BDL-0.3	BDL-0.2	BDL-0.5	BDL-0.3	0.2-0.4	BDL-0.1
SAC [-]	1-2.6	0.6-3.7	< 0.5-2.1	0.7-3.3	0.1-2.4	< 0.5
DO [mg/L]	4.2-7.8	4.5-5.7	4.6-7.5	5.5-6	3.9-5.8	5.9-6.1
Salinity [ppt]	0-0.2	0-0.2	0-3	0-14	0-3.8	0-0.1
Turbidity [NTU]	0.1-0.7	0.4	0.1-5	0.1-1.3	0.1-3.2	0.7
pH	7.53-7.81	7.36-7.62	7-7.25	6.42-7.35	7.34-7.6	7.21-7.5

Sample	1	2	3	4	5	6
	Watch tower	Field/HW1	Rose field	Hotel	Jasmine field	Friend house/HW3
EC []	1461-1865	1046-1788	1921-2793	1151-1638	1290-1312	1672-2080
Temp. [°C]	29-30	29--30	26.67-29.3	29.93-31	28-29.3	29.2-30.8

BDL = below detection limit

Annex 3 Water borne pathogens in groundwater samples in the check dam area between April and August 2013 (n=5)

Sample	1	2	3	4	5	6
	Watch tower	Field/HW1	Rose field	Hotel	Jasmine field	Friend house/HW3
E. coli [CFU/100mL]	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Enterobacter aerogenes [CFU/100mL]	n.d. - 10,000	n.d. -8,000	0 - 31,000	0 - 17,000	0 - 9,000	n.d.
Enterobacter species [CFU/100mL]	n.d. - 2,000	n.d.	n.d.	0 - 9,000	0 - 103,000	n.d.
Salmonella typhirmurum [CFU/100 mL]	n.d. - 9,000	n.d.	n.d.	n.d.	0 - 7,000	n.d.
Vibrio species [CFU/100 mL]	n.d.	n.d.	0 - 1,000	n.d.	0 - 33,000	n.d.