Saph Pani

Enhancement of Natural Water Systems and Treatment Methods for Safe and Sustainable Water Supply in India

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1 Introduction

India has one of the largest numbers of small and medium enterprises engaged in a variety of sectors including petrochemical, fertilizer, fine chemicals, pharmaceuticals and intermediates, dyes, paints, pigments as well as automobile and mechanical jobbing industry. Subsequent to the liberalization of economy and industry in the later part of last century, India has seen tremendous growth in industry as well as urbanized population. As a result, the Government of India has been investing in expanding and strengthening urban infrastructure sector over the past three decades. In that context, there have been systematic efforts of up-scaling of facilities for treatment and distribution of drinking water as well as collection, treatment and disposal of sewages (Arceivala and Asolekar, 2006; Asolekar et al., 2013).

The task of treatment and disposal of effluents generated by large-scale industries appear to be relatively under control when compared to the challenge posed by small and medium enterprises. Barring the few exceptions, the situation pertaining to collection, treatment and disposal of sewages in cities and towns continue to be inadequate in most of the municipalities in India (Arceivala and Asolekar, 2012; Kalbar et al. 2013). Furthermore, the challenge of treating sewages generated by rural communities has not been even addressed.

Rural, peri-urban and urban communities in India have been looking for avenues for augmenting their water supplies. Nearly no community can boast of having adequate water supply and infrastructure for collection and disposal of sewages across the country. Reportedly, water scarcity is being faced during the past four decades by nearly every developing and under-developed country worldwide. The challenge of water shortage and its consequences remain on the anvil nearly in all the key international water, environment and development related meetings and conferences. For example, the issues associated with drinking water, wastewater and contamination of rivers and oceans were debated for formulating the collective action in the recently held three international conferences, *namely*: United Nations Conference on Environment and Development, 3 to 14 June 1992, in Rio de Janeiro, Brazil; World Summit on Sustainable Development, 26 August to 4 September 2002, in Johannesburg, South Africa and United Nations Conference on Sustainable Development, 13 to 22 June 2012, in Rio de Janeiro, Brazil.

Several international platforms have been urging that the world will have to come together to address the challenge of pollution of our surface waters and marine costal ecosystems. It is recognised that the urban and rural communities worldwide are contaminating nearly all the water resources by disposing their domestic wastewaters into nearby water bodies. The threat has reached to such proportions, especially in the developing countries, that the communities are now forcing local self-governments and the national governments to solve the crises through social and political actions.

1.1 The context and overview

During the first four decades of urban development in free India (1947 to the early nineties) the emphasis was laid on fetching potable water from 50 to 100 km distances from pristine rural settings (water reservoirs of dams and lakes). Such water supply schemes cannot be planned and implemented anymore because they are not considered politically defensible. The Environmental Impact Assessment Regulation was passed by the Ministry of Environment and Forests, Government of India, in 1986 and all large development project needs to categorically approved by the team of experts at the Ministry of Environment and Forests as well as cleared through a scrutiny by the stakeholders in a public hearing. During the past two decades, it has become more complicated because the government policies not only favour inclusive growth of rural and tribal communities, but also factor in environmental and ecological costs in the impact analyses and cost benefit analyses performed before approving the development projects.

Presently, the Government of India does not support exploitation of tribal and remote rural locations and forests for the benefit of urban and peri-urban communities. Besides, as stated earlier, the tribal and rural communities have begun to exert their political pressure onto growth-related policies and programmes formulated and implemented by the Central and State Governments in the Union of India. Clearly, a time has come when alternate suitable technological solutions that are concurrent with the capabilities of local agricultural and natural ecosystems shall be favoured.

India's commitment to global warming related actions and Kyoto Protocol obviously has challenged the conventional approach of water supply and wastewater management in rural and urban communities. It is now expected that all municipal authorities will have to prepare their respective “resource consumption and environment management plan” and after deliberating on the short-term and long-term “sustainability” of their proposals funding would be released by the respective ministries. For example, the recent guidelines of the Ministry of Rural Development, the Ministry of Urban Development, Ministry of Environment and Forests as well as Ministry of Water Resources) and Ganga Rejuvenation for development of infrastructure for wastewater management in rural and urban communities lay emphasis on the decentralized and low-energy consuming solutions.

Clearly, greener eco-centric solutions will be typically favoured in the coming years. One more factor that is likely to influence the solutions to be implemented in the near future is the shortage of funds. These socio-economic and political realities are influencing the technological choices of municipalities. In this context, natural treatment systems (NTSs) are indeed emerging as the solution of preference - especially in rural and small communities in India.

1.2 Significance of natural treatment systems in the context of India

As reported by Asolekar (2002), disposal of untreated or partially treated effluents into rivers and lakes as well as runoff from urban and agricultural areas are the two main reasons responsible for deterioration of drinking water resources in India. It is clear that less than 10% of the generated sewages are treated effectively, while the rest of the sewages find their ways into the natural ecosystems in the vicinity. In addition, excessive withdrawal of water for agricultural and municipal utilities as well as use of rivers and lakes for religious and social practices and perpetual droughts limits the capacity of natural water sources to provide adequate dilution (Asolekar, 2002; Asolekar et al., 2013; Starkl et al., 2013; Chaturvedi et al. 2014).

According to the statistics of year 2005, presented by Chaturvedi and Asolekar (2009) on wastewater management in India, out of about 26,000 million litres per day (MLD) of wastewater reportedly collected cumulatively in two mega cities (population above 5 million), 11 large metro cities (population from 2 to 5 million), 26 small metro cities (population from 1 to 2 million), 384 class I cities (population from 100,000 to 1 million) and 498 class II cities (population between 50,000 and 100,000), which are inhabited by more than 70% of India's 500 million urban population, merely 27% of urban wastewater received some kind of treatment.

The statistics of year 2009 revealed a similar trend; 38,254 MLD of sewage were generated from class I cities and class II towns but only a treatment capacity of 12,000 MLD existed (CPCB, 2009). The class I cities of India are contributing to about 93% of total sewage generated by class-I cities and class-II towns. The sewage generated in class-I cities was estimated to be 35,558 MLD and treatment capacity exists for only 11,553 MLD in these cities, *i.e.*, only 32% of wastewater is being treated, whereas the rest is disposed untreated. In India, there are 35 metropolitan cities (with a population more than 1 million) which are generating sewage of 15,644 MLD but the existing treatment capacity is 8,040 MLD, which is only 51% of the total sewage generated in these cities. The generated sewage in class-II towns was estimated as 2,696 MLD and only 233 MLD treatment capacities exist in these cities, which show that only 8% of wastewater is being treated. Thus, there is a large gap between the amount of wastewater generation and treatment in India. Due to disposal of these untreated sewages into water bodies, both surface and groundwater are being contaminated. The CPCB (2009) also reported unsatisfactory operation and maintenance (O&M) of existing sewage treatment plants (STPs) and pumping stations, as nearly 39% sewage treatment plants are not conforming to the minimum standards prescribed under the prevailing regulatory standards meant for disposal of treated sewages into rivers and lakes (receiving water bodies).

The use of natural treatment systems (NTSs) for treatment of domestic sewages and sullage was practiced in ancient India. The community tanks in villages, water bodies maintained by temples for performance of religious functions and crimination rites, irrigation systems installed and maintained in community joint-forests invariably received controlled flows of sewages and sullages. These were some of the noteworthy examples of sustainable wastewater management in India's village ecosystems (Jana, 1998; Chaturvedi and Asolekar, 2009).

At the level of the Central Government, the Ministry of Rural Development, the Ministry of Urban Development, Ministry of Environment and Forests as well as Ministry of Water Resources and Ganga Rejuvenation have been incorporating the strategy of providing low-cost eco-centric treatment to sewages for correcting the pollution of natural water courses in India. The Jawaharlal Nehru National Urban Renewal Mission (JNNURM) and several programs have been implemented by the Government of India over the past three decades. Similarly, the State Governments in the Union of India have also been complimenting efforts in the respective states and favouring the decentralized treatment technologies to address issues associated with disposal of sewages.

Clearly, there exists a looming challenge of inadequate and insufficient infrastructure for treatment of sewages throughout India, both in urban as well as rural communities. The Union of India has exhibited a serious commitment to fulfilling this basic necessity of rural and urban communities –responding to the political pressure exerted by them. For example, as reported by Asolekar et al. (2013), in the context of rejuvenation and ecological upgradation of the Ganga River, the entire north India (almost 400 million people) has forged an alliance on political and social platforms.

Currently, the Honorable Supreme Court of India has ordered the responsible State Governments in the Union of India including the Ministry of Environment and Forests to ascertain that the untreated and partially treated sewages shall not be disposed into the tributaries and main stream of Ganga River. Already, over the past two decades, there have been concerted efforts in the direction of up-scaling of infrastructure for sewage treatment all over India. On one hand, there are several communities waiting eagerly to be included in the programme for improving sanitation, while on the other hand, the budgets allocated to sewage treatment facilities are not adequate.

At such a crossroad, identification and adoption of the so called "appropriate technological solution" will become more critical than ever - especially in the developing economy like India (Kalbar et al. 2012). The broad class of engineered natural treatment systems including horizontal sub-surface flow constructed wetlands (horizontal sub-surface flow constructed wetlands) are a strong candidates in dominate the platform of favoured technologies for treatment and recycling of sewages in warmer climates and increasing unmet demand for waters for irrigation and industry.

1.3 Natural treatment technologies practiced in India

A detailed review of a variety of NTSs practiced in Asia in general and India in particular has been presented in Chapters 9 through 11 by Arceivala and Asolekar (2006). Most of the natural treatment systems consist of a train of individual unit processes set-up in series, with the output of one process becoming the input of the next process. The first stage usually comprises of physical processes that take out pollutants in a physico-chemical manner. After this, biological processes generally treat the remaining pollutants further. These may 1) convert dissolved or colloidal impurities into a solid or gaseous form, so that they can be removed physically, or 2) convert them into dissolved materials, which remain in the solution and typically are not as undesirable as the original organic pollutants. The solids (residuals or sludges) which result from these processes form a side-stream and are typically treated for further stabilization and desirably converted into manure or soil conditioners and disposed off into the farms and commercial agro-forests and green city-spaces in the vicinity. These practices, however, are customarily regulated by the empowered agencies so that these stabilized sludges do not introduce trace toxic metals and other pollutants emitted by industrial activities into farms and soils and thereby contaminate food.

Typically, the sewage treatment plants based on waste stabilization ponds consist of a cascade of ponds in nearly all situations. Those ponds can be classified into three classes: 1) anaerobic ponds, 2) facultative ponds and 3) aerobic ponds. Alternately, on the basis of water depths, ponds may also be classified into two classes: a) shallow ponds and b) deep ponds. Shallow ponds (typical water depths<2.5 m) include conventional aerobic ponds as well as polishing or maturation ponds with marginal facultative conditions near sediment-zone. The deep ponds (typical water depths>2.5 m) include facultative ponds having aerobic, facultative and anaerobic layers. The ponds are also at times anaerobic owing to their greater depths of 5 to 10 m.

Typically, polishing ponds are employed in the trains of unit operations in sewage treatment plants to provide "polishing" of treated secondary effluents. The typical treatment train comprising of polishing ponds, adopted by the sewage treatment plants treating their effluents with the help of up-flow anaerobic sludge blankets reactors during secondary wastewater treatment, across India. Polishing ponds find their niche in the situations where up-flow anaerobic sludge blankets reactors have been employed by the rural communities engaged in the downstream processing of dairy or farm-products. Such communities generate wastewaters by combining sewages and sullages from the towns (or villages) and the wastewaters generated from cottage industries (often SMEs) and have fluctuating flows and occasional high concentrations.

The polishing ponds have demonstrated their capabilities of improving the quality of effluents from the up-flow anaerobic sludge blankets reactors, so that the final effluent quality becomes compatible with the prescribed legal standards and meet desired quality before disposal into river stretches. Thus, the residual organic material and suspended solids in the anaerobically digested sewages from up-flow anaerobic sludge blankets reactors are typically connected to polishing ponds. The main objective of polishing ponds is to improve the hygienic quality of resulting treated effluents, which is typically measured by the concentration of two indicator organisms: helminth eggs and fecal coliforms. The fecal coliforms removal is normally the slowest process and for that reason, it becomes the main design criterion for a polishing pond. In India depth of up-flow anaerobic sludge blankets polishing pond has been kept 1-1.5 meter and average hydraulic retention time (HRT) of 24 h. In most of the places, such short HRTs is insufficient to achieve desirable extent of feacal coliforms removal.

The sewage treatment plants based on the eco-centric technology of the duckweed pond has typically three treatment units, namely: 1) settling tank, 2) duckweed pond and 3) fishponds. After settling, the primary treated sewage is subjected to a duckweed pond, where major reduction in carbon, nitrogen and phosphorus from the sewage take place. The duckweed ponds are known for their combined action of phytoplankton, zooplankton and bacteria. The secondary treated wastewater, thus, from the duckweed pond finally is let into a fishpond to provide further polishing. The fishponds typically perform two functions. First, they provide some kind of polishing to the secondary treated sewage. Second, more importantly, they consume the duckweed and algae and in response produce more fishes - which could be harvested and sold in the market for earning profit and livelihood. It is interesting to note that the duckweed generated in response to treatment in the duckweed ponds need to be routinely harvested and transferred into the associated fishponds to feed the fishes. The duckweed typically doubles its mass in two to three days under supportive conditions of nutrients, sunlight and temperature. The algae, however, get developed in fishponds in response to algal-bacterial "polishing" of secondary treated sewage. Thus, treated sewages emerging from duckweed ponds can be safely used for irrigation. Sizes of different treatment units in such systems are customarily estimated on the basis of biological kinetics of degradation of duckweed pond and fishpond, life cycle of fishes, climatic conditions and feasibility of land available.

At many places in India, duckweed pond systems have been found to be quite effective for treatment and reuse of rural sewages. Also, they seem to perform well in various climatic conditions across India as well as meet the prescribed regulatory standards. One of the most commonly encountered systems for treatment of sewages in rural areas and small urban communities across India is the so-called "constructed wetland". There are, by and large, two variants of constructed wetlands encountered among the present installations in India. As a part of the shortlisted sewage treatment plants investigated in this survey, six horizontal sub-surface flow constructed wetlands and two Karnal-type constructed wetlands were studied.

Constructed wetlands, first developed in 1960 by Dr. K. Seidel in Germany, is now accepted to be the low-cost eco-centric technology, especially beneficial for small towns which typically cannot afford expensive conventional treatment systems (Billore et al., 1999; Billore et al., 2001; Vymazal, 2010). constructed wetland, a simple and effective wastewater treatment approach, consists of a shallow depression in the ground with a levelled bottom. With incorporation of sophisticated flow controls and monitoring devices, it is possible to build the sewage treatment plants with constructed wetlands technology to exercise a higher degree of control over the process and performance (Brix, 1997; Vymazal, 2013a). Constructed wetlands seem to cater for nearly any combination of sewage, sullage and biodegradable industrial effluent.

The constructed wetlands appear to perform all of the biochemical transformations related to degradation of a variety of pollutants present in sewages and industrial wastewaters including carbonaceous, nitrogenous and pathogenic constituents (Vymazal, 2013a; Vymazal, 2013b). The constructed wetlands can be employed in place of the commonly practiced conventional wastewater treatment strategy – which is not favoured on account of it being energy intensive and ineffective in removing pathogens. In a typical rural setting, constructed wetlands appear to treat sewages and sullages to a higher degree when compared with the more conventional rural alternatives including septic tanks, drain fields and other forms of land treatment.

1.4 The potential of constructed wetlands for treatment of sewages

The engineered NTSs have been incorporated into sewage treatment plants to treat sewages and sullages since early seventies – especially in the under developed and developing countries in Asia and Africa. Several sewage treatment plants employing variety of natural treatment systems have been studied and reported in literature (Arceivala and Asolekar, 2006 and 2012; Chaturvedi and Asolekar, 2009; Starkl et al., 2013; Asolekar et al., 2013; Chaturvedi et al., 2014). The Chapter 8 of this Handbook presents the lessons learnt from the national survey of engineered NTSs currently functioning in India – which was one of the outputs of the *Saph Pani* Project. Reportedly, there are 108 sites publicly operated across India where NTSs are used for treating mixtures of sewages and sullages and in some cases biodegradable industrial effluents. Among those, the 41 sewage treatment plants were studied in-depth by the authors during December 2011 to June 2014. The details of these 41 sites have been presented in the Report No. D3.1 of *Saph Pani* Project (Asolekar, 2013).

The 41 sewage treatment plants studied in-depth comprise of, 23 plants had waste stabilization ponds, 3 plants had duckweed ponds, 7 plants had polishing ponds and 8 plants employed horizontal sub-surface flow constructed wetlands or Karnal-type constructed wetlands. The constructed wetlands were preferred by small rural and peri-urban communities – especially to treat sewages and industrial biodegradable effluents to achieve removal of carbonaceous and nitrogenous organic pollutants. In some cases, the treated effluents from constructed wetlands were put to reuse for irrigation and rejuvenation of lakes (Asolekar et al., 2013). Vymazal and Brezinová (2014) also reported the similar observation from Czech Republic. The constructed wetlands were also found to be favoured in the situations wherein evaporation of treated effluents needed to be achieved. Several researchers, too, have reported the preference for CWs in several communities in the world (Burken and Schnoor, 1998; Mara and Pearson, 1998; Metcalf and Eddy, 2003; Kamath et al., 2004; Mara, 2004; Arceivala and Asolekar, 2006; Asolekar et al., 2013; Chaturvedi et al., 2014; Vymazal, and Brezinová, 2014, Starkl et al., 2014).

The sewage treatment plants based on engineered constructed wetlands are found comparable or better performing than the conventional treatment technologies which include, activated sludge plants, sequential batch rectors, trickling filters, oxidation ditches or extended aeration basins – especially when compared with consumption of electrical energy and chemicals. In developed countries, constructed wetlands have been used for treating variety of wastewaters including sewages (Cooper et al., 1997), acid mine drainages (Wenerick et al., 1989), agricultural runoff, landfill leachates (Staubitz et al., 1989), urban storm-water runoff and for polishing treated effluents for returning to freshwater resources.

The horizontal sub-surface flow constructed wetlands are typically employed for treatment and reuse of treated sewages and sometimes even for treatment of industrial effluents. Such wetlands include 'Reed beds' and 'Root-zone' treatment methods devised to obtain environmental duty from the macrophytes cultivated in trenches or on beds having saturated with sewages or wastewaters. Wetlands have also been suggested as an alternate for treating nitrate bearing contaminated aquifers, denitrification of nitrified domestic effluents and irrigation return flows (Baker, 1998). Furthermore, the denitrification efficiency in presence of low organic carbon was shown to depend on C: N ratio, with peak efficiencies occurring at C: N ratio of 5:1.

Constructed wetlands have also been used for treating the eutrophic water from Taihu Lake in China (Li et al., 2008), and for providing make-up water for Mansagar Lake in Jaipur, the State of Rajasthan, India as well as conservation of eco-system (Asolekar et al., 2013). The habitat of endangered species of birds was created on vegetated silt mounds in the Mansagar Lake, which received treated effluents from the City of Jaipur (Asolekar et al., 2013).

Mandi et al. (1998) reported a study on the treatment of domestic wastewater under semi-arid conditions of Morocco. At a hydraulic loading rate of 0.86–1.44 m^3 d^{-1} to a reed bed planted with *Phragmites australi*s, organic removal of 48–62%, TSS removal of 58–67% and 71–95% removal of parasites was reported. In Egypt, Stotts et al. (1999) achieved a 100% removal of parasitic ova from domestic wastewater intended for agriculture use. In Iran, a subsurface flow reed bed (*Phragmites australi*s) of 150 m^2 was reportedly employed for treating municipal wastewaters. At an organic loading rate of 200 kg.ha.d^{-1} ,which is higher than previously recommended rate of 133 kg.ha.d^{-1} (Metcalf and Eddy 2003), removal efficiencies of 86, 90, 89, 34, 56 and 99% for COD, BOD, TSS, TN, TP, and fecal coliform bacteria, respectively, were obtained.

Okurut et al. (1999) demonstrated the viability of constructed wetlands with indigenous *C. papyrus* and *Phragmites mauritians* in Uganda for treating municipal wastewater. In the *C. papyrus* systems, average mass removal rates for COD, TSS, NH_4-N, TN and o-phosphorus were 15.32, 6.62, 6.5, 1.06, 0.06 g m^2 d^{-1}, respectively. In *Phragmites mauritianus* systems, the rate for the same parameters was 2.25, 0.9, 0.66, 0.65, and 0.058 g m^2 d/1, respectively. The level of BOD and TSS in the effluents was below 20 and 25 mg per liter. A higher degree of fecal coliform removal was reported for the CW planted with *C. papyrus*.

The potential of constructed wetlands for application by small communities for wastewater treatment was examined in Nepal (Laber et al., 1999). A hybrid CW system comprising of horizontal flow and vertical flow beds (140 m^2 bed area for horizontal flow and 120 m^2 bed area for vertical flow) with *Phragmites karka* was tested for one year on full-scale for treatment of hospital wastewater. At a hydraulic loading rate of 107 mm d^{-1}, % removal efficiency for COD, BOD, NH_4-N, total-P, total coliforms, *Escherichia coli*, *Streptococcus* and TSS were 93, 97, 99.7, 74, 99.99, 99.99, 99.97, and 98%, respectively.

1.5 Scope and specific objectives ofthis report

The possible ways to improve the efficiency of natural treatment systems in general and engineered constructed wetlands in particular comprise of incorporating the most common and the best practices into sewage treatment plants at the design-stage itself. Also, a knowledge-based approach will have to be systematically implemented during construction, commissioning as well as and operating and maintaining the facility. The research and technology development activity undertaken in *Work-Package-3* of *Saph Pani* Project were planned and executed with this overall idea. It was also recognised at the outset that the enhancement of the performance of a given sewage treatment plant based on the engineered constructed wetland technology can only be achieved when the eco-centric technology implemented in the project performs according to the intended functions in the treatment train. Further, the natural treatment technology based sewage treatment plant will be suitably adopted, operated and maintained by the given community if the treatment train incorporates suitable tertiary treatment to produce recyclable treated sewage.

Some of the important factors that should be considered while deciding upon a strategy to improve the treatment efficiency of natural treatment systems include rate, extent and variability of wastewater reaching the system, climate changes, population changes, pattern of urban and industrial development, changes in agricultural practices, soil erosion and sedimentation, scope of construction activities in nearby areas, nutrient loading. Thus, under this task, the following areas for developing the options for improvement of natural treatment systems were elaborated:

- Improving operational stability (e.g. reducing the clogging propensity) through incorporation of advanced pre-treatment mechanized treatment technologies,
- Selection of an ideally suited plant system and timing of harvesting periods,
- Optimal arrangement of flow paths and
- Improving operational reliability with varying feed water qualities.

A multi-pronged experimental and modeling approach was planned and implemented under this task. Accordingly, the following outcomes, addressing the specific objectives pertaining to enhancement of the performance of engineered CWs (pursued in WP-3), are being communicated in the present D3.4 report:

I. Recommendations for interventions leading to improvement of treatment efficiency
II. Recommendations for incorporating pre-treatment
III. Recommendations for incorporating reuse-oriented post-treatment
IV. Recommendations for enabling strategies for success

In this report, however, recommendations pertaining to the other NTSs such as riverbank filtration (RBF), soil aquifer treatment (SAT), managed aquifer recharge (MAR) or some other riparian zone technologies to address agricultural and urban runoff have not been included.

2 Recommendations for interventions leading to improvement of treatment efficiency

Engineered constructed and natural wetlands as well as the other natural treatment systems investigated in this research appear to be suitable in the Indian context (and for that matter in the developing countries all over the world) owing to their virtues listed below:

- Capable of achieving reasonable removal of carbonaceous and nitrogenous BOD, phosphate and pathogens,
- Relatively inexpensive O&M as well as capital costs,
- Less mechanized,
- Do not need electrical power,
- Can be operated with the help of the skills of rural folks and
- Blend well with the rural and peri-urban landscapes.

In this context, an attempt has been made to assess the status of engineered natural treatment systems including horizontal sub-surface flow constructed wetlands installed all over India in order to manage sewages, sullages and in some cases mixed with biodegradable industrial effluents. As stated earlier, the highlights of learnings and recommendations pertaining to the other NTSs such as riverbank filtration, soil aquifer treatment, managed aquifer recharge or some other riparian zone technologies to address agricultural and urban runoff have not been included in this report.

Based on the survey of natural treatment systems in general and constructed wetlands in particular – especially the 41 sites visited for the in-depth study; several insights into the typologies of failure of engineered constructed wetlands were articulated. However, the lessons learnt should not be viewed as restricted to the respective sites because the case studies have addressed a diverse variety of institutional situations and technology related issues. It is hoped that the lessons learnt in this analyses would prove to be significant and helpful during future efforts of implementation and replication.

1) The national survey of horizontal sub-surface flow constructed wetlands and other natural treatment systems indicated that nearly 76% of the sewage treatment plants investigated were generally achieving the *Minimum National Standards* stipulated by the Water

(Prevention and Control of Pollution) Act and companion regulations. These regulations were passed by the Ministry of Environment and Forests, Government of India in 1974 for regulating disposal of treated sewages into legally permitted surface water bodies or for the purposes of land irrigation.

2) The success of the sewage treatment plant largely depends on the balance between the realistic inlet quality and quantity of wastewater and expectation of the community to treat it for certain kinds of reuse applications. Over the years, the demography, land-use pattern, economic activity and the extent of industrialization got transformed to a new state of equilibrium. Thus, the proportion of domestic and industrial effluents will vary and the sewage treatment plants may become relatively obsolete or redundant. This, however, is not only true for sewage treatment plants based on constructed wetlands but also for other wastewater treatment technologies as well.

A successful example of governance sustainably meeting changing expectations is the constructed wetlands at Mansagar Lake, Jaipur, which did not face the financial crises because the quality of secondary treated sewage is being ensured by the Jaipur Municipal Corporation and the O&M of phosphorus precipitation plant and constructed wetlands has been taken care by the public private partnership arrangements.

As regards to the social challenges, it is now clear that the modalities of access to the harvested biomass and entitlement of the community owning the sewage treatment plant based on constructed wetlands will have to be evolved and mutually agreed with. In absence of such systematic efforts, it is observed that the community feels alienated from the wetland beds. Such negative impression discourages the operators of the sewage treatment plant to the extent that no user fees are charged and O&M deteriorates.

3) It is to be noted that the *Minimum National Standards* stipulated by the Ministry of Environment and Forests for disposal of treated sewages into ambient aquatic environment were meant to be the guideline for ensuring the "minimum" performance expected from a given municipality. There are several communities, however, who believe in achieving much higher performance with respect to the quality of their treated sewages so as to minimize the impacts on surrounding aquatic bodies. The local self-governments as well as the regulatory authorities are fully empowered under the prevailing environmental regime to make such determinations and implement these stringent standards at local levels on case-to-case basis; in consultation with the community and the stakeholders. Also, several communities (especially the ones that are land-locked) have no receiving water bodies for disposal of their treated effluents.

There are several other locations where the farms and city-spaces have been facing the acute shortages of water for irrigation. In such instances, the Ministry of Environment and Forests and Ministry of Water Resources have been permitting land irrigation of treated sewages meeting certain norms acceptable to the regulatory framework and judiciously monitor the crops and vegetation in agriculture and commercial agro-forests. Thus, the GoI have developed and implemented the Minimum National Standards for disposal of treated sewages into ambient aquatic environment as well as for on-land application for irrigation in conjunction with several other standards and safeguards built in the prevailing regulatory framework.

The administrators and decision makers in the respective communities should be encouraged to thoughtfully gravitate to "engineered natural treatment systems" for treatment of the sewages generated by their communities. It was clear from the national survey that the applicable standards and guidelines play a crucial role in making the decisions with respect to the extent of treatment to be adopted as well as in determination of the type of technology to be implemented for treatment of sewages in a given community. Responding to the local requirements, a variety of NTSs have been chosen by the 41 communities investigated in the present survey.

4) The other variant of constructed wetlands, Karnal type constructed wetland (KT-constructed wetland), has been installed in some places in India – especially in land-lock regions where there was typically no option for disposal of treated effluents. These systems were found to be quite effective for achieving complete evapotranspiration of sewages subjected to them. In addition, the KT-constructed wetlands has a potential of generating fuel-wood as well as feedstock for pulp and paper industry and thus provide an opportunity to engage into commercial agro-forestry to the community. The nutrients as well as buffer capacity typically present in wastewaters and sewages can potentially create a novel opportunity of application onto acidified and infertile wastelands. Thus, probably, KT-constructed wetlands could become the most appropriate and economically viable proposition for the rural areas interested in restoring wastelands as well as generate biomass.

5) The sewage treatment plants based on engineered NTSs in general and constructed wetlands in particular have been adopted worldwide for treatment of sewages, sullages and biodegradable industrial effluents – especially in developing and under-developed countries. Among several variants of engineered constructed wetlands , the four varieties are typically practiced all over the world, which include horizontal sub-surface flow constructed wetlands, vertical flow constructed wetlands, free floating constructed wetlands and hybrid systems (Hybrid-constructed wetlands). The horizontal sub-surface flow constructed wetlands are gaining increasing acceptance among the rural, peri-urban and remotely located small communities to treat domestic wastewaters and reuse them to augment irrigation waters as well as conservation and sustenance of lakes and rivers in India

6) Typically, technologies like horizontal sub-surface flow constructed wetlands, KT-constructed wetlands as well as DPs seem to cater to the communities which generate

relatively smaller flow rates of sewages when compared with the technologies including WSPs and PPs. These data clearly suggest that size of a given community has a lot to do with selection of centralized versus decentralized technologies for management of their sewages.

7) The horizontal sub-surface flow constructed wetland systems were found to be quite effective for treatment and reuse of sewages and sullages generated by rural and town communities. The engineered wetland systems seem to be quite robust and versatile in a variety of climatic conditions across India as well as meet the prescribed regulatory standards.

8) Communities seem to prefer horizontal sub-surface flow constructed wetlands even more in the recent time owing to the innate advantages offered by them in the context of minimizing mosquito breeding and thereby minimizing the threat of cerebral malaria, dengue and several vector-based diseases.

9) Removal of organics and coliform bacteria exhibit the so-called pseudo-first order decay kinetics. Collection and analyses of experimental data to investigate the degradation kinetics of several pollutants of interest is in progress.

10) The effective reaction time in the wetland bed, the depth of the saturated zone in the bed and the recirculation of wastewater from the downstream to the upstream position were shown to improve the overall performance of horizontal sub-surface flow constructed wetland. More experimental runs are planned to investigate some of the field-scale issues.

11) Dry periods in-between the consecutive pilot-plant runs did not seem to be influencing the removal of coliform bacterial. More experimental work is in progress to investigate the kinetics of degradation and operational issues in this context. The results helped in suggesting measures for improving operational stability, minimising the clogging propensity as well as for determining best practices for operation and maintenance (O&M) of constructed wetlands.

12) The values for BOD5, COD and fecal coliforms, which are indicative of the efficacy of horizontal sub-surface flow constructed wetlands, were expressed as the ratios of the typical outlet to inlet concentrations in the respective locations. The engineered constructed wetlands are apparently relatively more effective in removing the biodegradable organic pollutants in sewages (indicated by BOD and COD). However, the systems are not as effective in removal of feacal coliforms – 3 to 4 log-reduction as it was observed for sewage treatment plants. The natural treatment systems (particularly constructed wetlands) are also capable of removing pathogenic entities relatively more effectively when compared with the technologies typically employed in the conventional sewage treatment plants (e.g. activated sludge process, trickling filters, extended aeration, sequential bio-reactor etc.).

13) The overall performance of horizontal sub-surface flow constructed wetland depends of appropriate synergistic of the biotic and abiotic components of the system, especially, the media and vegetation. It is known that the plant root provides the necessary surfaces for attachment of bacteria and also provide the oxygen for their metabolism. The carbonaceous as well as various forms of nitrogenous pollutants are being processed in horizontal sub-surface flow constructed wetland by bacterial degradation, plant uptake, adsorptive action of media for phosphorous *etc*.

14) Three plant species were most commonly found in constructed wetlands across India, *namely*: *Canna indica*, *Phragmites karka* and *Typha latifolia*. Clearly, these plan species should be considered to plan in constructed wetland-beds.

15) The tree species, which are fast growing and can transpire high amounts of moisture through evapotranspiration processes and are typically able to withstand high moisture contents in their root-zones, are the most suitable for KT-constructed wetlands. Raw wastewater is normally applied through furrows and trees are planted on the ridges. For example, *Eucalyptus* is one such species, which has the capacity to transpire large amounts of water, and grows rather fast – thereby giving high yield of timber and green biomass.

16) There are several problems associated with mixing of industrial toxic effluents with domestic sewages before subjecting into the treatment facility – although such practices are followed in several constructed wetland treatment plants. For example, the KT-constructed wetland facility, in the City of Ujjain in Central India, failed due to mixing of the industrial effluent generated by dyeing industry of cotton fabrics with urban sewages. This was self-evident from the colour of the mixture of sewage and textile effluents flowing into the KT-constructed wetland. In this instance, the trees (especially the foliage) were found to be wilting due to the toxic effects of industrial effluents. Reportedly, among the two KT-constructed wetland systems catering to the City of Ujjain, one KT-constructed wetland received only sewage (about half of the flow of sewage from the City) and the remaining half flow of sewage mixed with textile industry wastewater was subjected to the KT-constructed wetland described above. The operator of the facilities showed the difference in vitality of vegetation in the two KT-constructed wetlands. Similar observation was also made during field visit to WSPs wherein very poor performance was found (indicated by lower average % BOD_5 removal) due the mixing of industrial effluents with sewages entering the sewage treatment plants.

17) The most commonly encountered problems during successful operation of natural treatment systems across India include, mixing of industrial effluents and poor O&M of the treatment facilities which causes malfunctioning. The agencies which financed, built and commissioned the sewage treatment plants and subsequently transferred the sewage treatment plants to the respective urban local bodies for O&M were the glaring successful

examples. If the operating agencies planned and allocated adequate funds for O&M, the chances of success could even become more.

18) Typically, horizontal sub-surface flow constructed wetlands are designed to achieve removal of organics (typically carbonations BOD) and, in some cases, nutrients. It is reported that the horizontal sub-surface flow constructed wetlands improve the microbiological quality of treated wastewaters in terms of pathogen reduction during the course of treatment process. The removal of pathogens in horizontal sub-surface flow constructed wetlands has been widely studied using enteric indicator organisms, such as total coliforms, fecal coliforms, *E. coli*, bacteriophages, *etc*.

19) Based on the experience gained through the systematic survey of horizontal sub-surface flow constructed wetlands in India as well as the results obtained from the experiments being conducted in the present research, the real-life systems that are being operated properly are showing the number concentration reduction of pathogen in the range of 3 to 4 log-units. Thus, in the Indian context, a higher quality of treated sewages could be discharged in natural aquatic bodies and minimize pathogenic pollution in receiving water bodies if the sewages are treated with the help of engineered constructed wetland plants.

20) In designing of constructed wetland, two parameters namely, bed dimensions and media porosity play a crucial role in operation as well as in removal performance. Configuring of bed length and width may be the superficial horizontal velocity, Q/Ac, of the wastewater through the constructed wetland bed. It has been suggested (Boon, 1986) that superficial velocity be kept under 8.6 m/d to prevent disturbance of the root-rhizome structure and subsequent poor plant growth and to allow sufficient contact time for treatment. This guideline restricts the use of long, narrow beds or beds with steep hydraulic gradients. Although it seems reasonable to restrict the superficial horizontal velocity, there does not appear to be a strong theoretical basis for the maximum value published.

21) HSSF constructed wetland is normally a shallow bed, about 0.3-0.8 m deep filled with the layers of gravel (<15 mm) and sand (or sandy loam) of porosity around 42%. In certain situations, formation of the "root zone" need to be selectively created by mixing finer fraction with sandy soil or compost with local soil. The bed could be of any rectangular or curvilinear geometric shape in plan, preferably having four to five times longer flow path when compared with the distance between two parallel edges. In several situations, especially when percolation of sewages and industrial effluents should be minimised to prevent groundwater and sub-surface strata from contamination; the bottom and side walls of HSSF constructed wetlands need to be made impervious by lining it with clay layers or polythene membranes. Alternately, if the underneath strata bares properties that are not favourable for installing flexible or subsiding impervious layers; the leak-proofing of wetland bed may be achieved by tiling or installing reinforced cement concrete layer

coated with leak proofing chemical additives. Typically, the impervious layer is expected to achieve hydraulic conductivity of 10^{-8} to 10^{-9} m/s (Arceivala and Asolekar, 2006).

22) The inlet and outlet zones of the horizontal sub-surface flow constructed wetlands are rather important from the prospective of maintaining desirable hydraulic flow regime on one hand and ensuring uninterrupted operation on the other hand. Therefore, the both zones are filled with larger gravels (50-100 mm). A water level regulation chamber is also normally devised before final discharge. Arceivala and Asolekar (2006) describes the engineering design of the system complete with engineering details of baffle in the exit chamber. The adjustable heights of the baffle helps in maintaining the loss of head to the tune of approximately 50 mm of water throughout the operation of horizontal sub-surface flow constructed wetlands. Pre-treatment (conventional primary treatment or lagoons) of the sewages or industrial effluents is also highly recommended in all the cases wherein the macrophyte beds would receive raw sewages or effluents.

3 Recommendations for incorporating pre-treatment

Primary treatment plays an important role for long-term O&M of horizontal sub-surface flow constructed wetland. Therefore, adequate primary treatment units should be designed, installed as well as well to be maintained from the starting date of treatment plant. The important issue related with successful O&M of horizontal sub-surface flow constructed wetland happened to be of clogging of the constructed wetland-bed due to presence of high load of suspended solids in the feed wastewater. It is known that clogging has been recognized as the most serious practical problem of constructed wetland systems since it can cause a number of adverse effects such as short-circuiting, algal growth, odor problems, insect nuisance *etc*. and finally lead to the surface ponding of the wetlands, especially for horizontal sub-surface flow constructed wetlands. The main characteristics that affects the removal efficiency of constructed wetlands are the hydraulic residence time and temperature, while the effect of vegetation type and porous media have not been studied adequately yet. It is necessary then to find the optimal constructed wetland design characteristics as well as influencing factors so that the limitations can be minimize in order to maximize their removal efficiency.

1) The remedial measures *i.e.* removal of suspended solids may simultaneously tackle in for primary treatments and the constructed wetland system may work satisfactorily for a long span of time. Also, the primary treatment unit helps in reduction of shock load to the constructed wetland bed and the facility able to accomplish a uniform performance round the year. The uniform quality of treated effluent by the natural treatment systems has enhanced the acceptability of treated effluent as well as confidence of the treatment technology in the community owing the system.

2) The foremost objective of primary treatment is the reduction of suspended solids in wastewater, although additional treatment effects leading to organic content reduction and,

in some cases, the hydrolysis and stabilization of the generated sludge are also achieved. In this way, some primary treatment technologies can achieve removal of ≈50% of organics. In general, primary treatment operations are considered to be a convenient means of ensuring the perfect operation of subsequent constructed wetland-bed.

3) The characteristics of primary treatment units together with low technological requirements for NTSs make the systems particularly suitable for decentralized wastewater treatment in rural areas. Dahab and Surampalli (2001) found clogging in a HSSFconstructed wetland system after 3.5 years of treating wastewater with a load of 1.44 g TSS/m^2.d, which indicate TSS as the cause of clogging in the constructed wetland-bed. Winter and Goetz (2003) showed that in order to avoid clogging processes in a vertically flow constructed wetland the average concentration of TSS in the inflow should not exceed 100 mg/l, while the suspended solid load should not exceed 5 g TSS/m^2.d.

4) Primary treatment systems can achieve a TSS removal of 50–70%, generating primary effluent concentrations in the range of 50–90 mg TSS/l when they are operated well (Metcalf and Eddy, 2003). Furthermore, Septic and Imhoff Tank stabilize the sludge by anaerobic digestion, reducing the amount of sludge generated. Another classical pretreatment alternative, which is being used mainly for larger installations, is the primary decanter. Primary decanters offer similar TSS removal of 50–70%, but the high amount of primary sludge produced is their largest handicap. Further, 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 (Metcalf and Eddy, 2003).

5) Appropriately operated Septic Tanks installed before constructed wetland can potentially give good removal efficiency of suspended solids at a given organic load and temperature and thus will help in enhancing the performance of constructed wetland plants. Many old Septic Tanks, however, can pose problems to the constructed wetland-beds due to poor efficiency in removal of suspended solids in the overloaded Septic Tanks and also due to poor maintenance.

6) The horizontal sub-surface flow constructed wetland requires a primary treatment for raw wastewater before subjecting it to the wetland-bed. A primary treatment unit is normally installed in most of the treatment systems incorporating constructed wetlands to minimize the complications normally arising due to larger debris, garbage, floating polymeric wastes and fragments of packaging materials carried with the raw sewages. It has become clear to the operators of the constructed wetland-systems that the life of wetland-beds would prolong if the superior primary treatment units are installed to remove even fine suspended solids in the influents to the sewage treatment plants.

7) The engineered constructed wetlands in conjunction with adequate primary treatment and suitable tertiary treatment presents the possibilities of producing treated effluents of rather

high quality. Such treated effluents can be used for irrigation, gardening and even for recharging into contaminated urban lakes and ponds.

8) By and large, poor O&M of primary treatment unit (or absence of it) was found to be one of the major causes of failure of NTSs based on constructed wetland-technology. Two examples of such lapses found while visiting the *Ekant Park* horizontal sub-surface flow constructed wetland installed at *City sewage treatment plant*, respectively (both located in the City of Bhopal, State of Madhya Pradesh in Central India).It was evident during the site visit that there was no periodic cleaning of sludges accumulated in primary treatment unit.

9) Even the constructed wetland-beds faced the similar negligence on part of the respective civic authorities and the failure of NTSs based on horizontal sub-surface flow constructed wetland was feared by the operators of the facility of constructed wetland-bed (located in the City of Bhopal) and in the outskirts of the City of Ropar, State of Punjab (in northern India), respectively. At both sites, the constructed wetland-beds were chocked with weeds and unwanted growth of planted vegetation was evident. Though, both the sewage treatment plants were giving satisfactory quality of treated effluents at the time of the survey, but the need for systematic and disciplined harvesting of biomass as well as implementing de-weeding programme thoroughly from time-to-time cannot be overemphasized.

10) It was recognized at the outset that the challenges faced by an urban local body while restoring and rejuvenating a lake or a river subjected to the input of sewages in the respective city or town are completely different when compared with the challenges faced while treating domestic wastewaters generated by any peri-urban or sub-urban community. Likewise, not only the techno-economical but also the socio-cultural considerations play a crucial role when the sewages generated in a rural community need to be managed successfully.

11) There are two aspects while assessing the effectiveness of constructed wetland as a technology to deliberate choice during planning and designing a sewage treatment plant for a given community. First, the techno-economic evaluation of constructed wetland – especially if the technology is capable of delivering suitable quality of treated sewage acceptable to the regulatory agency and the municipal administration. Second, the equally pertinent consideration should be the affordability and manageability of the technology. Arceivala and Asolekar (2006) have emphasized these two aspects as the most relevant and critical for determining if a specified technology is “appropriate” in a given technological and socio-economic context.

12) The poor O&M of the eco-centric technology is typically resulting from inadequate primary treatment in almost all cases. Clogging of the porous media can have a domino effect on the efficacy of all the unit operations included in the treatment train. Another common challenge has been insufficient fund for O&M. One of the cardinal principles used in India’s

environmental jurisprudence has been: “the polluter pays”! Unfortunately, the institutional arrangements are either weak or non-existent when it comes to collection and utilization of the fees from the "users or polluters" who are sending their sewages to the sewage treatment plant.

4 Recommendations for incorporating reuse-oriented post-treatment

Reuse oriented technological options for treatment of sewages and up-gradation of contaminated ambient waters for the purposes of agriculture, process industry as well as uses in recreation and groundwater replenishment have been favored for public investment in the recent times.

1) Depending on the reuse option prescribed by the community; a high–class tertiary unit followed by disinfection should also be combined with the NTS so that treated wastewater can be gainfully reused.
2) There are high potential to reuse the treated effluent from constructed wetland systems. For that, infrastructure should be in place for transfer of the treated effluents from the treatment plants to the site. The effluent from constructed wetlands could also be used in some industrial processes after suitable post-treatment. Finally, artificial recharge of the treated effluent from NTSs is another attractive option to polish the effluent quality and to replenish the depleting groundwater levels in different places of India.
3) In most of the cases, the properly operated systems of wastewater treatment based on constructed wetlands are able to achieve up-to 3 – 4 log reduction in pathogenic bacteria count. In some cases, complete removal of pathogenic bacteria has also been reported. More importantly, the natural die-off of pathogenic bacteria may the best way because it does not require adding any potentially harmful substances like chlorine into the wastewater, the conventional practices being followed for disinfection. The most chemical and physical methods used to disinfect the wastewater (except chlorine) are either costly or ineffective for long-term practices, therefore constructed wetlands provide one of the most appropriate way of reducing the pathogenic count without adding any harmful byproduct in the wastewater.
4) It can be claimed that the performance of constructed wetlands with respect to removal of feacal coliforms is typically better by one to two orders magnitude than the conventional sewage treatment technologies. There is still a room for development of techniques for enhancement of the performance of constructed wetlands through targeted research and development. Clearly, the need for an effective post-treatment is eminent if one aims at reusing the treated sewages for irrigation applications involving body contact and other higher end-uses.

5 Recommendations for enabling strategies for success

Over the past three decades, the Government of India has made several efforts in supplying drinking water to communities in urban as well as rural India. Though there was a large investment concurrently made in creating infrastructure for sewages across India, the shortfall between the water supply and sewage treatment continues to grow at steep rates. Thus, there exists a large gap between the amount of wastewater generated and treated in urban and peri-urban communities. It is alarming that the water bodies, both surface and groundwater, are severely contaminated as a result of disposal of those untreated or partially treated sewages. Clearly, there exists a looming challenge of inadequate and insufficient infrastructure for treatment of sewages throughout India, both in urban as well as rural communities. The Ministry of Urban Development, Ministry of Environment and Forests as well as the Ministry of Water Resources and Ganga Rejuvenation have incorporated the strategy of providing low-cost eco-centric treatment to sewages for correcting the pollution of natural water courses in India.

1) Merely compliance-driven investments are being seen as ecosystem damaging and wasteful. It is concluded in this research that the most appropriate sewage treatment system in India would incorporate an excellent primary treatment unit followed by a secondary treatment unit based on natural treatment systems.

2) The constructed wetlands are simple to operate and can be easily combined with cultivation of fodder, production of recyclable water, production of fuel, timber for pulp and paper industry as well as up-gradation of lake or river ecosystem and develop habitats for fishes and birds.

3) Strengthening institutional arrangements and financial provisions, which are conducive for incorporating engineered constructed wetlands in sewage treatment plants as well as motivating community to own and operate such decentralized systems, is going to be a task to be addressed by the municipalities in the years to come.

4) In the Indian context, water, wastewater and the associated utility services is the “state subject” *i.e.* the funding for development of sanitation projects, O&M of the facilities, monitoring of performance, general administration and revenue collection related to the utility. The important agencies involved in these functions can typically grouped in four groups, *namely*: 1. Urban Local Bodies (ULBs; comprising of Municipal Corporation, Nagar Palika and Parishad and Village Council), 2. State and Central Governments (comprising of respective state governments, the Government of India, National River Conservation Directorate in the Ministry of Environment and Forests, Yamuna Action Plan and Public Health Engineering Departments in various states and in GoI), 3. Water Boards (comprising of State Jal Boards and Water Authorities, Water and Sewerage Boards and Environmental Planning & Coordination Organization) and 4. UNDP (United Nations Development Programme).

It was concluded from the national survey that the agencies that built, commissioned and transferred the sewage treatment plants to the urban local bodies for O&M were the glaring success stories. If the operating agencies plan and allocate adequate funds for O&M, the chances of success were even higher. In summary, providing capital investments to the community is as important as helping them in planning for providing adequate O&M costs.

5) The engineered constructed wetlands in conjunction with adequate primary treatment and suitable tertiary treatment presents the possibility of producing treated effluents of rather high quality. Such treated effluents can be used for irrigation, gardening and even for recharging into contaminated urban lakes and ponds. Strengthening institutional arrangements and financial provisions, which are conducive for incorporating engineered constructed wetlands in sewage treatment plants as well as motivating community to own and operate decentralized systems, is going to be a task to be addressed by the municipalities in the years to come.

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