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Investigating the working efficiency of natural wastewater treatment systems: A step towards sustainable systems

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ABSTRACT

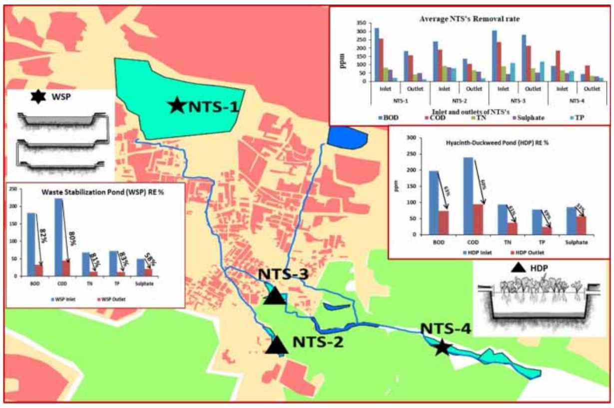
Globally, wastewater is a vital resource and requires appropriate treatment management strategies. Wastewater has become a major source of irrigation in the peri-urban areas of developing nations. With the increasing amount of wastewater generation, there are several complications in using treatment systems in terms of installation, operation and maintenance, and size in developing countries. Recently, natural treatment systems are gaining popularity due to less cost and maintenance and have been preferred in peri-urban settings. In this study, the working efficiency of the natural systems was assessed from case studies from Vizianagaram, Andhra Pradesh, India. The nutrient (Phosphorus and Nitrogen content) and organic matter removal efficiency of four natural treatment systems (NTS) having different operation, maintenance and loading rates were investigated. The study showed that natural treatment systems have good potential for peri-urban wastewater treatment. It was also observed that waste-stabilization based systems perform better than those based on duckweed and hyacinth plants. Regularly maintained and operated systems show removal efficiency on the order of 80% for organic and nutrients and performed better than others. The study indicates that decentralized, adequately maintained waste stabilization ponds (WSP) offer a viable, self-sustaining and eco-friendly alternative for wastewater treatment to supply irrigation water in rural areas.

Key words: hyacinth plants, natural treatment systems, nutrient removal efficiency, waste stabilization ponds

HIGHLIGHTS

- Working efficiency of natural treatment systems (NTS) in wastewater treatment.
- The results evidently support the NTS as a viable and sustainable alternative for peri-urban and even urban areas for effective treatment of domestic wastewater.
- This study bring awareness to farmers, stakeholders and policymakers about the working mechanism and significance of these systems and thereby their involvement in the maintenance.

GRAPHICAL ABSTRACT



ABBREVIATIONS (NOMENCLATURE)

NTS	Natural treatment system
WSP	Waste stabilization ponds
HDP	Hyacinth – duckweed ponds
CPCB	Central Pollution Control Board
WWTP	Wastewater treatment plant
DSR	District survey report
RE	Removal efficiency
$\bar{C}_i$	Average influent determinand concentration
$\bar{C}_o$	Average effluent determinand concentration
EC	Electrical conductivity
DO	Dissolved oxygen
BOD	Biological oxygen demand
COD	Chemical oxygen demand
TN	Total nitrogen
SO_4^{2-}	Sulphate
TP	Total phosphate
Mg^{2+}	Magnesium
Cl_2^-	Calcium
HCO_3^{2-}	Bicarbonate
Na^+	Sodium
K^+	Potassium
DEWATS	Decentralized wastewater treatment system
STP	Sewage treatment plant

INTRODUCTION

The water supply-demand is increasing globally, and as a result, wastewater generation has been proportionately increasing in the last few decades. As water supply increases to meet the demands of growing populations and industrial development, the volumetric gap between the water supply and treated water will also increase. According to Mateo-Sagasta *et al.* (2015), the wastewater generated worldwide is enough to meet the demands of millions of hectares of agricultural land. However, without improving the infrastructure for treating increased amounts of wastewater, most of it goes untreated in the oceans. In India, at present, only 31% of wastewater is treated, the rest being discharged to the environment and leading to various levels of pollution (CPCB 2013; Bitterman *et al.* 2016; Sonkamble *et al.* 2018; Manasa & Mehta 2020). According to Central Pollution Control Board (Drechsel *et al.* 2008; CPCB 2013), with the present status of treatment facilities, 120 km^3 of untreated wastewater will be disposed of annually by 2025. Much untreated wastewater is used for agriculture in India's peri-urban and rural areas (Raschid-Sally & Jayakody 2009; Qadir *et al.* 2010; Sonkamble *et al.* 2018). Studies like those of Amarasinghe *et al.* (2009), Li *et al.* (2017) and Ensink & Van Der Hoek (2009) have shown the impact of sewage disposal on ecosystem water quality and aquatic life. Long-term sewage application for irrigation reduces soil quality and results in groundwater contamination and health hazards.

Regions close to urban areas that receive large amounts of wastewater are particularly vulnerable, especially in regions with little natural drainage. The wastewater tends to go into ponds. Conventional treatment such as mechanical systems is not feasible because of installation and maintenance costs for such areas. As an alternative to the conventional wastewater treatment (WWT) plants, many studies (Vymazal 2007; Sonkamble *et al.* 2018) have proposed natural treatment systems (NTSs) as an effective method for decentralized, cost-effective wastewater treatment in peri-urban areas.

NTSs are optimal in treatment and confirmed as a good substitute for conventional wastewater treatment worldwide because of low energy, maintenance and installation costs (Vymazal 2002). NTSs include hyacinth and duckweed ponds (HDP), waste stabilization ponds (WSPs), Lemna ponds, fish ponds, algal-bacterial ponds, and polishing ponds of wastewater treatment plants (WWTPs). NTSs are helpful in carbon separation, groundwater recharge, nutrient reduction, toxin retention, flood control, and biodiversity management (Turner *et al.* 2000). BOD and COD removal and increasing DO in effluents are influenced by physical aeration and biological processes in NTSs. The nutrient reduction in such NTSs is performed by a combination of several processes such as denitrification, redox reactions, precipitation, absorption, heterotrophic consumption, matrix sorption, and plant growth and plant accumulation (Pester *et al.* 2012).

In many countries, particularly developing countries, these natural treatment systems are successfully adopted as alternative methods (Sonkamble *et al.* 2018). However, most of the time, the systems are not operating at their designed levels either due to improper management, increased stress and lack of maintenance. Therefore, it is crucial to study the real-time working efficiency of these natural systems in terms of their ability to treat wastewater. This study aims to study the efficacy of these natural treatment systems in the real world and the factors affecting their working efficiency. The study objectives were to: (i) assess the current NTS situation and working condition, (ii) estimate the pollution removal potential of field-scale NTS, and (iii) recommend suggestions to farmers, local communities, and policymakers for improving NTS removal efficiency. To fulfill these objectives, the research study was conducted in the urban and peri-urban areas of Vizianagaram city, Andhra Pradesh, India, in 2020.

MATERIALS AND METHODS

Study area

For this purpose, four NTSs of varying size and characteristics were chosen from a peri-urban area in South East India. Vizianagaram is an emerging commercial and industrial hub in Andhra Pradesh, India. About 40 to 50% of the populations are served by open, concrete-lined drains, some 40 km of which discharge the wastewater into nearby ponds. Vizianagaram Municipal Corporation (DSR 2018) has estimated that the northwestern part of the town (part of the old town) generates about 10 ML/d of wastewater and the rest of the city 10–13 ML/d. To date (Jan 2021), approximately 90% of the wastewater gets treated through the various natural treatment systems constructed across the city. There are many ponds of varying sizes across the region acting as a decentralized means of wastewater treatment. To evaluate the treatment system functioning, locations were identified where: (i) the systems had operated for at least five years, (ii) the systems operated at full scale, and (iii) the system's purpose is mainly treating wastewater for reuse. Based on these considerations, four NTSs were selected in the city centre and to its south. The purpose of the selection was to understand system efficiency and its relationship with the quantity and quality of wastewater and the hydraulic residence time. Figure 1 shows the locations of the NTSs studied, while Table 1 provides the design value for the parameters and the present values of the same.

NTS-1 (Waste Stabilization Pond (WSP))

Of the NTSs studied, the main one is Pedda Cheruvu (meaning Big Lake in Telugu, the vernacular language), covering about 6.4 ha. The system of stabilization ponds was established in 2004 to treat wastewater entering the main pond. It comprises a series of anaerobic, facultative and maturation ponds. It is designed to handle an inlet discharge from wastewater sources such as a residential area, food market and small-scale industries. Pedda Cheruvu is in the heart of the city and receives large volumes of wastewater and stormwater during the monsoon. The purpose of the system is to enable the treated wastewater to be reused for irrigation and aquaculture. Although the system performs satisfactorily, the environment is not maintained properly as plastic waste accumulates near the treatment system inlet, and the ponds are not maintained regularly.

NTS-2 (Hyacinth-Duckweed Pond (HDP))

This pond is near Dharmapuri village. It receives 30% of its influent from Pedda Cheruvu and the remainder from intermediate households. Wastewater enters the pond without pre-treatment. Most of the pond is covered by hyacinth plants; these plants play a significant role in treatment. Generally, with help from Vizianagaram Municipal Corporation, the local farmers harvest the plants and maintain the system. However, the maintenance is not regular and is occasional. The pond's average depth is around 2 to 3 m, and its outlet is controlled by a weir so that the excess discharge goes into downstream tanks for irrigation. The community is overall happy with the system.

NTS-3 (Hyacinth-Duckweed Pond (HDP))

This is a natural pond that receives wastewater majorly from intermediate residential areas and a small proportion (10%) from NTS-1. The pond had functioned well in the past, but due to lack of maintenance, desilting, and encroachment and dumping of building waste into the tank, the tank capacity decreased substantially. Based on field survey, most of the tank area is under dead storage; only a small part of the tank has live storage where it is 2 to 2.5 m deep. Plants such as hyacinths, duckweed, canna lilies are found to be grown in

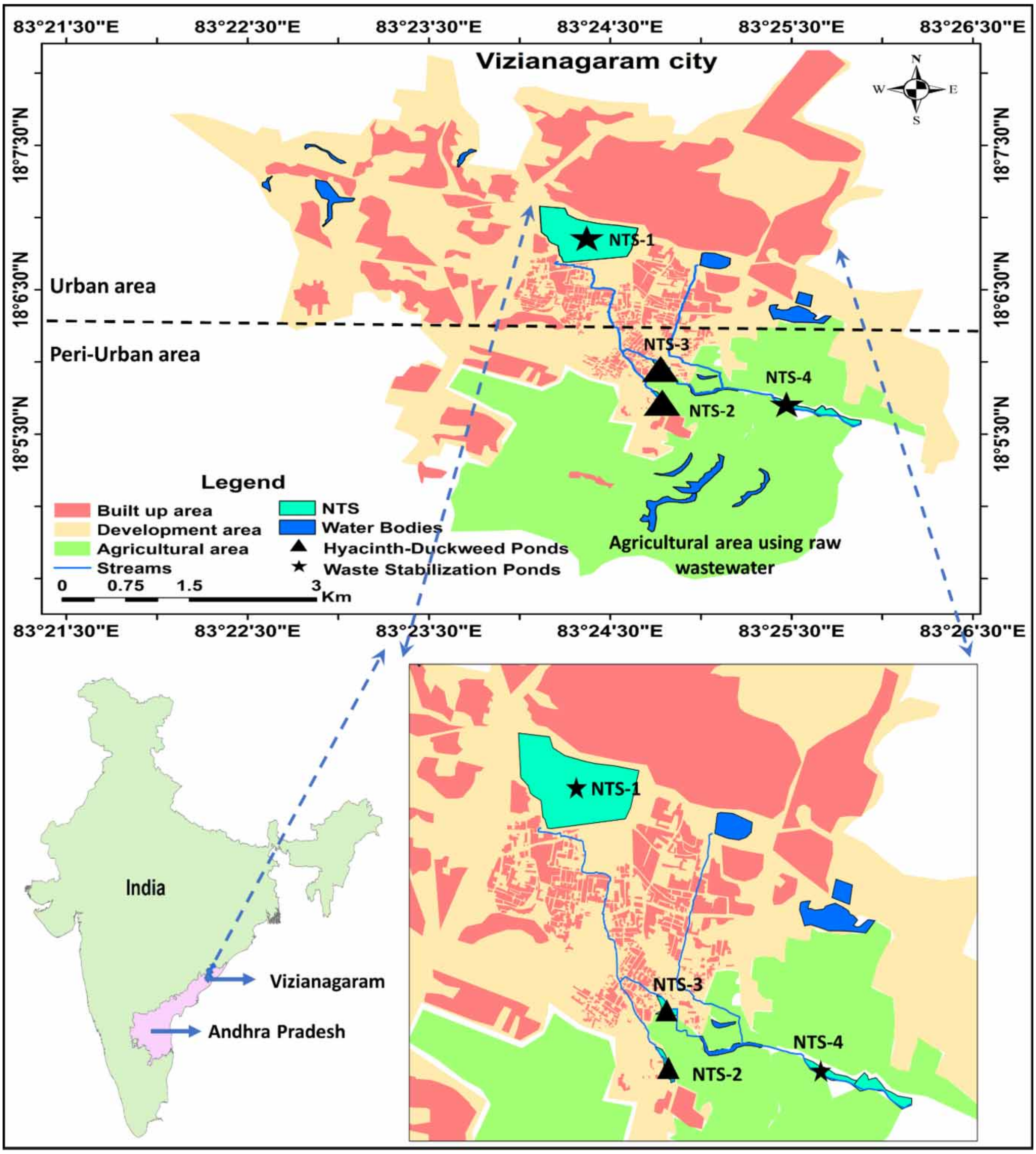


Figure 1 | Index Map and the land use map show the geographic locations of the natural treatment systems investigation in Vizianagaram, India.

the tank area. The water treated from NTS-3 has been used for irrigation by downstream farmers. Generally, farmers complain of issues related to odour, soil infertility and skin irritation.

NTS-4 (Waste Stabilization Pond (WSP))

This pond was developed as a waste stabilization pond and is maintained by the farmers in Jammu Narayanapuram. It comprises a series of anaerobic, facultative and maturation ponds of varying size and receives a continuous flow of wastewater from those parts of the city not draining into NTS-1. The effluent from the tank is the primary source of irrigation water for about 120 ha of agricultural land. The farmers take an active part in desilting and maintaining the inlet and outlet notches and are happy doing this. The maturation ponds are used for aquaculture and provide good yields.

Table 1 | Salient design parameters of the NTS and the present conditions

	Design parameters				Present conditions		
	Area (ha)	Mean depth	Design HRT	Design discharge	Live storage area (ha)	Average influent discharge (Pre-monsoon)	Average influent discharge (post-monsoon)
NTS-1	5.2	2	9	5	5	10	8
NTS-2	0.85	1.8	7	1	0.75	2	1.6
NTS-3	1.22	2	5	1.5	0.3	3	2.3
NTS-4	7.8	3	9	8	7.5	12	8.3

Sample collection and analysis

Manual grab samples were collected from the inlet and outlet of all four NTSs. Sampling locations are shown in Figure 1, and sampling was done from October 2018 to March 2020 in 5 cycles so that both the pre-and post-monsoon seasons are covered. In each cycle, 12 grab samples were continuously collected for ten days at the inlet and outlet locations. This is done to obtain the average values of these water quality parameters during the hydraulic retention period.

The wastewater samples were collected in 1 L polyethylene bottles and stored at 4 °C in an icebox and then a refrigerator, in transit from the NTSs to the laboratory. The different wastewater parameters were estimated as listed in Table 2 according to APHA (2012) guidelines and IS 3025: 2003 (BOD) and IS 3025 (Part 53): 2006 (COD). All tests were conducted at the Environmental Engineering Lab, MVGR College of Engineering.

Table 2 | Experimental methods used in the present study for estimating the wastewater parameters

Parameter Type	Parameter	Method
Organic	DO	Titrimetry
	BOD	VELF Sensor
	COD	Spectrophotometry
Nutrients	Total nitrogen	Spectrophotometry
	Total phosphorus	Spectrophotometry
	Sulfate	Nephelometry
	Nitrate	Spectrophotometry
Chemical constituents	Sodium	Flame photometry
	Potassium	Flame photometry
	Calcium	EDTA titration
	Magnesium	EDTA titration
	Bicarbonate	H2SO4 acid titration
	Chloride	$AgNO_3$ titration
	Hardness	EDTA titration

Removal efficiency assessment

Removal efficiencies during each cycle and for each of the parameters were estimated from the average influent and effluent concentration using Jamwal *et al.* (2019) Equation (1)

$$RE = \frac{(\bar{C_i} - \overline{C_o})}{\overline{C_i}} \times 100 \quad (1)$$

where $\bar{C}_i$ = average influent determinand concentration (mg/L) during a cycle; $\bar{C}_o$ = Average effluent determinand concentration (mg/L) during a cycle.

RESULTS AND DISCUSSION

A reconnaissance survey was conducted as part of the study to compare the conditions at the time of construction and the current working conditions and also to identify the changes in the boundaries, tank bathymetry, and measure discharges. Figure 2(a)–2(d) show the Google Earth pictures of NTS 1-4 during the year 2004, whereas Figure 2(e)–2(h) capture the present conditions of these NTSs. It is evident from the figures that for NTS-1, NTS-2 and NTS-4 (Figure 2), there are no significant changes in the surface area. But the analysis of the bed levels showed that the capacity of NTS-1 and NTS-2 had decreased drastically compared to the design depth (see Table 1). However, in the case of NTS-3, significant changes in the bed profile were observed wherein the most part of the tank was dead. It was also observed that there is a considerable encroachment in the case of NTS-3. Further, an interaction session with the farmers from the downstream villages who use the water from NTS-3 for irrigation revealed a substantial decrease in the crop yield in the last few years. Further, the farmers utilizing the water from NTS-2 suggested that the excessive siltation, lack of maintenance and encroachment

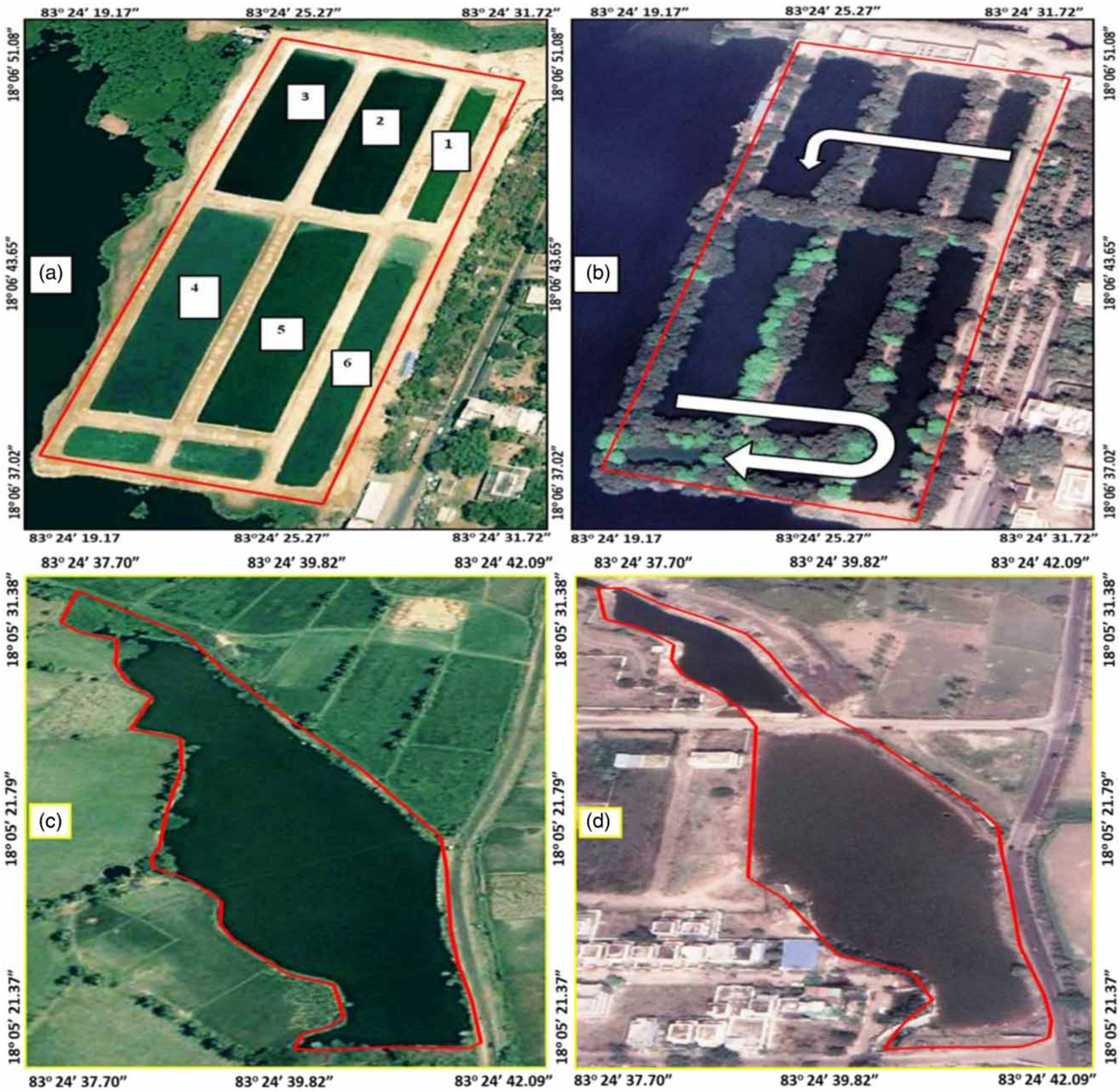


Figure 2 | Google Earth clips and field photos showing the status of the treatment systems NTS 1 -4 during the period 2004–05 (left column) and 2020–21 (right column). (a, b) – NTS-1 Waste Stabilization Ponds [1, 4 – Anaerobic Ponds, 2, 5 – Facultative Ponds and 3, 6 – Aerobic Ponds], (c, d) – NTS-2 Hyacinth and Duckweed Ponds. (e, f) – NTS-3 Hyacinth and Duckweed Ponds, (g, h) – NTS-4 Waste Stabilization Ponds [1 – Anaerobic Pond, 2 – Facultative Pond and 3 – Aerobic Pond]. (*Continued.*)

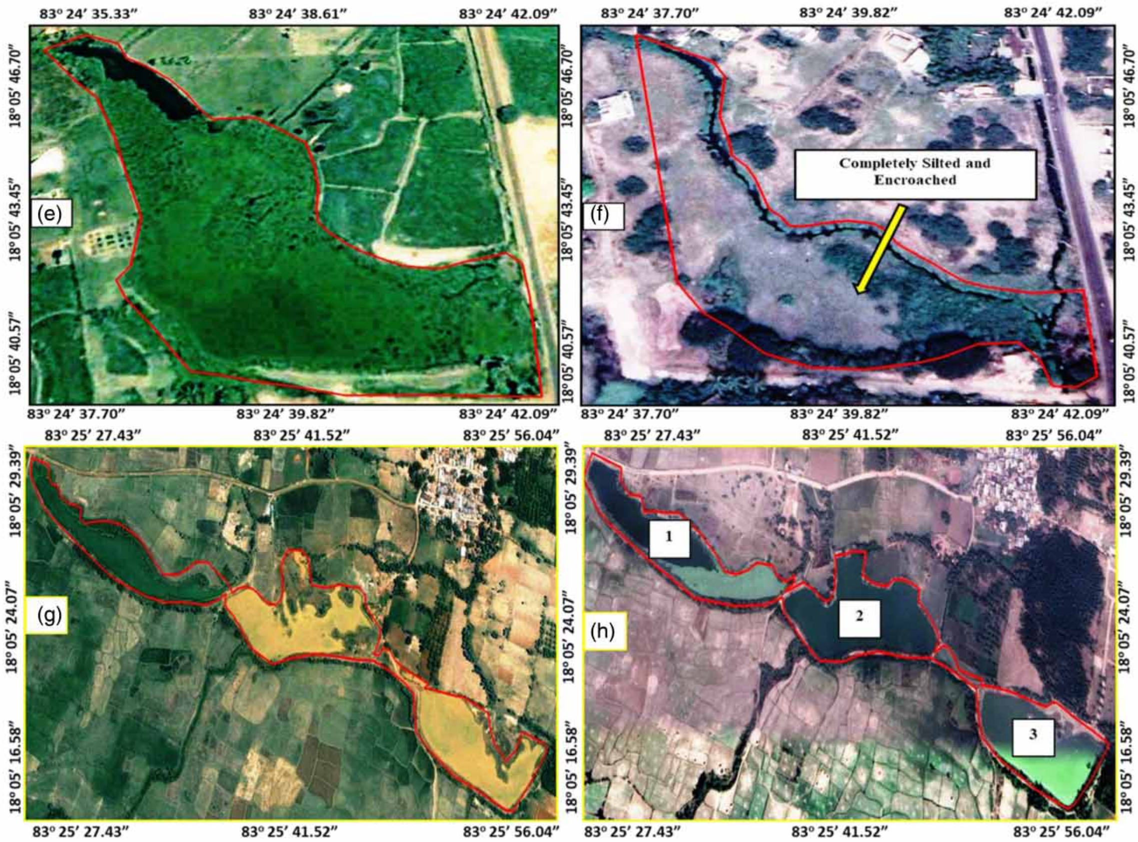


Figure 2 | Continued.

of the tanks has reduced the efficiency of the system. On the other hand, the farmers utilizing the effluent water from NTS-4 has no such issues.

The season-wise influent and effluent characteristics for all NTSs are shown in Tables 3 and 4 in terms of minimum and maximum values. Comparing the values of the concentration during the pre-and post-monsoon seasons, it is generally observed that the concentrations of BOD, COD, TN, SO_4^{2-}, and TP^- are higher during the summer than in the winter. Further comparing the variations across the different NTSs, it is observed that the concentrations of the DO values at NTS-1, 2, 3 are very low and close to zero in most of the times, whereas the values of DO are higher for NTS-4. Tables 3 and 4 show the typical constituent analyses of the wastewater entering and leaving the NTSs. Wastewater quality constituents BOD, COD, TN, TP, Mg^{2+}, Cl_2^-, and bicarbonate (HCO_3^{2-}) exceeded the permissible limits except for EC, K+ and calcium parameters in both seasons for all NTSs. The ranges of water quality parameters in from the pre and post-monsoon seasons were electrical conductivity (EC) ranges from 1,020 to 1,622 µS/cm, dissolved oxygen 0–10 mg/L, biological oxygen demand (BOD) 16–264 mg/L, COD 36 – 287 mg/L, total nitrogen (TN) 6 – 113 mg/L, sulfate (SO_4^{2-}) 12–86 mg/L, total phosphorus (TP) 6–120 mg/L, sodium (Na^+) 25–112 mg/l, potassium (K^+) 2–33 mg/L, calcium (Ca^{2+}) 14–162 mg/L, magnesium (Mg^{+2}) 16–181 mg/L, chloride (Cl_2^-) 98–480 mg/L, and bicarbonate (HCO_3^{2-}) 84–462 mg/L respectively (Tables 3 and 4). The concentrations of all parameters at the inlets of NTSs often exhibit low concentrations. NTSs physical and chemical characteristics may influence the concentrations. The NTS-3 had high nutrient concentrations due to the wastewater coming directly from intermittent sources. And also, the increase in all the parameters' concentrations at the outlet of NTS-3 can be observed.

From Figure 3, the temporal variations of water quality parameters at different NTS can be observed during the one cycle. The DO variation at the inlet at all NTSs signifies the BOD load variation, and there is a considerable decrease in the DO values, mostly less than 4 mg/l at NTS-1, 2 and 4. The DO levels are close to zero at NTS-3, signifying higher levels of organic loading. There is considerable improvement in the DO conditions at the outlet for NTSs 1, 2 and 4, whereas for NTS-3 there is no improvement. The BOD and COD levels at the inlets of NTSs on most days were above 200 mg/l. However, the outlet concentrations were significantly different

Table 3 | Influent and effluent characteristics of the NTSs during the pre-monsoon season investigated in this study

Parameters	WHO (World Health Organization) 1989/ IS recommendations	NTS-1				NTS-2				NTS-3				NTS-4			
		Inlet		Outlet		Inlet		Outlet		Inlet		Outlet		Inlet		Outlet	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
EC (μS/cm)	2,200	1,143	1,622	667	991	1,263	1,630	991	1,459	1,438	1,740	1,428	1,590	680	900	433	680
DO (mg/L)	5	0.0	0.0	2.7	3.6	0.0	0.2	0.4	1.3	0	0.4	0.1	0.4	0.4	8	5	10
BOD (mg/L)	30	192	256	102	167	192	260	119	224	238	264	189	220	80	121	16	43
COD (mg/L)	250	254	321	129	209	206	302	149	230	262	320	240	290	119	157	36	95
TN (mg/L)	100	80	102	42	67	78	94	58	78	89	113	78	92	38	68	6	32
SO_4^{2-} (mg/L)	200	57	86	26	70	44	78	22	85	44	66	50	60	42	62	12	31
TP (mg/L)	20	13	119	14	34	68	88	19	48	64	120	74	109	42	62	6	22
Na^+ (mg/L)	400	81	112	64	89	64	84	32	88	79	100	78	92	64	84	25	48
K^+ (mg/L)	20	12	22	4	16	7	16	2	13	8	24	6	16	11	16	2	6
Ca^{2+} (mg/L)	200	102	162	64	120	65	152	60	151	98	118	84	120	76	150	14	94
Mg^{2+} (mg/L)	50	65	181	74	138	60	188	16	154	88	172	70	144	43	162	16	124
Cl_2^- (mg/L)	300	264	480	284	521	154	285	98	278	298	480	302	521	168	332	98	214
HCO_3^{2-} (mg/L)	100	215	462	174	224	152	442	86	346	188	456	174	202	148	356	84	162

The values shown in the table show maximum and minimum for each of the water quality parameters during the study period.

Table 4 | Influent and effluent characteristics of the NTSs during the post monsoon season investigated in this study

		NTS 1				NTS 2				NTS 3				NTS 4			
		Inlet		Outlet		Inlet		Outlet		Inlet		Outlet		Inlet		Outlet	
Constituents (pollutants)	WHO/IS recommendations	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
EC (μS/cm)	2,200	1,020	1,152	802	840	1,094	1,124	741	884	1,230	1,259	1,275	1,328	702	742	326	432
DO (mg/L)	5	0	0.2	0.4	0.8	0.1	0.6	0.9	1.3	0	0.2	0.1	0.2	5.2	8	8.8	10.4
BOD (mg/L)	30	174	256	28	26	162	223	98	104	238	243	222	258	84	128	16	24
COD (mg/L)	250	223	321	74	92	219	256	117	125	254	287	235	274	167	264	44	51
TN (mg/L)	100	58	80	24	31	86	98	22	44	67	72	59	64	47	59	23	34
SO_4^{2-} (mg/L)	200	51	67	24	42	49	52	28	31	50	65	47	60	41	49	22	26
TP (mg/L)	20	28	36	19	21	59	62	22	34	74	82	79	68	44	58	13	22
Na^+ (mg/L)	400	61	74	35	52	71	92	41	45	57	61	49	75	82	94	41	66
K^+ (mg/L)	20	12	16	8	10	16	27	11	18	24	33	22	31	9	14	6	8
Ca^{2+} (mg/L)	200	120	150	62	98	80	110	54	72	94	102	105	121	81	124	54	69
Mg^{2+} (mg/L)	50	39	49	28	41	64	77	38	43	105	114	112	124	38	47	24	32
Cl_2^- (mg/L)	300	226	292	165	199	257	289	201	226	297	312	284	325	293	340	134	152
HCO_3^{2-} (mg/L)	100	221	191	152	187	245	342	207	223	293	336	285	324	221	250	124	182

The values shown in the table show maximum and minimum for each of the water quality parameters during the study period.

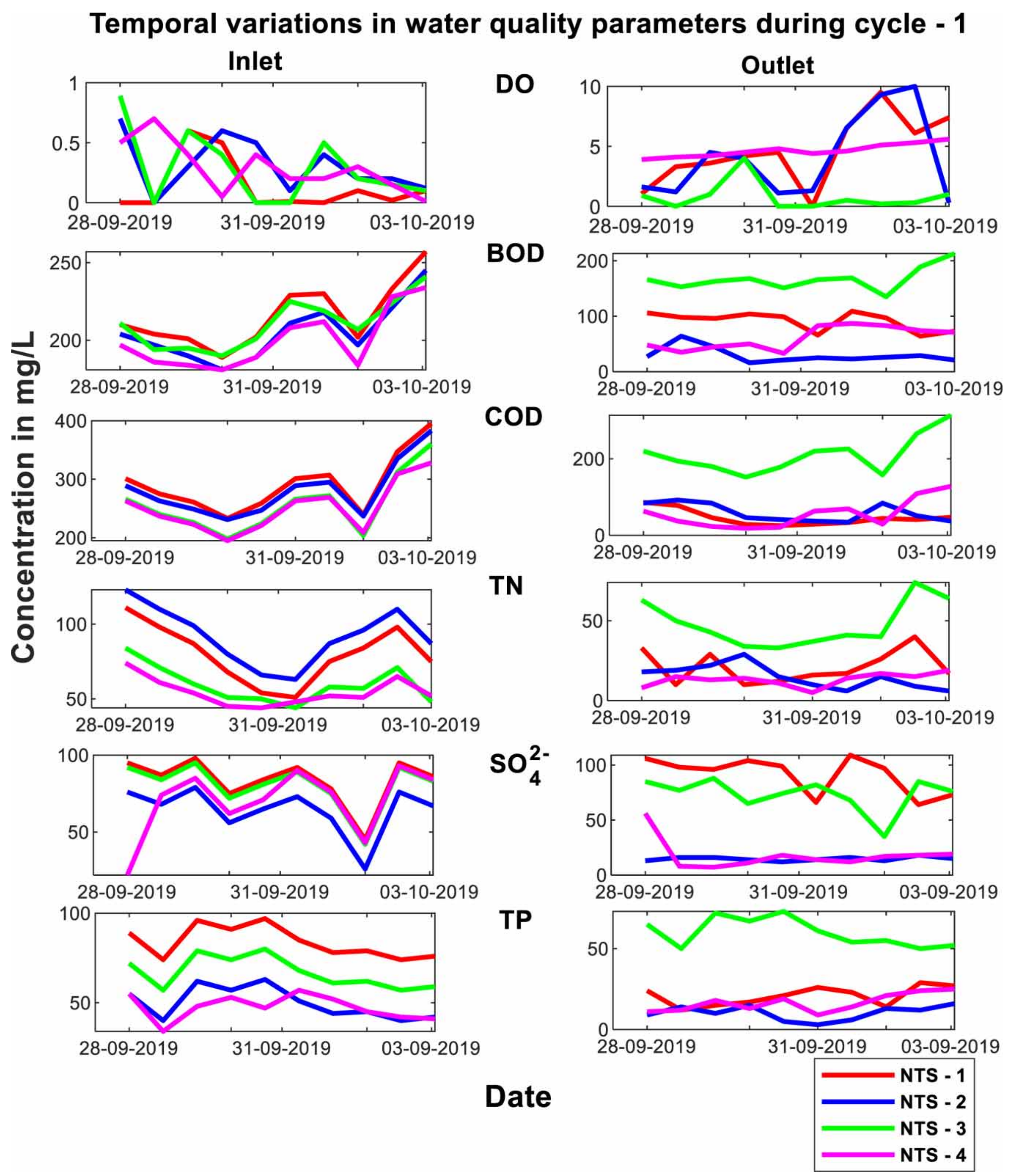


Figure 3 | Temporal variations of the water quality parameters during one sampling cycle at all the NTSs.

(using t-test) for all four NTSs. For NTS-2 and 4, the BOD levels were below 100 mg/l on most of the days and for NTS-1, the levels were near 100 mg/l, whereas BOD concentration was higher (around 200 mg/l) for NTS-3. Comparing the inlet and outlet conditions for NTS-3, there is no significant change between them, indicating the lower efficiency of the system. A similar pattern was observed for TN, sulphate and TP (Figure 3).

The removal efficiency for all parameters during each cycle was estimated and is shown in Figure 4 as a box plot. Figure 4 presents the ranges of the efficiencies observed during the investigation period for COD, BOD_5 and TP and nitrates. The results indicate that NTS-1 and NTS-2 possess satisfactory removal efficiencies for the organic content and the nutrients. On average, the efficiency for COD removal was around 40 and 50% for NTS-1 and NTS-2, respectively. The removal percentage was higher in NTS-4 with 80%, 77, 75 and 74% for

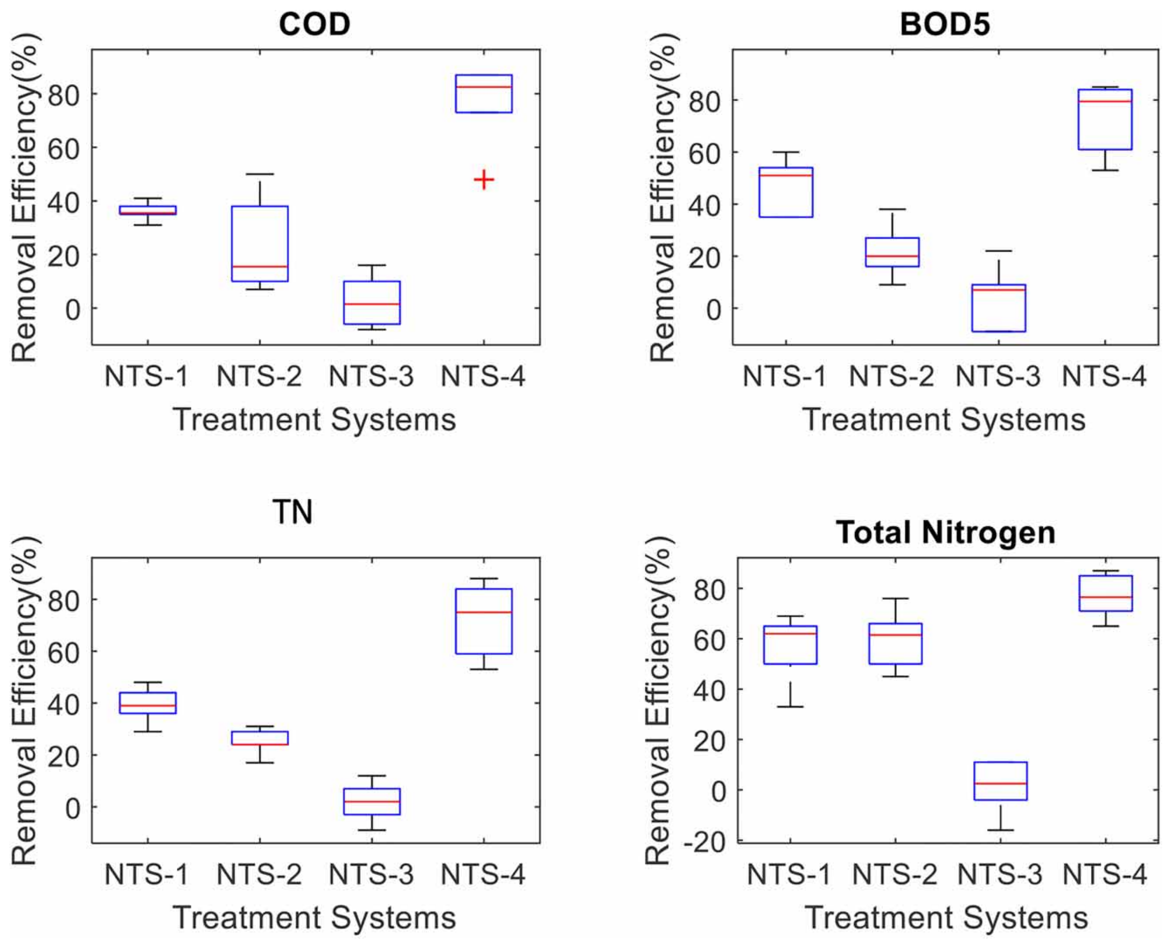


Figure 4 | Box plots of NTS removal efficiencies with respect to organic matter and nutrient content.

COD, BOD5, TP and total nitrogen, respectively. On the other hand, in NTS-3, the removal efficiencies were extremely low, ranging between 10–20% for all the constituents.

The pattern of removal efficiency was NTS-4 > NTS-1> NTS-2> NTS-3, as observed from Figure 4. From the analysis of the results, the NTSs NTS-1, NTS-2 and NTS-4 perform satisfactorily in reducing the concentration of pollutant levels. The nitrogen and phosphate concentrations in wastewater were found to be high in the effluent from NTS-2 and NTS-3, with the nitrogen and phosphate concentration exceeding the guideline value given by the FAO (Pescod 1992) and CPCB. Further, the BOD and COD levels of the effluent from NTS-3 and NTS-2 were also found to be high when compared to the CPCB (2013). However, the effluent's concentration from NTS-4 is well within the standard guidelines.

The differences in efficiencies among the NTSs can be attributed to the deviation in design parameters such as HRT, and loading rate. In NTS-3, the actual hydraulic retention time is less than the design value, and the hydraulic loading rate is also higher (Pearson *et al.* 2005). Among these, the low efficiency of NTS-2 can be attributed to the lack of participation of the farmers or stakeholders in harvesting the hyacinth plants and clearing the pond at regular time intervals. Further, the efficiency of NTS-1 (WSP) is comparatively less than NTS-4 (also WSP). This could be due to excessive loading of NTS-1 rather than its design-loading rate.

It is also observed that the performance of the NTS-3 is inferior and much less than that of the design standard. This can be mainly attributed to the lack of maintenance and encroachment of the tank areas through the dumping of construction waste, thereby drastically reducing the scope of the natural processes in the NTS.

Overall, of all the NTSs, the performance of NTS-4 is superior. This is because of the regular maintenance in terms of desilting, and bank stabilization by the farmers. NTS-4 can be considered an example of a self-sustaining model, wherein the farmers take active participation in the operation and maintenance of the system.

In a study by Sonkamble *et al.* (2018) on the importance of natural treatments in a peri-urban area, the authors proposed a decentralized model using natural processes as a viable strategy for wastewater treatment. NTS-4 is an

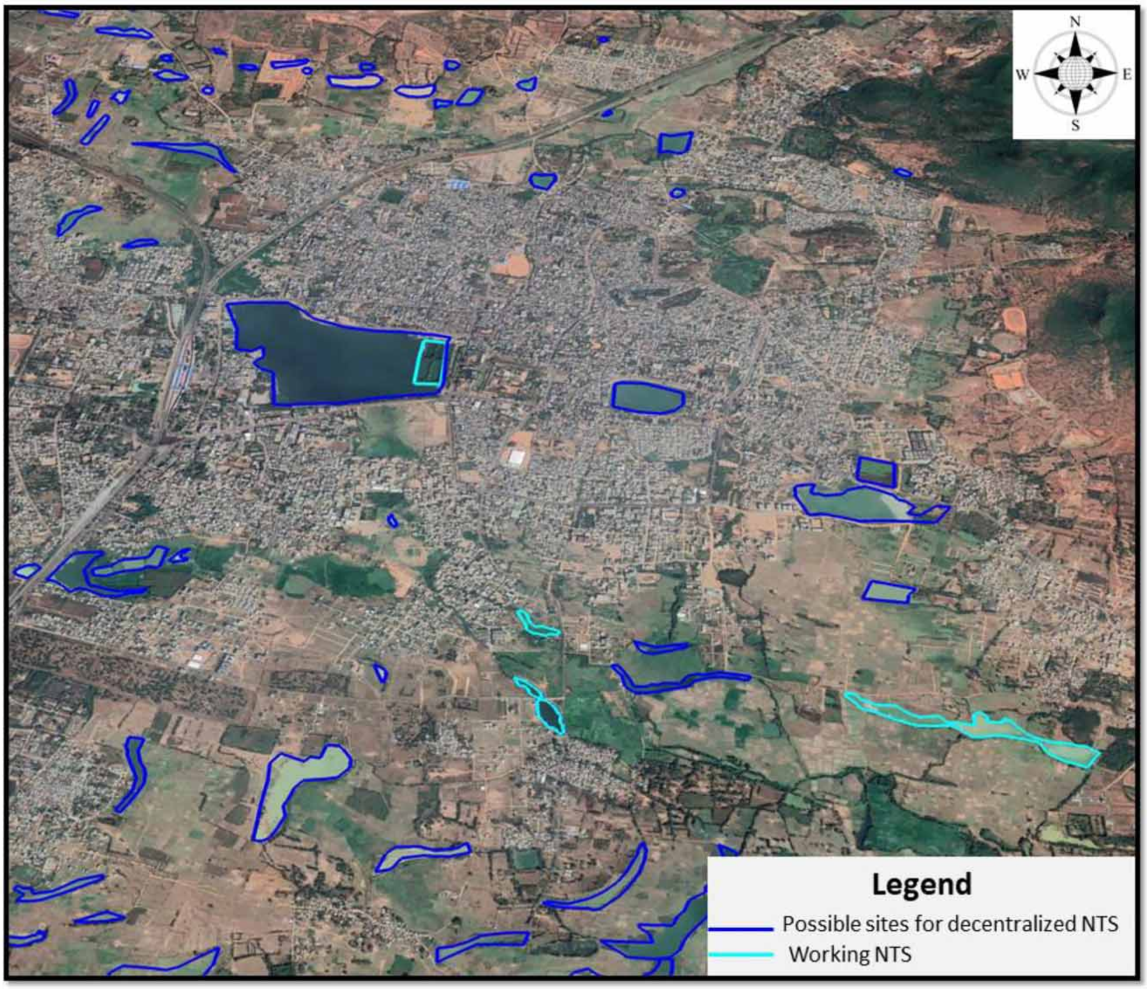


Figure 5 | Possible sites for NTSs and those already in use (adapted from Google Earth).

excellent working example of such a system where the particular village's farmers took responsibility for the wastewater treatment before it was used for irrigation. Similar working models can be established in other locations where the farmers are using the wastewater without treatment. Figure 5 shows the possible location of such a treatment system. These possible locations are based on the idea that the existing surface tanks that drain municipal sewage can be converted into treatment systems (Vymazal 2012). These tanks were identified to collect the municipal wastewater and discharge it into the cascade of tanks downstream. If these tanks are developed in natural treatment systems, these can be used as the DEWATS system proposed by Abdelwahab *et al.* (2009), where the treatment systems are localized and decentralized. However, a thorough geologic investigation must be done before construction/development of these sites.

Community interactions

Stakeholder meetings were organized to try to determine the perceptions of farmers and government officials on the use of raw sewage for irrigation versus treated water from NTSs. The farmers thought that raw sewage application had created several problems in both crop production and farmers' health. However, due to a lack of sufficient quantity of water for irrigation, they are forced to use direct sewage. With reference to NTS-treated wastewater, the farmers were supportive and suggested that systems similar to NTS-4 must be made available at strategic locations so that all the wastewater from the town can be treated.

Since the NTS-based treatment is entirely natural it can be termed as sustainable as there is no requirement for electricity, machinery and application of chemicals (Arceivala & Asolekar 2013; Starkl *et al.* 2013); however, these systems require periodic maintenance and monitoring to examine their efficiency. The farmers from

Dharmapuri village have shown interest in the community-managed development of NTSs and are eager to coordinate in redeveloping NTS-3 and rejuvenating it.

Recommendation

The results from the real-life working systems promote the suitability and compatibility of natural treatment methods in reducing the contaminants in domestic wastewater and contribute to the reuse of wastewater. Based on the analysis undertaken in this study, we recommend that the decentralized model of the NTSs is a viable and effective alternative for conventional STPs for peri-urban regions of India. However, as suggested by Sonkamble *et al.* (2018), a complete geophysical investigation of the geologic formation must reduce the possibilities of groundwater contamination. With the support from the Department of Science and Technology, India and Department of Water Resources Andhra Pradesh, India, a project has been sanctioned to rejuvenate the NTS-3 and NTS-2 to revive its function to design efficiency.

CONCLUSION

The study results observed that well maintained and operated waste stabilization ponds showed an efficiency of 70–80% in removing the organic matter and nutrients. On the other hand, the duckweed and hyacinth plant-based system showed lesser percentage removal in the order of 40–50% for significant constituents. Further, improper maintenance and encroachment, and clogging of the inlets can seriously reduce the working efficiencies of the natural system. The results from the present study clearly support the NTS as a viable and sustainable alternative for peri-urban and even urban areas for effective treatment of domestic wastewater. Further, the study shows the importance of stakeholder participation in maintaining these systems for effective operation and working. Awareness among the farmers who are utilizing the treated water on the working mechanism of these systems will undoubtedly invoke interest in them and thereby their involvement in the maintenance.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories at https://zenodo.org/record/4838687#.YLFfqqgzbIU.

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