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Natural treatment system models for wastewater management: a study from Hyderabad, India

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ABSTRACT

Wastewater generated on a global scale has become a significant source of water resources which necessitates appropriate management strategies. However, the complexities associated with wastewater are lack of economically viable treatment systems, especially in low- and middle-income countries. While many types of treatment systems are needed to serve the various local issues, we propose natural treatment systems (NTS) such as natural wetlands that are eco-friendly, cost-effective, and can be jointly driven by public bodies and communities. In order for it to be part of wastewater management, this study explores the NTS potential for removal of pollutants, cost-effectiveness, and reuse options for the 1.20 million m^3/day of wastewater generated in Hyderabad, India. The pilot study includes hydro-geophysical characterization of natural wetland to determine pollutant removal efficiency and its effective utilization for treated wastewater in the peri-urban habitat. The results show the removal of organic content (76–78%), nutrients (77–97%), and microbes (99.5–99.9%) from the wetland-treated wastewater and its suitability for agriculture applications. Furthermore, the wetland efficiency integrated with engineered interventions led to the development of NTS models with different application scenarios: (i) constructed wetlands, (ii) minimized community wetlands, and (iii) single outlet system, suitable for urban, peri-urban and rural areas, respectively.

Key words | Hyderabad, India, NTS models, stakeholder survey, wastewater treatment, wetland efficiency

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INTRODUCTION

Increasing water demands and rampant wastewater disposal are the current global environmental concerns to conserve the water resources. Globally, about 330 km^3/yr of municipal wastewater are generated, which would be theoretically enough to irrigate and fertilize millions of hectares of crops (Mateo-Sagasta *et al.* 2015). In India, wastewater generation is about 13.96 km^3/yr from Class-I cities and Class-II towns, and out of that only 31% of the

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wastewater is treated, indicating a large gap between generation and treatment (CPCB 2013). The government of India projected the increase in potable water supply from 116 km^3/yr in 2010 to 174 km^3/yr by 2025, resulting in a large volume of wastewater by 2025 which needs an economically viable treatment technology (Amerasinghe *et al.* 2012). Several studies carried out to assess the impact of waste disposal and industrial effluent discharge into the rivers reported that all the rivers in India are highly influenced by wastewater pollution (CPCB 2013). The population explosion and lack of economically viable technologies are the key catalysts to expedite the quality deterioration of water resources in India. CPCB 2013 reported that 38.254 million m^3 of wastewater generated in major cities, where the sewage treatment capacity is only 11.786 million m^3, and about 26.468 million m^3 (69.18% of total wastewater generation) of untreated wastewater is released into the environment per day from Class-I cities (498) and Class-II (410, population 0.05–0.1 million) towns in India. Since 1979 the wastewater generation, treatment, and management trend show a drastic rise without meeting the treatment capacity at the fullest (Figure 1). The prime causes of this large gap between generation and treatment are an inadequate number of sewage treatment plants (STP), the shortfall in financial support, non-operational STPs, reduced efficiencies of secondary treatment, and the high cost of operation and maintenance of STP (CPCB 2013).

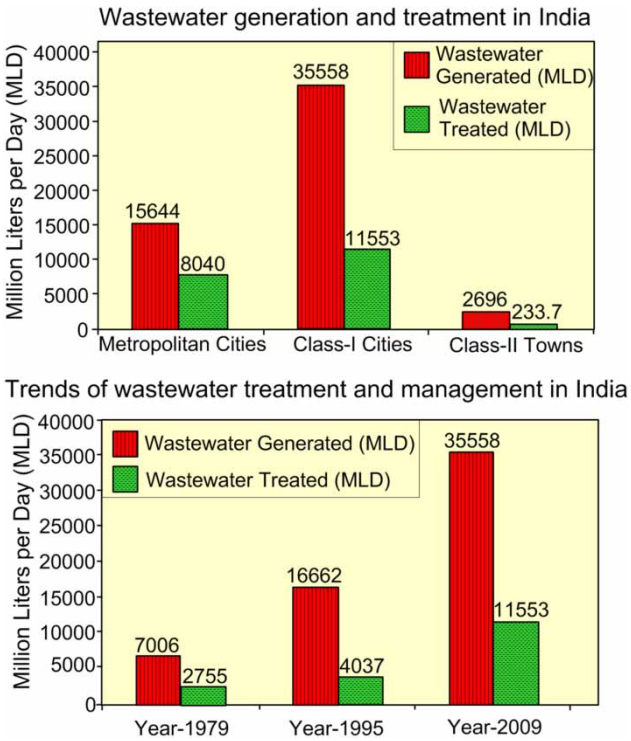


Figure 1 | Wastewater generation, treatment capacities, and trends of management in India (*Source:* CPCB 2013).

Although there were existing regulations and wastewater treatment methodologies, the quality of the urban, peri-urban, and rural environment continues to decline in Indian aquatic systems. The key reasons for this environmental crisis are the slack performance of the enforcement agencies owing to lack of budgetary support and inadequate planning. Article 48A in 'The Constitution of India' dictates the Acts and Policies that are relevant to the management and protection of the environment and its natural resources. The Union Government of India and individual states employ a range of regulatory instruments to preserve and protect its natural resources. Despite a number of concerned public bodies, most of the Indian STPs practices\ only primary treatment, releasing the elevated biochemical oxygen demand (BOD) sewage into the natural streams. The CPCB (2013) report also reveals the performance evaluation of 152 STP spread over 15 states in India with a total treatment capacity of 4,716 million liters per day (MLD) and actual treatment capacity utilization is only 3,126 MLD (66%). Out of the 152 STP, the treated effluent from 49 STPs exceeds the BOD standards and, with respect to chemical oxygen demand (COD), 7 STP violate the general standards of discharge. The report also reveals the most used state-wise treatment technologies, i.e. (i) upflow anaerobic sludge blanket (UASB; 37), (ii) activated sludge process (19), (iii) oxidation pond (34), and (iv) waste stabilization pond (31). Further, it is recognized that the current ways of fixing the environment are not working and hence the need to build a holistic approach to environmental management that is affordable and sustainable.

Natural treatment systems

The current scenarios of wastewater treatment and management are reported to be insufficient as evidenced by surface and subsurface pollution in most of the Indian rivers. Hence, it is argued that the novel treatment methods should meet the drawbacks of conventional treatment systems. Natural treatment systems (NTS) have been the choice of treatment and proven to be a better alternative to wastewater treatment worldwide because it requires minimum energy and reduced maintenance cost and build to suit the setting (Vymazal 2002). The various type of NTS is hyacinth and duckweed ponds, waste stabilisation ponds (WSP), lemna ponds, oxidation ponds and lagoons, fish ponds, algal–bacterial ponds, and polishing ponds of

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wastewater treatment plants (WWTP). Of these, the most common systems are the WSP, which accounted for nearly 73% of the cases (Amerasinghe *et al.* 2015). The natural wetlands and constructed wetlands (CW) can act as WSP, which are the simplest of all waste treatment techniques. WSP are most appropriate where land is inexpensive, climate favorable, and the simplest method of treatment is desired that does not require equipment and operational skills. The ecology of natural wetlands is simple with abiotic (O, CO_2, water, sunlight, and nutrients) and biotic (algae, bacteria, protozoa, and a variety of other organisms) components. The pollutant removal in NTS can be aerobic, facultative, and anaerobic conditions. The principle mechanism of contaminant removal includes sedimentation, nitrification, denitrification, assimilation by flora, and enhanced biodegradation using physical components of the systems including oxygen transferred at air–water interface, as well as solar radiation. The performance can be judged from the different viewpoints of (i) BOD removal, (ii) microbes reduction, and (iii) nutrients removal. It should also be noted that being natural systems, the performance of NTS varies depending on the latitudinal location, temperature, sunlight, and other climatic factors.

In the Indian scenario, adapting any new methodology to the extent of its practical applicability needs to be assessed for economic viability and endorsed by public bodies and communities. Hence, assessment of NTS for techno-scientific, economical, and socio-public levels is mandatory before its implementation at large scale. The current policies of tackling the wastewater management by government body alone are politically expedient in India. This advocated initiating a concrete step towards practical solutions for wastewater management and sustainability. The Union Government of India has therefore given top priority to the joint public body–community participation which plays a significant role in wastewater management in addition to control and mitigates the environmental pollution.

To contribute techno-scientifically under the effective wastewater management, a pilot experiment was carried out on wastewater-fed natural wetland in the proximity of Musi River (flowing with wastewater) at Hyderabad, India. The main objectives of the study are to (i) understand the wetland efficiency for wastewater treatment, (ii) develop NTS models that can serve communities of varying population using treated wastewater for agriculture purposes, and (iii) assess the current policies on wastewater to understand the need for a sustainable wastewater management. Based on the major scientific findings, we developed various models of NTS which can be upscaled for the entire nation at urban, peri-urban and rural level. The study presents a detailed assessment of structure and functions of existing natural wetland using hydrogeological, geophysical, and bio-geochemical investigations suggesting the efficiency of wetlands for wastewater treatment and quantification of treated wastewater. Further, assessing the study from various viewpoints including scientific findings, stakeholders endorsement, and financial estimates is imperative for adapting the NTS models in the Indian scenario. Thus, the developed NTS models are assessed from different aspects, including (i) farmers' and consumers' surveys on wastewater treatment and reuse for agriculture purposes, (ii) economic analysis, (iii) a stakeholder's workshop to strengthen the scientific understanding of the performance-determining processes and their concurrence, and (iv) upscaling the major output of pilot study as an element to wastewater and irrigation management, which can be driven by the joint public body–community on sustainable mode. Thus, this paper highlights the robustness and suitability of various NTS models as the only practical solution to prevent and mitigate the wastewater havoc of a cost-effective model that contributes significantly to wastewater management.

About the study area

The pilot study area of 2.8 km^2 in Hyderabad, India, has a micro-watershed over the banks of the Musi River (flows with wastewater) where wastewater has been used for agriculture production for a long time (25–30 yrs) (Figure 2). The source of wastewater is the Musi River, which receives over 1,200 MLD of wastewater from 6.8 million people residing in Hyderabad. The sewage mixture consists of partially treated and untreated wastewater and is a significant resource in this semi-arid peri-urban environment, where the cultivation of fodder grass, paddy, and vegetables (Figure 3) provide economic benefits and much needed perishable vegetables to many inhabitants of Hyderabad.

There are several natural wetlands located on the banks of the Musi River. Farmers in the peri-urban area directly use the Musi River wastewater for their farm lands by lift irrigation systems (Figure 2). In due course, the wastewater from farms proceeds (due to gravity flow) to these natural wetlands. Upon a preliminary examination of the wastewater quality from inlet and outlet points of an existing wetland, the enhanced wastewater quality at the outlet was observed to have a significant reduction in BOD, COD and nutrients *mutica*. These preliminary observations prompted the further study of understanding the treatment capacity and the potential to be replicated for community use at the peri-urban Hyderabad Musi River site (Figure 2). The study area demarcated as micro-watershed is characterized with sandy to

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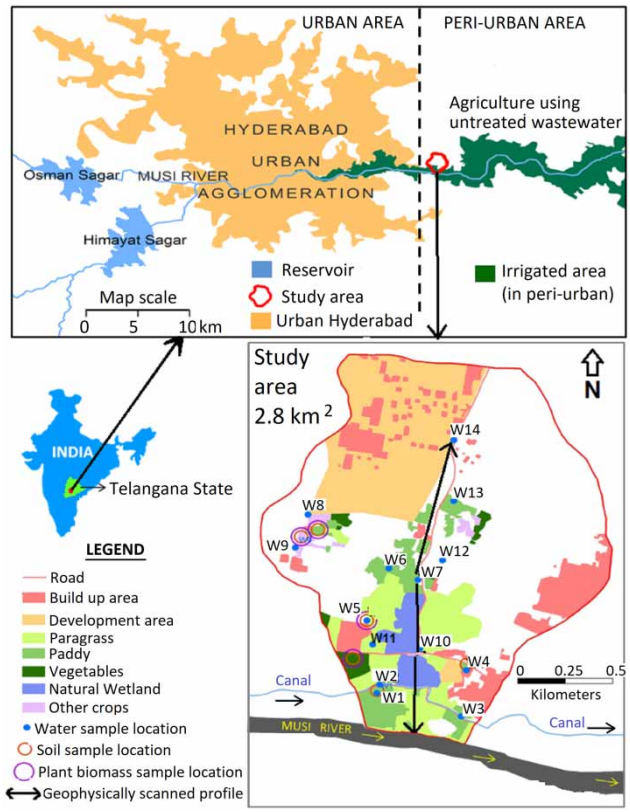


Figure 2 | Location map showing urban and peri-urban areas and the study area in peri-urban environ of Hyderabad, India.

loamy soil of regolith underlain by massive and hard granitic rocks, with an average annual rainfall of 750 mm and a semi-arid climate. The mean annual temperature is about 26 °C, although during the summer the maximum temperature can reach up to 45 °C. From a landscape view, the study area shows flat topography comprising agriculture land (irrigated with wastewater and groundwater), a small reed pond (wetland) in the middle, barren land, and built-up areas in the northern region (Figure 2). The major crops grown in the area are paddy, paragrass (*Urochloa mutica*), and vegetables. Both canal (flows parallel to the Musi River) wastewater and groundwater were used for cultivation, depending on the availability and access. Therefore, within the micro-watershed irrigation practices varied widely.

MATERIAL AND METHODS

Wetland characterization

The functional properties of the selected natural wetland (32×10^3 m^2) were determined by physicochemical and microbial analysis of water, soil, and plant biomass (Figure 2). The inlet and outlet points for the wetland were considered as W2 and W10, respectively (Figure 2). W2 is the wastewater canal from where the water is lifted for irrigation and released at a point north of the W10. We assumed that the W2 would serve as the inlet point for the wetland. The standard methods of collection and analysis of water samples were followed (APHA 1985). Thus, the two water samples from W2 and W10 points were collected for the two hydrological cycles during 2012–2013 and analyzed for chemical parameters, including BOD (test method IS 3025:2003), COD (test method IS 3025:2006), dissolved oxygen (DO) (test method IS 3025:2003), pH (using pH meter), electrical conductivity (EC; using EC meter), major ions (titrimetric and ion chromatography), trace metals (using inductively coupled plasma mass spectrometry (ICPMS)), nutrients (by ion chromatography), and microbiological parameters including sulfate reducing bacteria (SRB; test method IS:1622:1981), total plate counts (TPC; test method IS:5402:2002), coliforms (test method IS: 5401(P-1): 2002), faecal coliforms (test method IS: 1622: 1981), *Escherichia coli* 0157:H7 (polymerase chain reaction (PCR) method), *Salmonella* (test method IS: 5887(P-3)1999), *Shigella* (test method IS: 5887(P-7) 1999), and *Campylobacter* (PCR method).

Apart from before and after a monsoon, periodic monitoring of wastewater for indicative parameters such as pH, EC, BOD, COD, and DO were carried out on a monthly basis. Combining the different data sets, the chemical pollution gradient and fluxes were determined. The functional efficiency of the wetland was determined based on the overall pollutant removal trends. Engineering interventions to further enhance its efficacy was also discussed. Further, to decipher the subsurface horizontal layers precisely, the systematic geophysical scanning comprising non-invasive electrical resistivity tomography (ERT) was carried out on a 1,600 m length profile from north to south on the experimented wetland (Figure 2). The theory and practice of electrical resistivity methods for shallow subsurface exploration are well documented by Bhattacharya & Patra (1968) and interpretation of resistivity data are explicitly described by Zohdy (1965).

The quantification of wastewater and its dynamics within the wetland can be the deciding factor to know the wetland efficiency. The study of wetland dimensions and functions is important and was in this study area. The quantification is calculated by measuring the volume of input and outlet wastewater on a daily basis, the groundwater contribution, and also its residual time. This

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Figure 3 | Field snaps showing (a) canal flowing with wastewater, (b) lifting of wastewater from canal for irrigation, (c) discharge of untreated wastewater for growing paddy, (d) discharge of untreated wastewater for vegetable cultivation, (e) paragrass grown by untreated wastewater, and (f) vegetables grown by untreated wastewater.

quantification assists in replicating the pilot experiment at various scales as suitable in urban, peri-urban, and rural areas. The hydrogeochemical and geophysical findings of the natural wetland therefore led to developing various NTS models in this study.

Designing the CW as NTS

The ideal dimensions of CW necessitate quantifying the influent wastewater on a daily basis. In the Indian scenario, the recommended per capita usage of water is 135 liters/d (CPHEED 2011), and the wastewater generation is estimated 80% of total usage (CPCB 2013). Thus the dimensions of CW can be calculated considering ideal size population of a rural village as 2,000 and urban streets as 10,000 in the Indian perspective. The ideal dimension of CW suitable for the urban, peri-urban and rural area is shown in Figure 6, where the length and width can vary depending on the dimensions. The top layer of filling material was 0.5 m thick with pebbles (size 10–50 mm), the middle layer 0.5 m thick with coarse gravel (5–20 mm) and the bottom layer of 2.0 m with medium to coarse soil (size 0.5–5.0 mm). The hydraulic conductivity of various media (Domenico & Schwartz 1990) as filling material is recommended to be followed within the range 30–50 m/d for the top layer, 20–30 m/d for the middle layer and 10–15 m/d for the bottom layer. Further, the CW needs to grow the plants such as Bulrush (*Typha capensis)* and Common reed (*Phragmites australis)* which are well known for removal of pollutants in CW (Chen *et al.* 2014).

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The ideal dimensions of the CW can be designed considering the hydraulic loading rate (HLR) (m/d), hydraulic retention time (HRT) (d), pollutant loading rate (PLR) (g/m^2 d), removal rate (RR) (g/m^2 d), and removal efficiency (RE) (%) (Lin *et al.* 2015) using the following equations:

$$C_e = C_0 \exp(-kt) \quad (1)$$

$$HRT = \frac{Q}{V} \quad (2)$$

$$HLR = \frac{Q}{A} \quad (3)$$

$$PLR = HLR \times C_o \quad (4)$$

$$RR = HLR \times (C_0 - C_e) \quad (5)$$

$$RE = \frac{C_0 - C_e}{C_0} \times 100\% \quad (6)$$

where C_e = mean effluent concentration, C_0 = mean influent concentration, k = temperature-dependent decay rate constant (1/d), t = HRT (d), Q = average flow rate (m^3/d), A = wetland surface area (m^2), and V = wetland volume (m^3). The flow rate, length, and the interaction between flow rate and length influences the effluent pollutant fraction significantly (Rengers *et al.* 2016).

Stakeholders' views and farmers-consumer surveys

The various models of CW are proposed to be established at an urban, peri-urban and rural level for wastewater treatment and reuse. To strengthen the scientific output and replicate at a large scale, the findings of NTS were shared with stakeholders, farmers and government authorities to invite their opinion and recommendation. Workshops were conducted to seek responses as well as explore civic body support for small-scale farmers. Considering the concluding points of the stakeholder's workshop, the final models of NTS are designed as techno-scientific interventions to wastewater and irrigation management.

Farmers using untreated wastewater as an irrigation source were also interviewed and linked to their preferences for using treated or untreated wastewater, their willingness to pay for treating irrigation water, and their preferred policy options. Also, a consumer survey was conducted to assess the consumer's opinion on treated wastewater irrigation. It was linked to their perception-based policy options and willingness to pay more if vegetables were grown with treated wastewater. The survey was carried out at a local market, and a sample of 24 consumers was interviewed using a validated questionnaire (Starkl *et al.* 2015).

RESULTS AND DISCUSSION

General characterization of wastewater and pollutants removal mechanism

The composition of raw wastewater can be the reference to estimate the potential reduction of pollution load in natural wetlands. The analytical results of raw wastewater from the canal (W2) revealed concentrations of BOD as 60 mg/L, COD 184 mg/L, DO 0.28 mg/L, NO_3^- as N 142 mg/L, SO_4^{-2} 305 mg/L, PO_4^{-2} 8.3 mg/L. Other trace elements can be seen in Table 1. Further, the microbial strength in untreated wastewater is recorded as SRB present per 100 ml, TPC 7.27×10^6 CFU/ml, coliforms 110×10^3 CFU/100 ml, faecal coliforms 1,600 MPN/ml, and absence of *E. coli*, *Salmonella*, *Shigella* and *Campylobacter*.

The wetland in the natural state was able to treat wastewater to a level that was acceptable for agriculture (Table 1). The analysis results of the wastewater from the inlet (W2) and outlet (W10) points of natural wetland with the removal percentage of pollutant are shown in Table 1. Table 1 shows a significant percentage removal of pollutants in natural wetland with their reducing capacity for EC: 44.69%; organic strength: 76.08–78.33%; nutrients: 77.70–97.18%; major ions: 0.0–67.54%; trace elements: 8.00–94.73%; agriculture suitability: 7.88–51.22%; and microorganisms: 99.56–99.99%. The removal mechanism for organic pollution is aeration, the addition of oxygen by photosynthesis, and the bacterial release of oxygen (Lin *et al.* 2015). For nutrients, sedimentation, denitrification, reduction by SRB and plant assimilation, heterotrophic consumption, adsorption, precipitation, matrix sorption, and plant uptake are responsible for their reduction (Pester *et al.* 2012). Major ions are reduced by sedimentation, flocculation, adsorption, cation and anion exchange, complexation, redox reactions, precipitation, plant uptake, etc. (Lazareva & Pichler 2010) and trace elements concentration is reduced by adsorption and cation exchange, complexation, precipitation, plant uptake, microbial oxidation/reduction, bound to articulate

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Table 1 | Analysis results of raw wastewater and wetland treated wastewater with the pollutant removal efficiency and mechanism observed in existing natural wetland

Constituents (pollutants)	Raw wastewater (wetland inlet)	Wetland treated wastewater (wetland outlet)	Percent reduction	Removal mechanisms
Ionic strength				
EC (μS/cm)	2,640	1,460	44.69%	Precipitation and Evapotranspiration
Organic contents				
BOD	60	13	78.33%	Aeration, addition of oxygen by Photosynthesis, Bacterial release of oxygen
COD	184	44	76.08%	
DO	0.15	3.34	Added 22 folds	
Nutrients (mg/L)				
NO_3^- as N	142	4	97.18%	Sedimentation, Denitrification, Reduction and Plant assimilation
SO_4^{-2}	305	68	77.70%	Reduction by SRB, Heterotrophic consumption, Adsorption, Sedimentation and Precipitation.
PO_4^{-2}	8.30	1.45	82.53%	Matrix Sorption, Precipitation and Plant uptake
Na^+	234	151	35.47	Sedimentation, Flocculation, Adsorption, Cation and anion exchange, Complexation, Redox reactions, Precipitation, Plant uptake, etc.
K^+	4	8	−100%[a]	
Ca^{+2}	80	80	0%	
Mg^{+2}	151	49	67.54%	
Cl^-	500	210	58.00%	
F^-	1.64	1.38	15.85%	
HCO_3^-	250	272	−8.08%[a]	
Trace elements (μg/L)				
Al	146.60	14.30	90.24%	Adsorption and cation exchange, Complexation, Precipitation, Plant uptake, Microbial oxidation/ reduction. Bound to articulate matters, deposited on the beds of water bodies, and sorbed onto the sediments
Si	8.47	15.07	−44.64%	
V	4.60	3.30	28.26%	
Cr	7.60	6.30	17.10%	
Mn	72.70	83.90	−13.34[a]	
Fe	155.20	73.60	52.57%	
Ni	6.30	7.40	10.81%	
Co	0.61	0.56	8.19%	
Cu	7.70	11.20	−31.25%[a]	
As	1.30	0.60	53.84%	
Se	17.60	18.75	6.13%	
Rb	7.60	0.40	94.73%	
Sr	279.90	462.80	−39.52%[a]	
Mo	0.16	0.50	−68.00%[a]	
Ag	0.02	0.01	50.00%	
Cd	0.52	0.04	92.30%	
Sb	0.05	0.02	60.00%	
Ba	37.50	29.10	22.40%	
Ti	0.02	0.015	25.00%	
Pb	3.10	1.30	58.06%	

(*continued*)

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Table 1 | continued

Constituents (pollutants)	Raw wastewater (wetland inlet)	Wetland treated wastewater (wetland outlet)	Percent reduction	Removal mechanisms
Agriculture suitability parameters of water				
TH as $CaCO_3$	820	400	51.22%	
SAR	3.55	3.27	7.88%	
Microbial contamination				
Sulphite reducing bacteria (/100 ml)	Present	Present	–	Sedimentation/filtration, UV radiation, Excretion of antibiotics from roots of macrophytes
Total plate count (CFU/ml)	7.27×10^6	1,000	99.99%	
Coliforms (CFU/ml)	110×10^3	17	99.98%	
Faecal coliforms (/100 ml)	1,600	7	99.56%	
E. coli O157:H7 (/g)	Not detected	Not detected	–	
Salmonella (per 250 ml)	Absent	Absent	–	
Shigella (per 250 ml)	Absent	Absent	–	
Campylobacter (CFU/ml)	Not detected	Absent	–	

TH: Total hardness as $CaCO_3$; SAR: Sodium adsorption ratio for agriculture suitability (categorized as Excellent 0–10, Good 10–18, Doubtful 18–26, Unsuitable >26 (Richards 1954).
[a]Increase % of pollutant in wetland).

matters deposited on the beds of water bodies, and sorbed onto the sediments (Amin *et al.* 2009). Further, microorganism population is decreased by sedimentation/filtration, UV radiation, and excretion of antibiotics from roots of macrophytes (Arias *et al.* 2003).

However, as is also noted in Table 1, there is an increasing trend in the wetland for parameters such as K^+ and HCO_3^- of major ions and Si, Mn, Cu, Sr and Mo from trace elements as indicated by negative (–) sign. The enrichment of these elements in the natural wetland is due to the dissolution (through water–rock interactions) of granitic minerals such as *Orthoclase* ($KAlSi_3O_8$) and *Anorthoclase* ((Na, K) $Alsi_3O_8$)) by chemical weathering (Sonkamble *et al.* 2012), and Pyrolusite (MnO_2) and Rhodochrosite ($MnCO_3$), Chalcopyrite ($CuFeS_2$), Sr-bearing plagioclase feldspar and Pyroxenes. The enriched concentrations were found within the range of permissible limit of WHO (1989) standards for agriculture.

Functions of natural wetland and dominating process

The pollutant removal capacity of NTS has been governed by several mechanisms which are known to be dominant processes for the specific pollutant (Table 1). While assessing the dominant processes, physical aeration and biological (flora & fauna) release of oxygen are found to be responsible for the reduction of BOD, COD and an increase of DO in wastewater in NTS. Further, denitrification, reduction, precipitation, adsorption, and plant assimilation enhances the quality of wastewater regarding nutrients. Furthermore, sedimentation, adsorption, ion exchange, redox reactions, complexation, and plant uptake are found to be the significant removal processes for major ions and trace element reduction in wastewater of natural wetland in the study area. Thus, the processes can be replicated by the techno-scientifically designed natural or constructed wetlands.

Geophysical scanning to decipher subsurface structure of natural wetland

The geophysical scan comprising ERT of 1,600 m length profile was carried out from north to south covering the natural wetland (32×10^3 m^2) in the study area (Figure 4). The interpreted geo-electric results of ERT survey at the wetland showed the soil profile as topsoil (0–10 m depth), weathered zone (10–18 m depth), fractured zone (18–25 m

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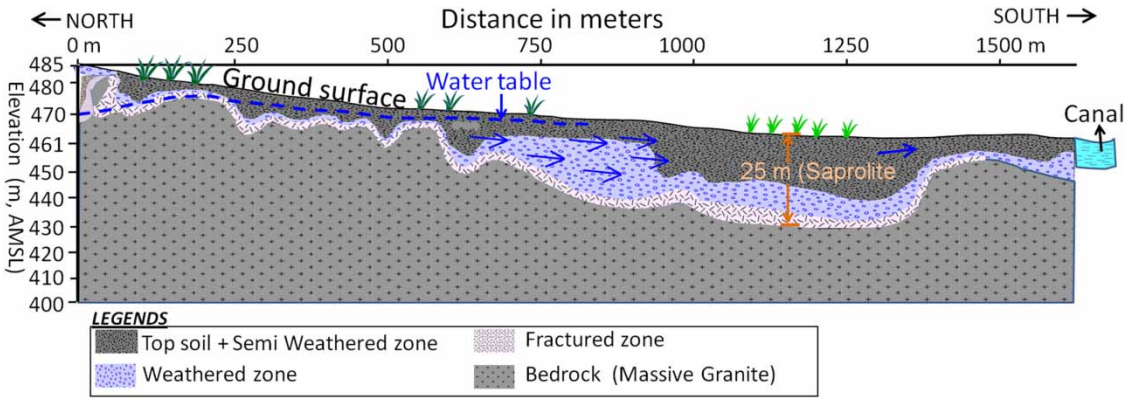


Figure 4 | Geophysically derived subsurface structure of existing natural wetland in the study area.

depth) and depth to hard rock (massive granite below 25 m depth) (Figure 4). The top soil consists of medium to coarse grain sand followed by the weathered soil of coarse grain. The top soil and semi-weathered zone together constitute the saturated zone and the depth up to 3 m plays a significant role in wastewater treatment.

The ideal depth and grain size was of great importance to the design and development of various NTS models. Hydrogeological studies have revealed that the transmissivity (T: water flow through unit cross section area, m^2/d) was measured at 293 m^2/d and hydraulic conductivity (K: measure of a material's capacity to transmit water, m/d) of integrated top soil (medium–coarse sand) and semi-weathered zone was 12 m/d with 30–39% porosity. Thus, the hydro-geophysical investigations confirm the robustness of natural wetland for its replication at urban and rural areas.

INTEGRATED MODELS OF NTS AND SOCIO-ECONOMIC EVALUATION

NTS models for wastewater management

Based on the varying population size of community and quantity of wastewater generation, various models of NTS are developed as a wastewater management practice, suitable for urban, peri-urban, and rural areas in the Indian context.

Decentralized system as NTS in urban area

Decentralized wastewater treatment system (DEWATS) is now being given increasing attention since people are finding centralized systems more expensive to build and maintain (Arceivala & Asolekar 2013). However, its practical applicability is little known especially in developing countries like India and others. The DEWATS using CW in urban areas have been proven for its practical feasibility in Indian scenarios. Based on the pilot experiment, we propose DEWATS model using CW in Hyderabad urban area as techno-scientific interventions to wastewater management (Figure 5).

The study suggests establishing the CW at the outlet of the population settlements of about 10,000 with a water usage of 130 liters per capita per day (lpcd). Thus, the calculated wastewater generation (80% of usage) from the average urban street is 1.04 MLD (1,040 m^3) which can be channeled to pass through the CW before its discharge into the main sewage system. As part of the preliminary treatment process, the screening is essential to remove the floating material and can be installed before the wastewater passes through the CW. To design the dimensions of the wetland for the wastewater Q = 1,040 m^3/d, the it is essential that the filling medium is characterized by hydraulic conductivity 12–15 m/d, mean porosity 30%, and HRT 15–24 hours. Hence, the dimensions of CW can be calculated as 40 m (L: length) × 30 m (W: width) × 3 m (D: depth) = 3,600 m^3 to tackle with 1,040 m^3 of wastewater (Figure 6).

NTS models for peri-urban agriculture

Land application of wastewater has been the common practice in peri-urban areas in India which catalyses pollutant entry into the food chain and food web (Drechsel *et al.* 2010). Hence, irrigation with wastewater needs an ecosystem approach to ensure sustainability of the 'soil-crop-wastewater' system. Based on this pilot study various scenarios of natural and artificial wetlands have been proposed for

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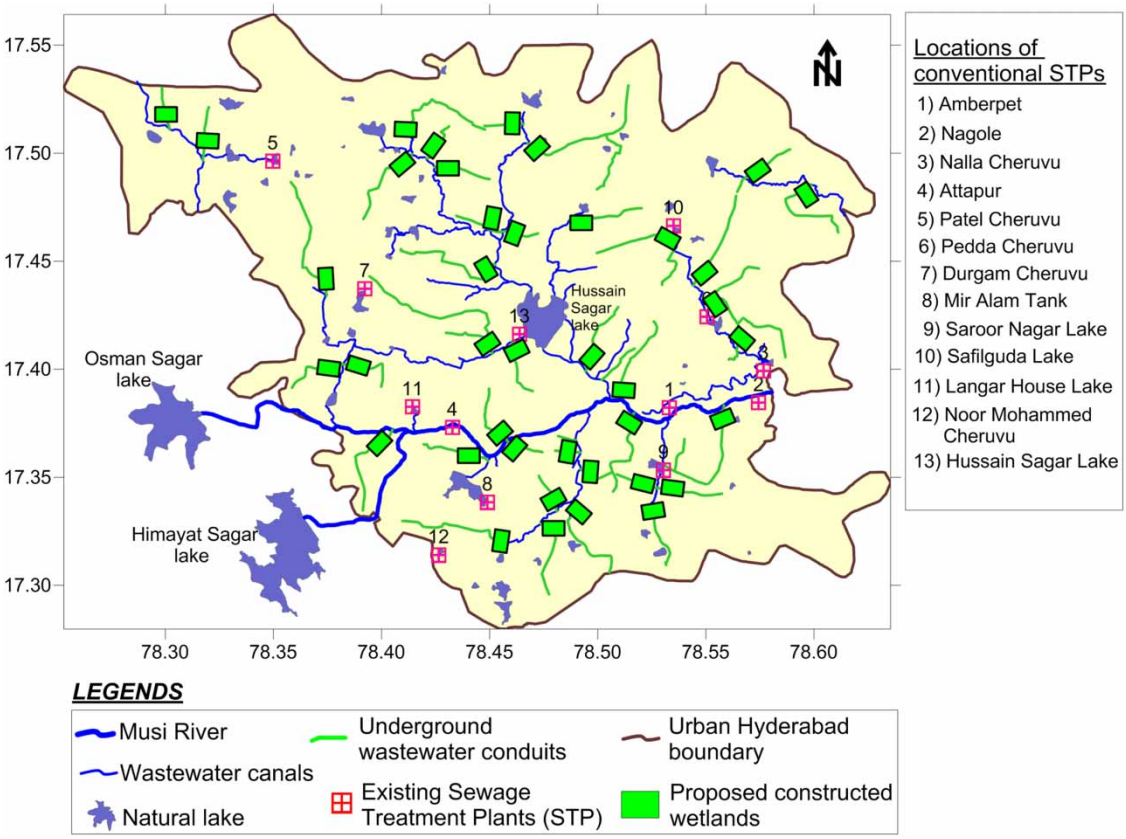


Figure 5 | Proposed model of CW as decentralized wastewater system in urban area at Hyderabad, India.

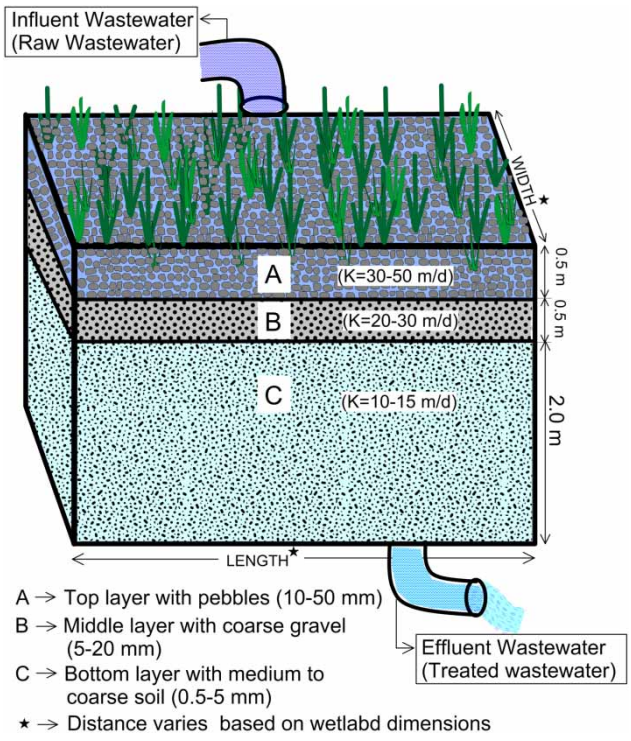


Figure 6 | Conceptualized dimensions of CW suitable for urban, peri-urban, and rural areas.

wastewater treatment and reuse for agriculture purposes (Figure 7) in peri-urban areas. The proposed scenarios are (A) community-driven natural wetlands, (B) modified natural wetlands, and (C) mini wetlands for individual farmers which are demarcated in the study area (Figure 7).

In community-driven natural wetlands, the existing natural wetlands along the Musi River can be monitored for influent and effluent quantity of wastewater by the community and shared as appropriate planning. The current discharge of wetland-treated wastewater in the study area was observed to be 1,728 m^3/d (Figure 7(a)). For modified natural wetland, the Musi River wastewater can be diverted to the topographically low-lying areas along the river course and can be monitored jointly by the public bodies–community (Figure 7(b)). Monitoring includes regulating the constant flow to wetland, periodic analysis to ensure effluent quality and appropriate distribution of treated wastewater among farmers. Moreover, mini-wetlands for an individual farmer can be established and monitored by the individual farmer. The mini wetlands are suggested for upstream of the farm land, and wastewater can be fed from upstream so that the effluent wastewater can irrigate the field by gravity flow

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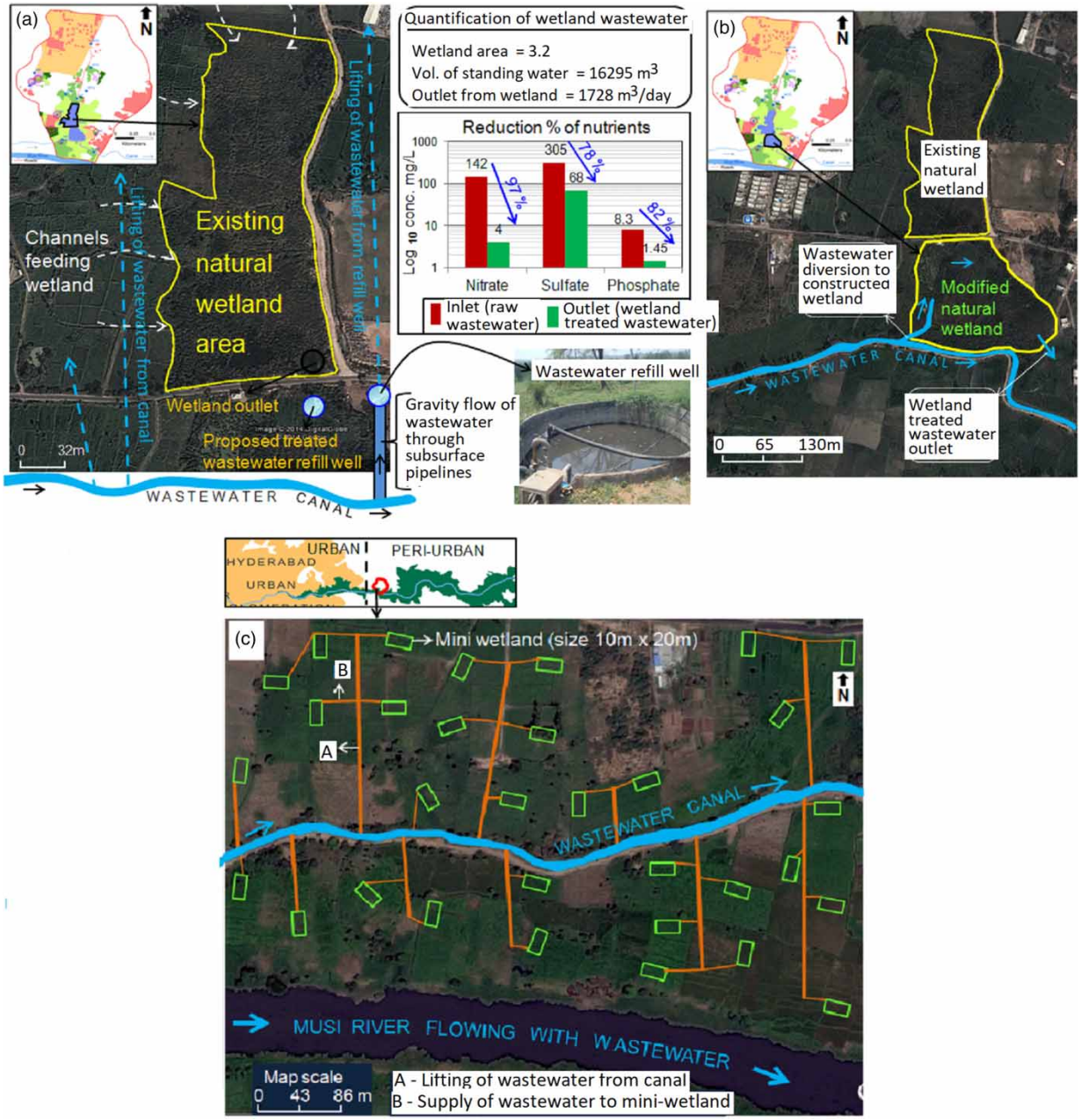


Figure 7 | NTS models at the peri-urban area with various scenarios: (a) community driven wetland, (b) modified natural wetland, and (c) mini wetland for individual farmers. A model from Hyderabad, India.

(Figure 7(c)). Ideal dimensions of the mini wetland are based on the quantity of effluent wastewater. For example, if a farmer requires 54 m^3/d of water to irrigate 1 ha of farmland, then the dimensions of the CW should be 10 m (L) × 6 m (W) × 3 m (D) = 180 m^3 considering the suitable hydraulic parameters of the filling medium. Further, it is concluded from the Stakeholders Workshop that the farmers should be encouraged by way of financial subsidies from public bodies. To ensure the wetland efficiency and sustainability, the quality parameters of wetland-treated wastewater need to be monitored periodically by public bodies.

Single outlet model at rural areas

A large section of the Indian population (68.8% Census of India, censusindia.gov.in) lives in rural villages that are

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poorly established with sewer lines. The Clean India Mission is promoting toilet facilities to every household by way of financial subsidies and construction of a sewage network in rural sections. Given this, the 'single outlet model' is proposed to cater with wastewater treatment. As shown in Figure 8, the single outlet model of CW can be placed at the sewage discharge point before its opening to the environment (Figure 8). Consider the ideal population size of a rural village of about 2,000 people and a water usage of 130 lpcd with 80% of wastewater generation, the dimensions of the CW could be 208 m^3/d. Considering the 30% porosity and 12–15 m/d of hydraulic conductivity of the filling materials, the ideal dimensions could be 20 m (L) × 12 m (W) × 3 m (D) = 720 m^3. Further, the wetland-treated wastewater can be reused for agriculture practices. Monitoring by joint public body–community activity is recommended in order to achieve the green sanitation concept and objectives of the Clean India Mission, which in turn will reduce the water scarcity problems for irrigation.

Views of stakeholders

Stakeholder surveys were conducted to assess the perception of farmers, consumers, and government officials on the use of wetland-treated wastewater for agriculture production. The major findings of the study were shared during the farmers' survey and stakeholders' workshop at Hyderabad. The workshop was aimed at exchanging the views on the various models of CW, financing and policy implications for reuse of wastewater for irrigation (Starkl *et al.* 2015). It concluded, that the specific treatment process suggested was a low-cost natural and constructed mini wetland system that farmers can use either at a community level or individually in the peri-urban environs.

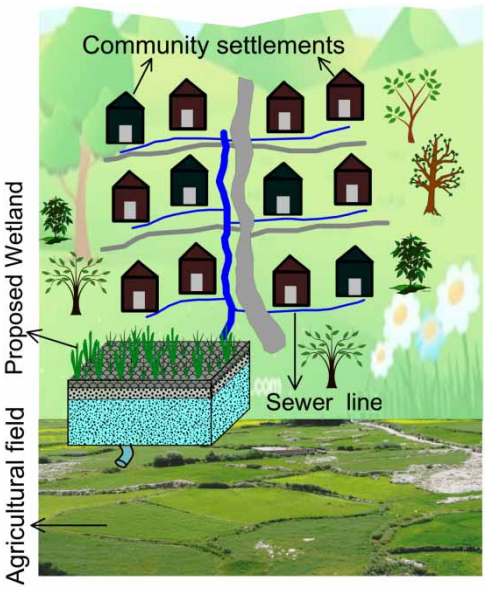


Figure 8 | Single outlet CW model suitable at rural area.

Sustainability and socio-economic evaluation of NTS

Operation and sustainability of NTS

The NTS models are characterized by eco-friendly treatment and gravity based flows, and they are therefore designated as maintenance-free regarding its electricity requirement, workforce, application of chemicals, etc. However, they should be monitored periodically to examine their efficiency and sustainability for wastewater treatment. Peri-urban and rural areas need to be jointly driven by financial subsidies to peri-urban farmers, for capital cost, precautions to protect from physical damage by farmers, and efficiency monitoring by public bodies, etc. Multi-objective environmental management in the CW is needed for its sustainability (Benyamine *et al.* 2004). Moreover, the literature survey shows, NTS such as facultative ponds of 1.2–2.4 m in depth have been in use for more than 100 years in the USA (EPA 2011) and are not mechanically mixed or aerated. Most of the biochemical reaction takes place at a shallow depth up to 3 m in the wetland. Further, the local community experience reveals the existence of wastewater-fed natural wetland over the last 25 years in the pilot area. This confirms the NTS are proven for their carrying capacity for wastewater and are needed to tackle wastewater on the sustainable mode in India.

Cost-benefit analysis of NTS

The cost-benefit analysis (CBA) estimates the current net value of the investment in sewage treatment using the capital costs and operation and maintenance costs. It is well known that any techno-scientific interventions to wastewater treatment should be cost-effective and energy-efficient especially in developing nations. Given this, we assess the CBA of the conventional treatment system of STP and various models of NTS suitable at urban, peri-urban, and rural areas in India scenario. Table 2 illustrates the capital cost of proposed models which are 2–10 times cheaper than the conventional STP in wastewater treatment with relatively more efficient for pollutant removal. Moreover, the proposed NTS models are operation- and maintenance-free. However, the quality of influent and

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Table 2 | CBA of conventional STPs and various NTS models suitable at urban, peri-urban and rural areas

			NTS models at peri-urban			
	STP (Conventional)	NTS-CW at urban	Existing natural wetland	Engineered natural wetland	CW-Mini wetland for individual farmers	CW as single outlet at rural village
Capital cost[a] (Indian Rupees ₹ in Lakhs, (US$))	₹ 68.00/MLD (US$ 103,371) (source: CPCB 2013)	₹ 31.50/MLD (US$ 47,885) (For wetland Size: 40 m × 30 m × 3 m)	Nil	₹ 5.00/5 MLD (US$ 7,591) (To divert wastewater to low lying areas up to max. 100 m)	₹ 1.44/0.05 MLD (US$ 2,186) (For only CC wall size: 10 m × 6 m × 3 m)	₹ 4.32/ 0.2 MLD (US$ 6,558) (CC wall and base of size: 20 m × 12 m × 3 m)
Operation and maintenance cost (₹ in Lakhs)	₹ 0.3/month/ MLD (US$ 455) (source: CPCB 2013)	₹ 0.03/3 months (US$ 45) (for analysis of influent and effluent quality)	₹ 0.03/3 months (US$ 45) (for analysis of influent and effluent quality)	₹ 0.03/3 months (US$ 45) (for analysis of influent and effluent quality)	₹ 0.03/3 months (US$ 45) (for analysis of influent and effluent quality)	₹ 0.03/3 months (US$ 45) (for analysis of influent and effluent quality)

[a]Cost as per the present market rates as (a) CC construction charges ₹ 1,500/m^2 and (b) filling material ₹ 3,000/15 m^3 (truck carriage capacity); MLD-million L/day; ML-million Liters; CC-concrete construction.

effluent wastewater is required to be monitored by the public bodies on quarterly (90 days) basis which incurs about ₹ 3,000 (US$45) for testing two water samples for BOD, COD, DO, *E. coli*, and major ions.

Socio-economic and bureaucratic surveys

The farmer-consumer survey conducted at urban and peri-urban area reveals that both farmers and consumers were willing to pay extra for cleaner water and produce that was safe for consumption respective. The tendency of consumers to pay extra for safe vegetables indicates that farmers will gain 20–30% enhanced price for their vegetables once they obtain the label of 'vegetables from treated water' by a public body (Starkl *et al.* 2015). Further, the proposed NTS models and their robustness are explained to various public departments of the Telangana State Government. The responses from bureaucrats of Greater Hyderabad Municipal Corporation, Rural Development, Commissioner of Agriculture, and Groundwater Department were encouraging for the implementation of NTS as part of wastewater and irrigation management.

CONCLUSIONS

The pilot study performed on a natural wetland at the peri-urban area of Hyderabad, India, has been proven techno-scientifically to contribute to wastewater management through investigations on the environment, health and safety, economic, social, and institutional aspects in India. The major conclusions for the techno-scientific interventions to wastewater management include the significant removal of organic, inorganic and microbial pollutants from wastewater, which is observed up to 99.9% in the natural wetland. The wetland sediments that are rich in medium to coarse grain soil (up to 3 m depth) characterized by 30–39% porosity and 12–15 m/d of hydraulic conductivity is found to be a potential interaction zone for wastewater treatment. The pilot experiment on natural wetland has led to developing various NTS models such as CW, mini and community, and a single outlet model suitable for urban, peri-urban, and rural areas, respectively, for wastewater treatment and reuse for agriculture production. Further, the economic evaluation of proposed NTS models estimates that these are 2–10 times cheaper than the conventional STP providing 1.200 million m^3/day of treated wastewater as irrigation source in Hyderabad and 38.254 million m^3/day in the Indian context. Farmer-consumers surveys and stakeholders' workshops endorsed with the joint public body–community driven models of NTS as a long-term practice to contribute to wastewater management on a sustainable mode.

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