Potential of natural treatment technologies for wastewater management in India

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ABSTRACT

High population growth, increasing urbanization and rapid economic development are exerting pressure on the already scarce water resources in India. Treatment and reuse of wastewater can play an important role in addressing some of the urban water challenges. Conventional treatment plants have many challenges, therefore, natural treatment systems (NTSs) are viewed as a cost-effective alternative, which are more suitable in the Indian context. This study builds on a desktop study of NTSs and presents a rapid sustainability assessment of 12 NTSs, highlighting the potential and viability of NTSs in India. The results show that the NTSs have a high potential for wastewater treatment. However, there are still gaps in knowledge related to aspects that hinder the sustainability of the systems. Risks associated with reuse of treated wastewater in agriculture, operational problems and social acceptance were perceived as frequent challenges. Self-sustaining financing methods and the use of by-products were viewed as added benefits.

Key words | constructed wetlands, duckweed ponds, natural treatment ponds, rapid sustainability assessment, waste stabilization ponds

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INTRODUCTION

High population growth and rapid economic development are exerting pressure on already scarce water resources in India. Untreated wastewater from human settlements causes high levels of environmental pollution and contaminates the rivers which provide water to many centralized water supply systems. In an effort to treat sewage in areas where networks are absent, cities are looking for treatment options that are less energy intensive and less expensive to provide primary and secondary treatment. The natural treatment systems (NTSs) typically fill the gap, as they incur relatively low operation and maintenance (O&M) costs and require less energy compared with conventional primary and secondary treatment alternatives (Arceivala & Asolekar 2006).

NTSs are based on natural processes that use attenuation and the buffering capacity of natural soil-aquifer and plant-root systems, and the process of contaminant removal is not aided by the input of significant amounts of energy and/or chemicals (Sharma & Amy 2010). NTSs can be classified as soil-based and aquatic treatment systems. Soil-based systems are subsurface flow constructed wetlands (SFCW) or planted filters (PF). Aquatic systems are duckweed (DWP) or waste stabilization ponds (WSP). They can be used as secondary or tertiary treatment systems and in combination with conventional and other NTSs (hybrids). It has been reported that a combination of different treatment technologies allows for improved water quality of the effluent (Kaseva 2004; Mbuligwe 2004; Alvarez *et al.* 2008).

Another classification distinguishes between [I] intrinsic and [II] engineered systems (Chaturvedi & Asolekar 2009). The intrinsic natural systems are typically the so-called natural waterways and aquatic systems which can be further subdivided into two divisions, namely, self-supporting and stressed systems. A self-supporting system typically allows

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degradation of pollution without altering its own mechanisms and processes; for example, rivers and lakes polishing traces of biodegradable organic matter or treated sewage with the help of plants and microorganisms present in the system. It must be noted that the natural systems also concurrently process other biodegradable loads of pollution reaching the system via other natural biogeochemical routes, including the routine humification of natural organic matter. The stressed natural systems, however, are usually characterized by the inability to cope with and degrade rather large amounts of contaminants reaching the system (for example, rivers and lakes receiving large loads of sewage and wastewaters from urban or peri-urban communities).

OVERVIEW OF NTSS IN INDIA – DESKTOP STUDY

An overview of existing NTSs in India is given in Table 1.

WSPs are large artificial water bodies that can be used individually or combined in a series of three or more anaerobic and aerobic working ponds. WSPs have been the most popular treatment technology covering over 72% of the treatment capacity in Class II towns with 100,000 inhabitants (CPCB 2005). However, only a few performance evaluation reports are available for assessment. The technical evaluation showed that WSPs are capable of reaching the Indian discharge standards, but algae growth and power cuts (affecting aeration) appeared to impact the performance, in some instances. Polishing ponds are a type of WSP that are often found as a tertiary treatment step in up-flow anaerobic sludge blanket (UASB) systems.

Table 1 | Review on natural treatment systems in India

Wastewater treatment technology	Selected references
Waste stabilization ponds	Arceivala & Asolekar (2006), Central Pollution Control Board (CPCB) (2005), Chaturvedi & Asolekar (2009), Punjab State Council for Science & Technology (PSCST) (2003)
Constructed wetlands and planted filters	Arceivala & Asolekar (2006), Consortium for Dewats Dissemination (CDD) (www.cddindia.org), Chaturvedi & Asolekar (2009), Fardin *et al.* (2010), Juwarkar *et al.* (1995), Punjab State Council for Science & Technology (2003), The Hindu (16 September, 2011), Vipat *et al.* (2008), Wafler & Heeb (2006)
Hyacinth and duckweed ponds	Arceivala & Asolekar (2006), Ansal *et al.* (2010), Chaturvedi & Asolekar (2009), Punjab State Council for Science & Technology (PSCST) (2003), Iqbal (1999)

Constructed wetlands (CWs) (also called reed beds or planted gravel filters) are NTSs that consist of a bottom-lined bed filled with appropriate soil media. CWs are used as secondary treatment systems or as a tertiary treatment step after anaerobic baffled reactors or anaerobic filters. One example of a CW as secondary treatment system is located in Bhopal, Madhya Pradesh. It was evaluated after its implementation in 2003 by Vipat *et al.* (2008).

DWPs are similar to WSPs, but in addition, a mat of duckweed or water hyacinths covers the surface of the ponds creating anoxic–anaerobic conditions which favour denitrification (Arceivala & Asolekar 2006). The Government of Punjab has launched a plan to revive dirty village ponds for fish farming by adopting duckweed technology. Around 20 systems have been implemented in rural Punjab so far (PSCST 2003; Ansal *et al.* 2010), but no evaluation of the performance is available.

FACTORS INFLUENCING SUSTAINABILITY

It is evident from the desktop survey that technical performance evaluation took priority over assessments of health, institutional, economic and social aspects. Some of the findings and important issues that will impact the long-term sustainability of NTS are given below:

1. Health and environmental aspects of reuse of treated wastewater: WSPs and CWs have to be tested for their ability to remove coliforms. The Central Pollution Control Board (2008) has published recommendations for coliform concentrations for a variety of reuse purposes; as such, there is increasing awareness of discharge standards. On the other hand, the performance of WSPs may vary seasonally due to overloading, high evapotranspiration and

siltation. Also, when treated water is used for irrigation of parks, there may be imminent risk to the children who play on the lawns, especially if routine monitoring is not maintained (Starkl *et al.* 2010a, b). Even though guidelines on safe use of wastewater exist (e.g., WHO 2006), the scientific evidence of their application and relevance, especially on health risks, in relation to the Indian context is meagre.

2. Institutional aspects: Information on institutional arrangements for NTSs management was meagre. In the case of the WSPs, when compliance was poor, it was said to be due to weak O&M of the plant. However, no systematic studies have been carried out to confirm these perceptions. Institutional aspects, in particular, the organization of O&M, as well as monitoring and control, are crucial for the successful functioning of any treatment system and these aspects should be documented for performance evaluation of the NTSs that are operating in India.
3. Economic aspects: Documentation of cost–benefit analysis and cost recovery processes for NTSs was also poor, despite the importance of these aspects for long-term sustainability.
4. Social aspects: The acceptance of the use of treated wastewater from NTSs has not been assessed in a systematic way so far. Other aspects, such as user participation and user acceptance, are other crucial issues to ensure long-term sustainability of NTS. Overall, the literature survey yielded limited information.

Therefore, this study was undertaken to study especially the non-technical aspects of selected case studies, and the four major sustainability factors identified above.

METHODOLOGY FOR CASE STUDY EVALUATION

Case study selection

In order to further examine the non-technical aspects, case studies were identified based on the following criteria:

- Preference of wastewater treatment technologies that aim at reuse of water.
- Implementation under 'real-life conditions': The case studies in university campuses or pilot plants were not considered as institutional, and social aspects are hardly challenged under artificial conditions.
- Systems that have been operational for at least one year.
- Accessibility: Systems located in an area that is not too difficult to access.

The 12 case studies that were assessed were categorized into four types of technologies (Table 2). Each type of technology was elaborated using one example. The results of the others are summarized in the Discussion section. The locations and the descriptions of the case studies are given in Figure 1 and Table 2.

Table 2 | Evaluated case studies (in bold) presented in this paper

Technology	Capacity of selected case study (in million litres per day (ML/D))	Occupied area (acres)	Location/State of selected case study
Waste stabilization pond (WSP)	**14.5**	**40.12**	**Mathura/Uttar Pradesh**
	13.59	37.6	Mathura/Uttar Pradesh
	4	11.1	Mathura/Uttar Pradesh
	10	27.7	Agra/Uttar Pradesh
	2.25	6.2	Agra/Uttar Pradesh
Duckweed and hyacinth pond	**0.25**	**4**	**Naruana/Punjab**
	0.35	5.22	Saidpur
	0.25	not known	Bathinda district
Constructed wetland (CW)	**0.15**	**0.195**	**Bhopal/Madhya Pradesh**
	0.07	0.2	Bhopal/Madhya Pradesh
Natural treatment systems as post-treatment	**30**	**14**	**Hyderabad/Andhra Pradesh**
	0.05	0.1	Agra/Uttar Pradesh

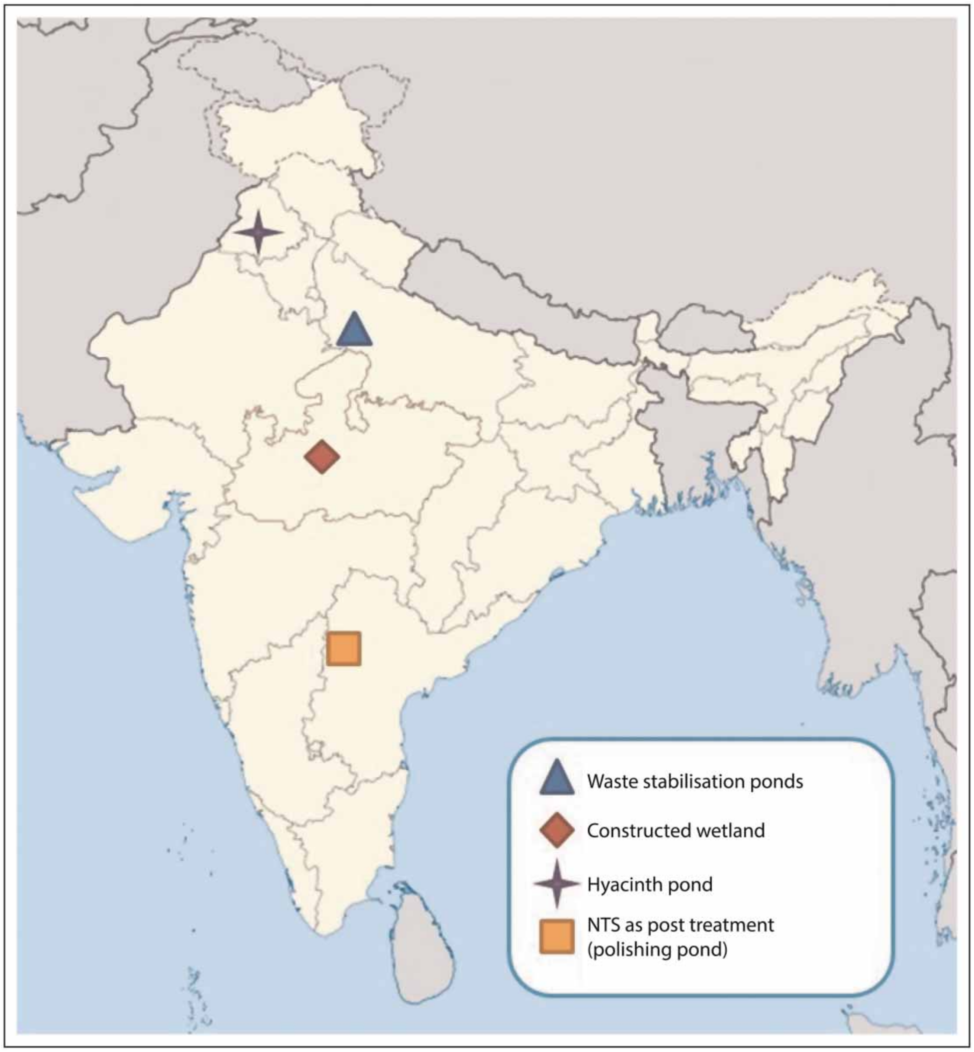

Figure 1 | Location of the four case studies presented in detail.

Assessment methodology

A rapid assessment methodology that was validated (Starkl *et al*. 2010a, 2010b) in India and Mexico was used to collect the information for NTSs in the present study.

It is a qualitative methodology based on expert visits and initial interviews with targeted stakeholders and users. The assessment was aimed at obtaining a quick qualitative and quantitative picture of the overall performance of the systems for which a statistically representative user survey is not required. The method employed the technique of conducting in-depth interviews with a small number of users to collect the information required, which enables the collection of details of the systems that might not be available in the literature. A standardized questionnaire that included the following topics was utilized: general information, financial details, downstream use of treated wastewater, health and environmental risks, institutional and operational aspects, problems and reasons for success, opinion of users on treated wastewater. The first assessment criterion was to see whether the intended benefits of the technologies were fulfilled, that is the improvement of the provision of and access to safe water. Other additional benefits expected were economic benefits from fish cultivation, reuse of water in agriculture or the improvement of environmental conditions. Finally, we attempted to examine

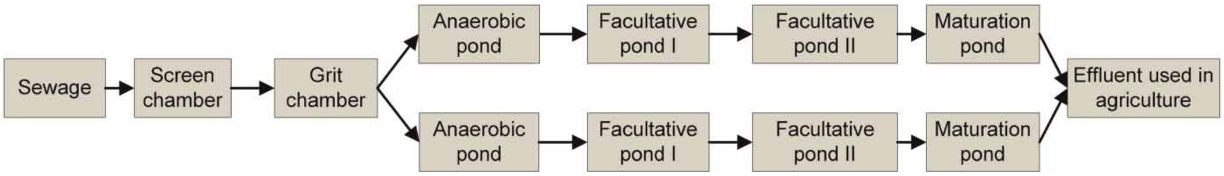

Figure 2 | Schematic flow chart of waste stabilization pond.

whether there were risks involved in not achieving the intended benefits, for the present and the future.

RESULTS OF CASE STUDY EVALUATION

Waste stabilization pond – Mathura, Uttar Pradesh

This WSP was built around 10 years ago in Mathura by the local water board. It has a capacity of 14.5 ML/D and treats domestic wastewater in a series of anaerobic and aerobic ponds (see Figure 2).

The intended benefit was not only the treatment of wastewater according to norms, but reuse of treated wastewater in agriculture.

Although the system was running normally, its external environment was not maintained well. Plastic wastes were floating in the anaerobic pond and the surrounding of the pre-treatment unit appeared unclean. The treated water was being reused in agriculture. Farmers preferred this water over groundwater due to the presence of nutrients. The following sections summarize the findings related to economic, institutional, health, environmental and social aspects.

Economic aspects

The municipality pays 700,000 Indian Rupees (INR) per year to the private company for O&M. The land next to the WSP is leased to local farmers who use the treated water. Based on the perceptions of two groups of farmers ($n = 13$) and one individual farmer, the annual benefit of using wastewater was 8,500 INR per year (see Table 3).

Table 3 | Economic benefits of wastewater use in agriculture, Mathura I WSP

Costs	INR
1 bag of urea (50 kg)	500
1 bag of diammonium phosphate (DAP) (50 kg)	1,200
Irrigation with groundwater, 1 cycle	600–800/per acre (average 700)
Annual financial input	
Fertilizer (2 bags urea (100 kg), 1 bag DAP (50 kg))	2,200
Groundwater, 9 cycles	6,300
Total	8,500

Institutional aspects

The main institutions involved are the Mathura Jal Board (Water Board), CPCB and a private company that is contracted for one year by the the Mathura Jal Board. The CPCB monitors the quality of the effluent and monitoring wells. The actual O&M is handled by the private company, with the support of three operators. One technical supervisor, a junior engineer of the Mathura Jal Board, is responsible for technical aspects. He, in fact, supervises all wastewater treatment plants in Mathura. While the treatment performance is monitored every month by the Mathura Jal Board and CPCB, the information about performance was not available in the public domain. The salary of the operators was reported to be 32,000 INR/year.

Health and environmental risks

The main agricultural crops irrigated were eggplants, cucumber, pumpkin and cereals. The farmers were aware of the treatment process (anaerobic digestion) of the WSP and know that this water is not fit for domestic use. No microbial risk assessments were carried out, to the best of our knowledge.

The use of treated wastewater for vegetables such as cucumbers that are eaten raw can pose a risk to consumers if the contaminant removal is not known. An Italian study

(Cirelli *et al.* 2010) investigated the quality of tomatoes and eggplants irrigated with treated wastewater from a conventional treatment plant which received additional tertiary treatment in a CW. The results showed that the microbiological quality of the products was at levels acceptable for human consumption. However, despite that fact that the treatment system was more advanced than in the Indian case, microbial contamination was observed in products that came directly into contact with the irrigated soil.

Social aspects

The perceptions of three groups of farmers (group 1: seven male farmers; group 2: family of six people, mainly women; group 3: three farmers, who used groundwater and wastewater for irrigation) on the use of groundwater and wastewater irrigation are summarized below. The leasing of the land was conditional upon the use of wastewater for irrigation and the price varied according to soil fertility (range 16,000–48,000 INR/year per acre). The treated wastewater was used year round, to irrigate a total of 100 acres. While the farmers would have liked to have worked more land, the distribution pipes are a limiting factor.

When asked which type of water they preferred for irrigation, treated wastewater was the primary choice, as ground water abstraction was expensive and had no nutrient value. Farmers engaged in three crop cycles per year, and did not have to use any chemical fertilizer, as they did before, which was considered as a saving on input expenses. The annual savings in fertilizer and groundwater due to wastewater use total 8,500 INR per year (Table 3).

Additional benefits due to higher availability of water depend on the local situation and can result in up to 80% higher yields (Naandi Foundation 2009) depending on the type of crops planted.

Water hyacinth pond – Naruana, Punjab

The water hyacinth pond is located close to a rural community in Naruana near Bathinda, Punjab. It receives 0.25 ML/D of domestic wastewater from the local households. Wastewater is conveyed through an open sewer drain without pre-treatment to a system of ponds (Figure 3). The sewer system conveying untreated wastewater to the existing village pond located within the village was constructed 30 years ago. In 2007, the treatment system was extended by adding a pond with water hyacinths and an oxidation pond. The existing village pond is now used as a fish pond. The community is happy with the system as it provides irrigation water for farming. Water for irrigation is extracted from the oxidation pond and the fish pond which receives additional water from the nearby irrigation channel if necessary. The intended benefit is treatment of wastewater and reuse of water for irrigation. Aquaculture was an added benefit.

While the wastewater is treated, its quality is not monitored. The water hyacinths in the first pond are not used for any purpose.

Economic aspects

The construction costs are not known but based on experiences from other systems in the area they are around 300,000–400,000 INR (Punjab State Council for Science and Technology 2003). Labour for construction was provided through the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) which is a legal guarantee for a 100 days of work at minimum wage for every adult living in rural households.

The water hyacinths are removed annually during the communal village cleaning campaign initiated by the local sports club, but are not used for any purpose. The fish

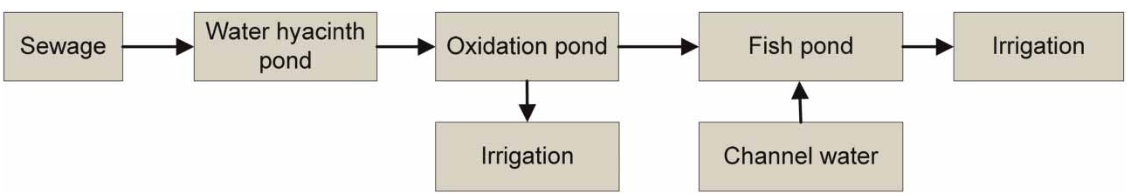

Figure 3 | Schematic flow chart of water hyacinth pond.

which are reared in the village pond are auctioned once a year and the revenue (100,000 INR) is added to the village community fund.

Excess water is used for irrigation purposes. One farmer reported that the crop yield increases by 5–10% if he uses the treated wastewater instead of canal water.

Institutional aspects

The local sports club organizes the annual cleaning operations and attends to the upkeep of the water hyacinth ponds. The community participates in a process where new plants are seeded every year. There are no permanent operators assigned and the quality of the treated wastewater is not monitored.

Health and environmental risks

The treated wastewater is used to irrigate wheat, sorghum and cotton, and farmers are aware of the risk of applying it to vegetables eaten raw. The quality of the effluent water is not known, as such, the risk of groundwater contamination cannot be estimated. The quality of the fish has been tested by the Food Corporation of India for heavy metals and pathogens, which showed that fish was suitable for consumption. Potential health risks can be expected during heavy rains, due to flooding.

Social aspects

Two farmers that use the treated water for irrigation and one member of the local sports club which organizes the annual cleaning campaign stated that they were aware that the pond system was used for treatment of wastewater. Their perception was that the water is better than the water from the irrigation channel as the yields increase by 5–10% without additional use of fertilizers. Further, the community is aware that the water should only be used for irrigation purposes. The main restrictions concerning availability of water are related to the distance of the fields. In future, it is expected that a community pumping station will be built which will allow more farmers to be supplied with the treated wastewater.

Constructed wetlands – Bhopal, Madhya Pradesh

The assessed CW is located in Bhopal, Madhya Pradesh. It treats 0.5 ML/D of wastewater collected from the households of the slum area where it is located. The wastewater passes through a settling unit and a septic tank before entering a horizontal SFCW (Figure 4). The intended benefit was treatment of wastewater which is then discharged into an underground sewer.

Information on wastewater flows and quality of the effluent was not available. The intended benefit of the system appears to be fulfilled. The nuisance aspect of mosquitos was a complaint made by communities living close to the ponds and there was concern about the potential risks for children.

Economic aspects

The wetland was constructed ten years ago, at a cost of 1.1 million INR, which does not include the cost of the land. The system is not maintained, and as such, there are no O&M costs.

Institutional aspects

There is no formal O&M arrangement, but in emergency situations, such as clogging or fire (see below), the Bhopal Municipal Corporation (BMP), who was responsible for constructing the treatment plant, takes charge.

Health and environmental risks

The group affected by this wetland is the slum community living close to it. The system is not well maintained and

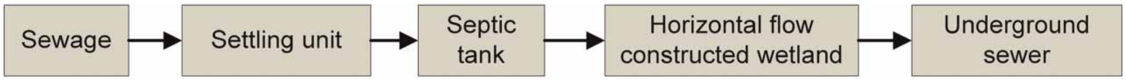

Figure 4 | Schematic flow chart of a constructed wetland in Bhopal.

the accumulating wastewater is an ideal breeding ground for mosquitos and rats who could possibly transfer diseases to the neighbours of the treatment plants, who live only a few metres away. The pre-treatment units are inaccessible as they are covered, and therefore direct contact with wastewater is avoided. However, given the design, both inlet and outlet are inaccessible, and further, monitoring results are not available to assess the environmental risk as a whole.

Social aspects

The CW is directly located within a residential area. Houses and treatment plant are only separated by a fence and a narrow alley. The respondents ($n = 7$) were aware that the wetland served as a treatment unit for sewage water. Those living close to the wetland found mosquitoes, rats, clogging and foul smell to be a nuisance. The positioning of the wetland, 1 m below the pavement level, and without adequate protection, poses a risk to humans, especially children who can fall into it. The lack of adequate protective measures in the design, as well as O&M, are considered to be potential risks by the community.

Natural treatment systems as post-treatment: upflow anaerobic sludge blanket (UASB) with polishing pond – Hyderabad, Andhra Pradesh

In this case study, the NTS considered was a component of a conventional treatment system (UASB). It serves as a post-treatment unit to improve the quality of the effluent before discharge. The assessment was made for the entire treatment plant as it is not possible to evaluate the functioning of the pond alone.

The wastewater treatment plant was constructed in 2009 at Nallacheravu in Hyderabad. Its design capacity is for the treatment of 30 ML/D. Currently, it receives around 15 ML/D and should receive the full volume once the city network coverage is completed. After passing through the pre-treatment unit consisting of screens and grit chambers, wastewater enters four UASB reactors, then an aerated pond and finally a polishing pond. The final effluent is chlorinated (Figure 5).

The intended benefit is treatment of wastewater according to the Indian norms for stream disposal. An additional benefit is the improvement of the environmental conditions in the surrounding area.

The system is working well and fulfils its intended benefit. There are no problems with the load and there is still capacity to connect more people. Clogging occurs from time to time, because of rough debris, especially plastics. Since the law against use of plastics (APPCB 1998) was implemented, less low density plastics reach the sewage treatment plant (STP). In terms of risks, the power cuts and rapid turnover of technical staff are perceived as risks.

Economic aspects

The cost of installing the STP system was 150 million INR, with annual O&M costs of 675,000 INR per year, of which, 225,000 INR are personnel and maintenance costs and 450,000 INR are for electricity. The costs for post-treatment activities are not known; the amount of chlorine used is 2 mg/L. The costs are covered by the Hyderabad Municipal Water Supply and Sewerage Board (HMWSSB). A fee is levied for sewage treatment which amounts to 30% of the water bill (at present it is a flat rate of INR 212/household monthly).

While there are opportunities for revenue generation from by-products (sludge, treated water, biogas), no gainful economic benefits are reported at present. Some reasons given are that the amount of wastewater received at present is not sufficient for economical production of biogas; further, the generator that has been installed is a duel fuel generator, which costs more to operate than the energy that can be harnessed from the plant.

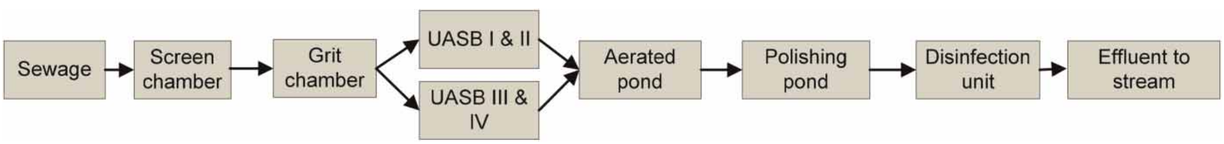

Figure 5 | Schematic flow chart of the UASB treatment system at Nallcheravu, Hyderabad.

At present, there is no market for sludge, as there are no takers. Currently, the sludge is dried on the premises, and used for gardening purposes within the site. As for the treated water, the interest of downstream farmers is low, as the wastewater they use is rich in nutrients and allows savings on the purchase of fertilizer, according to the staff at the treatment plant.

Institutional aspects

A private company is contracted for O&M. At present, 19 company personnel and two people (one full time, one part time) from the municipality are working in the treatment plant. It is perceived that the total manpower is not sufficient to cover all the activities, especially for sludge drying, which requires emptying and drying under natural conditions. The contract for O&M has to be renewed every three years; retaining trained and experienced staff is considered as an important part of renewal of contracts.

The quality standards (and even more parameters) are checked daily for the inlet, UASB effluent, facultative lagoon effluent and the final outlet effluent for pH, temperature, BOD, COD, TSS, faecal coliforms (FC) in a laboratory within the treatment plant. Also, the volume entering the treatment plant is monitored. The institutional arrangements are well coordinated at this plant and the discharge standards meet the criteria set by the CPCB (2008). Table 4 shows the annual average values for selected parameters at the inlet and outlet for the year 2011.

Health and environmental risks

Within the system, health risks have not been reported so far, and the treated water from the system is discharged to a stormwater stream nearby. The water in the stream which is already polluted gets diluted beyond the point of discharge, and the water is used for many purposes, including agriculture, which is mostly in the peri-urban regions close to the city.

The potential threat at present is the release of untreated wastewater into the waterways during power cuts. This could be addressed if biogas generation is augmented to self-sustain the system in the future.

Table 4 | Performance of treatment plant in Nallacheravu, Hyderabad (annual average 2011, provided by manager of the treatment plant)

	Water quality before treatment	Water quality after post treatment
pH	7.7 ± 1.05	7.9 ± 0.16
Total suspended solids (mg/L)	452.06 ± 55.96	47.73 ± 21.25
Chemical oxygen demand (COD) (mg/L)	452.93 ± 75.31	86.44 ± 11.05
Biological oxygen demand (BOD) for 5 days at 20 °C (mg/L)	177.56 ± 42.77	17.72 ± 4.5
Faecal coliform (MPN/100 mL)	$6.41 \times 10^5 \pm 0.76 \times 10^5$	6,317.64 ± 796.41

Social aspects

The effluent water is not used for irrigation. One farmer cultivating vegetables (e.g., spinach, amaranth, tomatoes) downstream of the STP was satisfied with the quality of water she received even though the quality of the water is worse than the quality of effluent. The farmers were tenant farmers that paid INR 1,200/0.5 acre for leasing the land, which included the water supply as well.

DISCUSSION

In this section, the results of the case studies presented above are compared with the other eight case studies, and specific problems, differences or similarities between the visited case studies are highlighted.

Performance

This study shows that there is a wide variety of natural wastewater treatment systems present in India, functioning at different performance levels. From 12 case studies, the performance levels could be ranked from poor to excellent based on beneficiary perception and expert observations. Real-time challenges and research needs were highlighted by key informants, such as the managers, operators and communities that were living close to the NTSs. The design capacities ranged from 0.05 to 30 ML/D and, based on the level of sophistication, systems varied and reflected the different possibilities of application of NTSs.

The performance of the WSPs in the other four visited case studies is similar to the one presented in detail above. Only in one case study, in Mathura, was there no maintenance at all and the pre-treatment unit was already partly blocked. Reuse of water for agricultural purposes was observed in two of the five case studies.

The one duckweed and two water hyacinth systems had similar capacities, but the operational structure was different. For the effectively working DWP system, operators for the harvesting of duckweed were assigned. The two water hyacinth systems were either communally managed (example presented above) or not maintained at all. In the latter case, the excessive growth of water hyacinths has become a problem. The village pond receives domestic wastewater from the local community and five years ago water hyacinths were planted in this pond. Even though the bad odour from the wastewater has disappeared, the excessive growth of water hyacinths in the pond makes its use for cattle watering and irrigation impossible as the water has disappeared under a layer of plants. Recommendations for planning of duckweed and hyacinth ponds indicate that preferably there should be at least two ponds to control the growth (Punjab State Council for Science and Technology 2003).

The CWs in Bhopal face similar problems: neither are well maintained and pose risks to humans. The case study in the slum area has already been described above but also in the second case study, health risks were observed: raw wastewater is conveyed to the treatment plant in an open unlined channel. Visitors, especially children who are not aware of the water quality, can easily come into contact with the untreated wastewater. As well, a large stream of untreated wastewater crosses the park. Operators employed in maintaining the park have no special equipment and have direct contact with the treated wastewater which is used to irrigate the park.

The two case studies where NTSs serve as post-treatment units are very different in size, but both work well due to well-organized O&M.

Land use and economics

Land availability is a crucial issue as NTSs require more space than conventional systems. Land requirements for NTSs are in the range of 1.5–6 m^2 per person (Arceivala & Asolekar 2006; Ulreich *et al.* 2009). Considering the high land costs for accessible land in rural or urban areas, the initial investment can be very high. Even in rural areas, such as in Punjab, easily accessible land required for wastewater treatment systems can be very expensive. Based on personal communication with local people, the type of land required for wastewater treatment systems costs up to 12.5 million INR per acre, which corresponds to an initial investment of 4,500–18,500 INR per person (see Table 5), depending on the area required. As Punjab is the main producer of wheat in India and agriculture is highly developed, land may be cheaper in most other rural regions in India.

Operation and maintenance and cost recovery

The municipalities where the WSPs were situated were all outsourcing the operation and management of the systems while keeping the role of overall management under their jurisdiction. This method appeared to offer a better service to the public than before, and gave the opportunity to revise the O&M system every one to three years.

Innovative ways of recovery of O&M costs were observed for a DWP system in Punjab and a baffled septic tank and baffled anaerobic reactor with a PF as post-treatment in Agra:

Table 5 | Space requirements and land costs

Technology	Space required/person (m^2)	Source	Land costs (INR/person)[a]
Waste stabilization pond	~3 m^2	Arceivala & Asolekar (2006), Ulreich *et al.* (2009)	9,266
Constructed wetland	1.5–2.5 m^2	Arceivala & Asolekar (2006), Maldonado (2007)	4,633–7,722
Duckweed ponds	2.5–6 m^2	Arceivala & Asolekar (2006)	7,722–18,533

[a]12,500,000 INR per acre, personal information from farmers in Punjab, November 2012.

- In the case of the DWP, revenues from the auction of fish are used to recompense those people that harvest the duckweed and feed it to the fish. An additional benefit is generated by planting orange trees around the DWPs. Oranges are not sold, but can be picked by anybody in the community.
- The O&M costs of the wastewater treatment system in Agra are recovered by the revenues from the 'Mughal Heritage Trail', which was initiated by the same NGO that implemented the wastewater treatment plant. The revenues from the trail are sufficient to pay the salary of five guides on the trail and two operators in the treatment plant.

CONCLUSIONS

The study has shown that institutional and organizational issues are of high importance for the sustainable functioning of NTSs in India. This observation is consistent with experiences reported from other regions/countries, such as CWs in Mexico (Starkl *et al.* 2010b) and Thailand (Brix *et al.* 2010). Therefore, these aspects need to be already considered in the planning phase.

Multiple benefits of by-products of natural treatment plants have been demonstrated elsewhere, especially for floriculture and irrigation (Belmont *et al.* 2004). The study in India has shown that economic benefits from by-products of wastewater treatment are numerous and not only limited to the use of treated wastewater, but also rearing of fish, duckweed or other communal uses of the area where the treatment plant is located. However, potential risks for the consumers of vegetables irrigated with the effluent need to be further investigated. Following the multi-barrier approach of the World Health Organization (WHO), it is always advisable to take measures to reduce contamination even at household level, by washing and disinfecting vegetables before consumption.

The decentralized NTSs can be suitable for countries where cities cannot keep pace with rapid population growth. Such systems require less maintenance and energy input than conventional treatment systems (Nogueira *et al.* 2007). The important aspect in all of the cases studied was that the system required low or even no energy input; nevertheless, as water is usually pumped from pumping stations to the treatment plants, power cuts can affect NTSs.

Due to high land prices in peri-urban and urban areas, NTSs are mainly suitable for rural areas; however, they may be used for green areas in urban areas and be integrated into urban landscaping as done in Bhopal. In rural areas, space can be saved if the existing village ponds are integrated into the wastewater treatment system as the examples from Punjab have shown.

Municipalities should take particular care if the NTSs are close to human habitations and ground water aquifers – to anticipate health-related issues, and be ready to address them. For the users, health risk assessments should be mandatory, and for the product, food safety measures and testing should be part of the agricultural production process.

One of the limitations of this study is that the information obtained stems from single visits to the wastewater treatment plants. Even though the visits were well prepared and operators and operating organizations were helpful in providing information, a long-term assessment over months may yield further insights. The lack of available performance data shows the need for a public environmental information system.

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