



# Reuse-focused selection of appropriate technologies for municipal wastewater treatment: a multi-criteria approach

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## Abstract

Wastewater treatment technologies (WWTs) are employed across the world, and the selection is mainly based on ‘past experiences’ aimed at ‘pollution prevention’ in the receiving water bodies. This paper aims to develop a methodology for the selection of an appropriate wastewater treatment chain that produces effluent suitable for the defined reuse. Adopting the least weighted cost approach, four decision criteria: Capital cost, Operation and Maintenance cost, Land requirement, and Energy requirement, have been used and the Full Consistency Method (FUCOM) has been employed for obtaining weights. Quality expectations for 14 reuses have been enlisted, and 25 WWTs have been evaluated in a total of 360 combinations. In Kanpur city, for water reuse in industrial cooling under restricted land and challenging influent quality conditions, a combination of Membrane Bioreactor (MBR) with Wuhrmann process (WP) is obtained as the most preferred suggestion. For non-potable domestic reuse, Anaerobic Anoxic Oxidation (A<sub>2</sub>O) with Ultrafiltration (UF) and Reverse Osmosis (RO) is the most preferred combination. In Varanasi city, for vehicular washing operations and for flow augmentation (inland surface water), under energy-constraint scenario, high-rate activated sludge-based biological filtration and oxygenated reactor (BIOFOR-F) is suggested. For technology supplementation to existing ASP-based STPs in the city to obtain effluent for inland surface water augmentation, WP in combination with microfiltration (MF) and reverse osmosis (RO) is suggested. Thus, the developed model may be used as a decision-making tool for planning a reuse-focused water reclamation program or for upgradation of existing STPs as per resource availability and target reuse objectives.

**Keywords** Municipal wastewater treatment · Appropriate technology · Reuse · FUCOM · Least weighted cost

## Abbreviations

A <sub>2</sub> O	Anaerobic anoxic oxidation process	C.Tech	Cyclic ASP process
AHP	Analytic hierarchy process	COD	Chemical oxygen demand
AL + SP	Anaerobic lagoon + Stabilization pond	CW	Constructed wetland
AOP	Advanced oxidation process	DPS	Duckweed pond system
ASP	Activated sludge process	e-flow	Environmental-flow
BIOFOR	Biological filtration and oxygenated reactor	FAB	Fluidized aerated bed
BIOFOR-F	High-rate activated sludge BIOFOR technology	FC	Fecal coliform
BNR	Biological nitrogen removal	FUCOM	Full consistency method
BOD	Biochemical oxygen demand	ha	Hectare
BWM	Best worst method	KWh	Kilo-Watt hour
		LCA	Life cycle assessment
		MBBR	Moving bed bio-film reactor
		MBR	Membrane bioreactor
		MCDM	Multi-criteria decision making
		MF	Microfiltration
		mg/l	Micrograms per liter
		MLD	Million liters per day
		MLE	Modified Ludzack–Ettinger process
		MPN	Most probable number
		MWh	Mega-Watt hour

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PROMETHEE	Preference ranking organization method for enrichment evaluation
RO	Reverse osmosis
RSF	Rapid sand filter
SAFF	Submerged aerated fixed film reactor
SBR	Sequencing batch reactor
SBT	Soil bio-technology
SP	Stabilization pond
STP	Sewage treatment plant
TDS	Total dissolved solids
TN	Total nitrogen
TSS	Total suspended solids
UASB + EA	Up-flow anaerobic sludge blanket reactor + Extended aeration
UF	Ultrafiltration
VIKOR	Vlse Kriterijuska Optimizacija I Komoromisno Resenje
WP	Wuhrmann process
WSP	Waste stabilization pond
WWTP	Wastewater treatment plant
WWTs	Wastewater treatment technologies

## Introduction

Water scarcity has been regarded as a global risk with potentially devastating impacts (Global Risks Report 2019). Such conditions are prevalent in India and many other countries due to climate change, exploding population, and industrialization (Lyu et al. 2016). To tackle this imbalance between water demand and its safe availability, wastewater reclamation can be seen as a potential source of water, which if treated, can boost water availability as well as prevent environmental degradation (Asano 1998). When treated wastewater is reutilized after treatment, it is referred to as wastewater reclamation (Asano 1998).

Municipal wastewater is considered a limitless source of water due to its high biodegradability and low toxicity profile (Fane et al. 2011). Globally, 80% of the wastewater generated is disposed of in the environment, causing hazardous impacts on the receiving water bodies (WWAP 2017). The burden of environmental degradation and water scarcity can be significantly reduced by utilizing treated wastewater as a water source (Coe and Laverty 1972).

In the past two decades, the importance of wastewater treatment has become more apparent due to the prevalence of epidemics, like ongoing COVID-19 infection which has affected millions of lives worldwide (Amoah et al. 2020). Coronaviruses can enter wastewater streams via biomedical waste and municipal waste mainly due to related viral particle shedding in human feces and urine (Han et al. 2020; Ling et al. 2020). Such a scenario can lead to the unprecedented spread of this infection and can cause potential

contamination of water system (Amoah et al. 2020). In a study conducted by Asano and Levine (1996), a 5-log removal of virus from wastewater streams was reported after chlorinated tertiary treatment of wastewater and so, the significance of wastewater treatment for containing such infections and building a safer society cannot be overstressed.

Numerous wastewater treatment technologies belonging to primary, secondary, tertiary, and emerging category are available, but a sensitive and reliable method for selection of an appropriate technology combination aimed at the reuse of reclaimed water in the local environment based on resource availability of the area is not yet well established. A technology which satisfies the demand of user with optimum resource utilization is appropriate. The concept of appropriate technology was given by economist Schumacher in his book “Small is Beautiful” (Schumacher 1973). Appropriate technology has the potential to serve the desired purpose with no social, economic, and environmental ramifications. It is people-centric, local condition-specific, cost-efficient, and sustainable in nature (Akubue 2000).

Several studies have been conducted for selection of appropriate technology for specific type of waste waters, e.g., domestic (Kalbar et al. 2012), molasses-based wastewater (Syutsubo et al. 2013), industrial wastewater (Castillo et al. 2017), disinfection technologies selection for reuse (Gomez-López et al. 2009), etc. However, the procedure for the selection of an appropriate technology that suits both local environment and reuse quality criteria is not yet defined. Till now, technology selections are entirely based on past results and perceived efficiencies of previously installed technologies, thereby leading to under-performance of STPs and huge debt-burden on governing agencies (CPCB 2013). The investment in sewerage and sewage treatment infrastructure does not reflect as gain to water economy.

Multi-criteria decision-making (MCDM) tools have been used for appropriate wastewater treatment technology selection in different fields. Analytic Hierarchy Process (AHP) is the most applied MCDM tool in environmental decision-making problems owing to its more realistic, easy implementation, and transparent methodology. In a study conducted for technology selection for coking wastewater, AHP was applied using four major decision criteria, namely technical, economic, environmental, and administrative factors, and six alternatives were obtained by varying oxygen phases in an ASP (Wei et al. 2020). Zeng et al. (2007) applied AHP with gray relational analysis (GRA), (which is effective in solving relationship problems between different parameters) for optimal wastewater technology selection and four alternative conventional technologies were rated against technical, economic, administrative, and performance criteria. It was reported that GRA fails to give a feasible result (Wei 2009). Kalbar et al. (2012) utilized the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method



for ranking of four alternative technologies against seven criteria including several environmental indicators including sustainability, eutrophication, etc., and operational indicators such as land needs, manpower needs, and cost attributes. TOPSIS often suffers from rank reversal problem which compromises the accuracy of results (Yang 2020). Ilankumaran et al. (2013) utilized fuzzy AHP and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) tools for optimal wastewater treatment technology selection out of 5 technologies: electro-coagulation, SBR, reverse-osmosis, ultrafiltration, and anaerobic digestion based on three criteria: (1) Social and environmental, (2) Economic, and (3) Technical. Dursun (2016) suggested the Vlse Kriterijska Optimizacija I Komoromisno Resenje (VIKOR) method for obtaining appropriate technology. Zhou et al. (2020) employed the AHP-VIKOR method for the selection of technologies for municipal sludge disposal, but the VIKOR method is complex in nature and cannot be used for performance-based problems (Kraujalienė 2019). Alfonsín et al. (2015) utilized life cycle assessment (LCA) to study the environmental viability of two biological treatment methods, namely, bio-trickling filter and biofilter, and two physical/chemical processes such as activated carbon tower and chemical scrubber. But LCA is a very detailed and time-consuming method. It is not feasible while working in multiple criteria and multiple alternatives scenarios (Wastiels and Decuyper 2019). It also does not provide a direct interpretation of result (Hermann et al. 2007).

The present study employs a weighted sum method for comparison of different technologies. The weighted sum approach is not yet utilized in the wastewater treatment technology selection process. In this method, the governing criteria are given importance weights to reflect the local conditions about resource availability. The values under each decision criteria are then converted into cost form, and this weighted cost is utilized for the ranking of technologies. This method will reflect the actual advantages and disadvantages of technology and also inculcate the features of the local environment through importance weights. The importance weights are required from the users as per their assessment. Selection of importance weights is the most important step in this study as it significantly affects technology selection. For the purpose, the Full Consistency Method (FUCOM) (Pamučar et al. 2018)

was used to evaluate weights for decision criteria. This is a new method which relies on pairwise comparison of decision criteria. Unlike other MCDM methods, FUCOM requires least number of comparisons which makes the process easier while results obtained are consistent with those of other methods.

It is observed that technical, economic, operation and maintenance, and capital cost are the common criteria in most of the previous studies. Therefore, in this paper, the performance, land requirements, energy needs, capital cost, and O&M costs for all combinations have been focused.

In this work, the objective is to develop a reuse-centric model for selection of appropriate wastewater treatment technologies. This model considers the resource constraints and converts them into weighted costs for technology prioritization. FUCOM avails an easy and simple environment for obtaining prioritization weights of decision criteria. The approach can be used for two purposes:

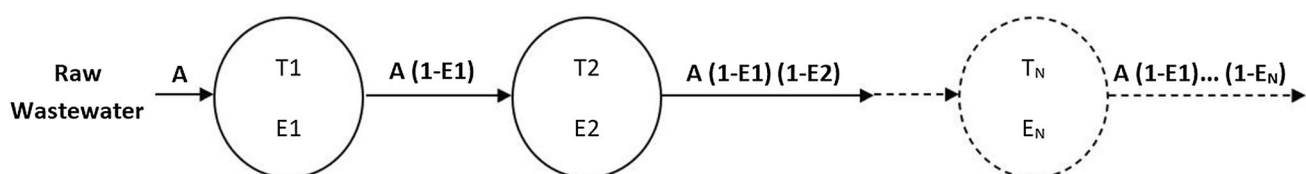
- (i) Selection of appropriate technology chain for a new sewage treatment infrastructure to meet quality criteria for defined reuse, or
- (ii) Technology upgradation of existing STPs considering the resource-constraints.

The resource requirements including costs for selected technologies have been considered for Indian conditions. The method can be useful in other countries and climatic conditions as well using actual observed efficiency of treatment methods adopted, quality criteria required for reuse in the local contexts and other cost factors.

## Materials and Methods

### Effluent quality prediction

The procedure for obtaining contaminant concentration in the effluent is as shown in Fig. 1. The removal efficiency of one technology compounds with that of the other technology to obtain the effective contaminant concentration in the treated effluent (Metcalf and Eddy 2004).



**Fig. 1** Estimation of effective contaminant concentration in a train of treatment processes. \*A: Initial contaminant concentration;  $T_1, T_2, \dots, T_N$ : Treatment Process;  $E_1, E_2, \dots, E_N$ : Efficiency of respected treatment process

## FULL Consistency method (FUCOM)

FUCOM (Pamučar et al. 2018) is a new credible and reliable MCDM approach applied for the evaluation of importance weights for conflicting criteria. This model produces similar results as obtained by methodologies like AHP, BWM but presents the advantage of requiring very few pairwise comparisons, that is,  $n - 1$  ( $n =$  number of criteria), whereas AHP requires  $(n(n - 1)/2)$  and BWM requires  $2n - 3$  pairwise-comparisons.

FUCOM method is utilized in studies involving subjective assessments made by decision-makers (DMs). The FUCOM procedure is illustrated in the following steps:

- (a) Firstly, the decision criteria (say  $n$ ) are ranked by DM in descending order of significance, where the most important criterion is ranked 1 while the least significant criteria are ranked last.

$$C1 > C2 > C3 > \dots > Cn$$

- (b) Secondly, the ranking decision criteria are then compared and assigned priorities by DM on a defined scale, where the most important criterion is assigned 1, while the least important criteria are given the highest value in comparison with other criteria.

These priority values are then utilized to obtain the comparative priority of the decision criteria. The comparative priorities depict the advantage of former criteria ( $k$  rank) in comparison with the later criteria ( $k + 1$  rank), given by,  $(\phi_{k/(k+1)})$ .

- (c) In this step, final weights for each criterion are obtained. These weights are subjected to two conditions:
- (d) Ratio of weights should be equal to comparative priorities of respective criteria.

$$\phi_{k/(k+1)} = W_{k/(k+1)}$$

- (e) Weights should satisfy mathematical transitivity, i.e.,

$$W_{k/(k+2)} = \phi_{k/(k+1)} * \phi_{(k+1)/(k+2)}$$

Under the above conditions, a linear programming model is formulated to minimize  $\mathcal{X}$  and obtain weight coefficients, such that:

$$\left| \frac{W_j(k)}{W_j(k+1)} - \phi_{k/(k+1)} \right| = \mathcal{X}, \quad \forall j \quad (1)$$

$$\left| \frac{W_j(k)}{W_j(k+2)} - \phi_{k/(k+1)} * \phi_{(k+1)/(k+2)} \right| = \mathcal{X}, \quad \forall j \quad (2)$$

$$\sum_{j=1}^n W_j = 1, \quad \forall j$$

$$W_j \geq 0, \quad \forall j$$

## Weighted sum method (WSM)

Weighted Sum Method (Fishburn 1967) is one of the simplest and most popular MCDM methods. In this method, a multi-objective optimization is converted into a scalar point by minimizing a weighted sum. If there are  $m$  alternatives and  $n$  criteria, a weighted sum is represented by:

$$\text{Weighted Sum} = \sum_{j=1}^n W_j \cdot R_{ij}, \quad \text{for } i = 1, 2, 3, 4, \dots, m$$

$W_j$  = importance weight for each criterion

$R_{ij}$  = Rating of each alternative

The above equation is restricted by the following condition:

$$\sum_{i=1}^n W_i = 1$$

The WSM has found its applications across several fields such as ranking of renewable energy sources (Lee and Chang 2018), ontology ranking (Fonou-Dombeu 2019), and so on. WSM method is applicable on homogenous rating values and requires conversion of different objective values into a uniform dimension.

In this study, WSM is emphasized to reflect the direct relevance of resource constraint on appropriate technology selection. The weighted costs thus obtained are used for ranking different technology trains.

## Model development

### Defining reuse quality criteria

Municipal wastewater is considered as the potential source of water in this study. The first step while planning a responsible municipal wastewater treatment plant is to identify the potential reuse purposes in the concerned city to obtain the desired effluent quality characteristics (CPHEEO 2013).

A list of potential reuse purposes was prepared along with the quality requirements of each reuse from the review of the scholarly literature as shown in Table 1. Since stringent and similar quality criteria for a reuse purpose were observed in different studies conducted in various parts of the world,

these quality criteria are adequately representative of quality of each reuse purpose.

As a factor of safety, the quality considerations are taken without any tolerance limits and without considering removals in preliminary and primary stages which assure strict adherence to required criteria. When a group of reuse purposes is being addressed through a single WWTP, the minimum quality requirement corresponding to each parameter should be taken to satisfy the requirements of all the required purposes.

## Wastewater treatment technologies (WWTTs)

### Performance characteristics

The municipal wastewater treatment process starts with preliminary treatment which involves mainly three operations: screening for removal of large floating materials, grit chamber for removal of sand and grit, and skimming tank for removal of oil and grease to avoid any inhibition to bioactivity of microorganisms. Around 15–30% reduction in BOD is observed after this stage of treatment (Peavy et al. 1985). Primary treatment is the second stage in wastewater treatment. This stage may or may not be employed depending upon the technology utilized in the secondary treatment. It aims at the removal of large organic materials from wastewater by settling and comprises a sedimentation tank which generally causes a 50–70% reduction in BOD (CPHEEO 2013). This stage is followed by secondary treatment which aims at the removal of biodegradable dissolved compounds from wastewater by employing aerobic or anaerobic microorganisms (Metcalf and Eddy 2004). Normally, secondary treatment lacks the removal of nitrogen from water due to more time required for nitrification to start. To aid nutrient removal, various emerging technologies are being employed, which utilize alternative oxic and anoxic phases to promote simultaneous removal of nitrogen and phosphorus from wastewater (CPHEEO 2013). Tertiary treatment is employed for obtaining more polished effluent quality (Metcalf and Eddy 2004). All these stages are utilized simultaneously in a sewage treatment plant where the quality of effluent required is very high.

Different technologies belonging to secondary, tertiary, and emerging category and their reported performance efficiencies are given in Table 2. The data regarding the performance of technologies is based on claimed efficiencies (CPCB 2013) and case studies of applications in the published literature.

### Land, energy, capital cost, and O&M cost requirements

Land, energy, capital cost, and O&M cost are taken as the key decision criteria in this study. Land cost falls under fixed

cost category, that is, it is incurred independent of the functioning of the plant and depends on the desired treatment capacity only. The cost incurred once has been distributed over the design period for selection of technology in this study. Land cost is not included in capital cost to highlight land-constraint scenario (if any) at the site of installation. Energy cost is taken separately so as to include scenarios where energy supply is difficult or costly, therefore, it is not included in O&M costs. This study considers total energy required for the functioning of the STP throughout the design period of the plant. Capital cost falls in fixed cost category. It is the investment made on machinery, technology installation, automobiles, equipment, etc. These costs are also distributed over the design period for technology selection. O&M cost refers to the cost incurred for the functioning of the plant. It includes, salaries, rents, etc. In this study, for technology selection, total O&M costs for the design period are considered. At present, this study has not included an elaborate sustainability assessment for technology combinations selected, but focuses on meeting the desired water quality criteria for reuse only. Assessment of long-term environmental gains and challenges are part of future works planned under this study.

The accuracy of the model will depend entirely on the preciseness of data used as no other assumptions are made in this work. The treatment efficiencies are obtained from working STPs in India and from case studies based on different technologies around the world. These treatment efficiencies can broadly be used for other tropical countries as well while changes may be required for drastically different climatic scenarios.

The capital cost and operation and maintenance cost associated with various technologies were based on different years, and hence, an average inflation rate has been considered to normalize the costs for the year 2021. The following formula has been applied:

$$\text{Future Value} = \text{Present value} * (1 + i)^n$$

where  $n$  is the number of years between base year and the required year,  $i$  = average inflation rate.

Land requirement, energy requirement, capital cost and O&M cost for each technology is summarized in Table 3.

## Technology combinations

Eighteen secondary treatment technologies, four emerging technologies, and three combinations for tertiary treatments have been included in this study. A total of 360 combinations were obtained by considering one secondary technology as the base technology and one or no emerging technology with one or no tertiary technology, respectively. Example of the combinations of technologies considered in this study is illustrated in Table 4.

**Table 1** Quality criteria for application of reclaimed water in various reuses

S.No	Desired reuse	Source	pH	Tur- bidity (NTU)	COD (mg/l)	BOD (mg/l)	TDS (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)
1	Toilet flushing	(Asano et al. 1996; Lazarova et al. 2003; Lyu et al. 2016)	6–9	5	–	10	1500	10	10	200
2	Construction purposes	(Asano et al. 1996; Adewumi and Oguntuase 2016; Chen et al. 2017)	6–9	20	–	15	1500	10	20	200
3	Road cleaning	(Shuval 1977; Lyu et al. 2016; Chen et al. 2017)	6–9	10	–	15	1500	10	10	200
4	Landscape	(Coe and Lavery 1972; DeCook 1977; Smith et al. 1979; Adewumi and Oguntuase 2016)	6–9	5	–	20	1000	10	20	2000
5	Industrial cooling	(DeCook 1977; Asano et al. 1996; Lyu et al. 2016; Chen et al. 2017)	6.5–8.5	5	30	10	1000	10	10	2000
6	Irrigation	(Asano et al. 1996; Adewumi and Oguntuase 2016; Chen et al. 2017)	5.5–8.5	–	100	40	1000	10	–	20,000
7	Vehicle washing	(Zaneti et al. 2012; Pei et al. 2013; Lyu et al. 2016; Chen et al. 2017)	6–9	5	–	10	1000	20	10	2000
8	<i>Environmental flow</i>									
a	Inland surface water	(CPHEEO 2013)	6.5–9	–	250	30	–	100	100	10,000
b	Surface waters used as a source of drinking water		6.5–8.5	–	–	10	–	10	10	2300
9	Fire protection	(Shuval 1977; Okun 2002; Lyu et al. 2016)	6–9	10	–	15	1500	10	10	200
10	Laundry washing	(Japan Sewage Works 1993; Tamanna et al. 2011; Adewumi and Oguntuase 2016)	6–9	2	–	10	2000	10	–	250
11	Dust control	(California Guidelines 1994; Lyu et al. 2016)	6–9	20	–	15	1500	10	20	200
12	Snow making	(California Guidelines 1994; Asano et al. 1996)	6–9	10	–	15	1500	10	10	22
13	Outdoor bathing	(BIS 1992)	6.5–8.5	–	–	3	–	10	10	5000
14	Groundwater recharge	(Smith et al. 1979; Idelovitch et al. 1980; Adewumi and Oguntuase 2016)	6.5–8.5	2	10	5	50	1	1	1



**Table 2** Performance efficiencies of wastewater treatment technologies (WWTTs) and their combinations

S. No	Technology	Source/Reference	Removal (%)				
			BOD	COD	TSS	TN	FC
<i>Secondary treatment technologies</i>							
1	ASP	(Tare and Bose 2009; CPCB 2013)	78.37	84.09	87.76	10.00	90.02
2	MBBR		66.86	56.57	71.43	10.00	99.12
3	SBR		95.50	90.00	95.67	75.00	99.99
4	WSP		35.14	46.43	30.00	34.43	99.99
5	DPS		66.86	56.57	71.43	37.80	30.00
6	A2O	(CPHEEO 2013)	98.83	91.06	98.92	76.91	99.87
7	UASB+EA	(CPCB 2013; Vashi et al. 2019)	82.19	90.00	85.15	10.00	90.00
8	MBR	(Tare and Bose 2009; Ajmi et al. 2018)	97.60	96.50	95.00	60.00	99.99
9	Anaerobic lagoon + SP	(CPCB 2013)	70.00	51.33	70.00	10.00	90.00
10	SAFF	(Tare and Bose 2009)	96.67	87.50	76.40	10.00	99.99
11	BIOFOR-F		97.00	95.40	92.00	70.00	99.99
12	FAB		47.95	74.4	88.79	10.00	90.00
13	BIOFOR	(Tare and Bose 2009; Sharma and Singh 2013)	95.20	93.40	90.00	70.00	99.99
14	Oxidation Pond	(CPCB 2013)	66.89	51.25	71.08	10.00	99.39
15	C.Tech		96.00	97.64	81.60	80.00	99.99
16	Trickling Filter		71.43	64.66	88.31	10.00	90.00
17	Constructed Wetlands (CW)	(Ramachandra et al. 2017; Thalla et al. 2019)	77.00	60.00	90.00	67.00	78.21
18	SBT	(Stefan et al. 2017)	80.99	83.13	71.92	70.00	99.99
<i>Emerging technologies</i>							
19	Modified Ludzack Ettinger (MLE)	(CPHEEO 2013)	0	0	0	75.5	90.00
20	Wuhrmann Process (WP)		0	0	0	81.25	90.00
21	Step-Feed BNR		0	0	0	62.50	90.00
22	Bardenpho Process		97.30	0	99.40	88.90	90.00
<i>Tertiary treatment technologies</i>							
23	Coagulation + Flocculation + Rapid Sand Filters (RSF)	(Hamoda et al. 2004; Üstün et al. 2011)	65.00	53.34	52.14	30.00	80.00
24	Ultrafiltration (UF) + Reverse Osmosis (RO)	(Pizzichini and Russo 2001)	72.79	60.97	85.00	94.00	99.99
25	Micro Filtration (MF) + Reverse Osmosis (RO)		41.27	24.19	85.06	92.24	99.99

As shown in Table 4, while considering ASP as the base technology, it is combined with each emerging technology or tertiary technology individually as well as with each other together.

The procedure for appropriate technologies selection for producing effluent satisfying quality criteria of desired reuse based on multiple criteria is illustrated in Fig. 2.

Firstly, all 360 technological combinations are tested for their ability to satisfy desired quality criteria. After filtering on this basis, the resources required by each technology train are converted into their respective costs, incurred over the design period of 15 years, to obtain uniformity in the basis for selection. These costs are then multiplied with their respective importance weights to obtain final weighted costs. The resulting technological combinations are further sorted based on least weighted cost. Also, upper limits on resources (if any) are required to be filled by the user to obtain more real-condition-specific combinations. Application of this

selection model gives top 10 technologies which satisfy effluent quality requirements and give least weighted cost.

## Results and Discussion

### Kanpur City

Kanpur is one of the earliest industrialized cities of India. It is located at 26.44° North latitude and 80.33° East longitude on the right bank of the mighty river Ganges. Kanpur is the main industrial and commercial hub of Uttar Pradesh state. It has huge domestic water demand of 600 MLD, while the existing supply is only 385 MLD due to lack of infrastructure (Bassi et al. 2019).

As per the Pollution Assessment Report (CPCB 2011), sewage generation in Kanpur is about 339.3 MLD and the Ganga river water quality deteriorates considerably

**Table 3** Land, energy, and cost characteristics of different WWTTs

S.N	Technology	Source/reference	Land (ha/MLD)	Energy (KWh/ML)	Capital Cost (million Rupees/MLD)	O&M Cost (million Rupees/MLD)	Avg. Annual Inflation# (%)	Projected Capital Cost (2021) (million Rupees/MLD)	Projected O&M Cost (2021) (million Rupees/year/MLD)
<i>Secondary treatment technologies</i>									
1	ASP	(Tare and Bose 2009; GRBMP 2010)	0.200	202.5	10.8	1.25	6.02	20.5	2.36
2	MBBR		0.055	220.0	10.8	1.27	6.02	20.5	2.40
3	SBR		0.055	150.0	11.5	0.90	6.02	22.0	1.70
4	WSP		0.610	2.0	6.3	1.00	6.02	12.0	1.90
5	UASB + EA		0.110	120.0	10.8	1.23	6.02	20.5	2.32
6	DPS		4.000	2.0	3.0	0.18	6.02	5.7	0.34
7	MBR		0.045	300.0	30.0	0.50	6.02	57.0	0.95
8	A2O	(Park and Dho 2018)	0.060	170.0	10.0	1.00	6.02	19.0	1.90
9	Anaerobic Lagoon+SP	(Tare and Bose 2009; GRBMP 2010)	0.335	18.0	2.5	0.35	6.02	4.7	0.66
10	SAFF		0.050	390.0	7.0	1.14	6.02	13.2	2.15
11	BIOFOR		0.040	277.5	7.3	0.86	6.02	13.85	3.51
12	BIOFOR-F		0.080	180.0	5.2	0.18	6.02	10.0	0.34
13	FAB		0.060	134.5	4.0	0.67	6.02	7.60	1.26
14	C.Tech		0.150	175.0	11.0	1.40	6.02	11.0	2.65
15	Trickling Filter		0.500	180.0	4.5	0.50	6.02	4.5	0.95
16	Oxidation Pond	(CPCB 2013)	0.150	2.0	2.5	0.25	5.11	3.70	0.36
17	CW	(Ramachandra et al. 2017)	0.315	4.0	5.0	0.50	4.51	5.85	0.60
18	SBT	(Stefan et al. 2017)	0.030	121.0	20.0	0.20	4.51	23.4	0.23
<i>Emerging technologies</i>									
19	MLE	(USEPA 2013)	0.040	120.0	12.0	0.60	6.85	27.12	1.35
20	Step-Feed BNR		0.040	135.0	17.0	0.20	6.85	38.42	0.45
21	Bardenpho		0.090	150.0	28.0	0.20	6.85	63.28	0.45
22	WP		0.040	120.0	14.0	0.60	6.85	31.64	1.35
<i>Tertiary treatment technologies</i>									
23	Coagulation-Flocculation + RSF	(Hamoda et al. 2004; Üstün et al. 2011)	0.100	140.0	5.0	0.50	6.83	12.0	1.20
24	UF+RO	(Pizzichini and Russo 2001)	0.050	180.0	20.0	0.60	6.21	64.14	2.00
25	MF+RO		0.080	150.0	18.0	0.60	6.21	57.72	2.00

\*1 United States Dollar (1 USD) = 73.44 Indian Rupees (2021); Value of USD at the time of this study can be used for converting Rupees into USD #Source: IMF 2021





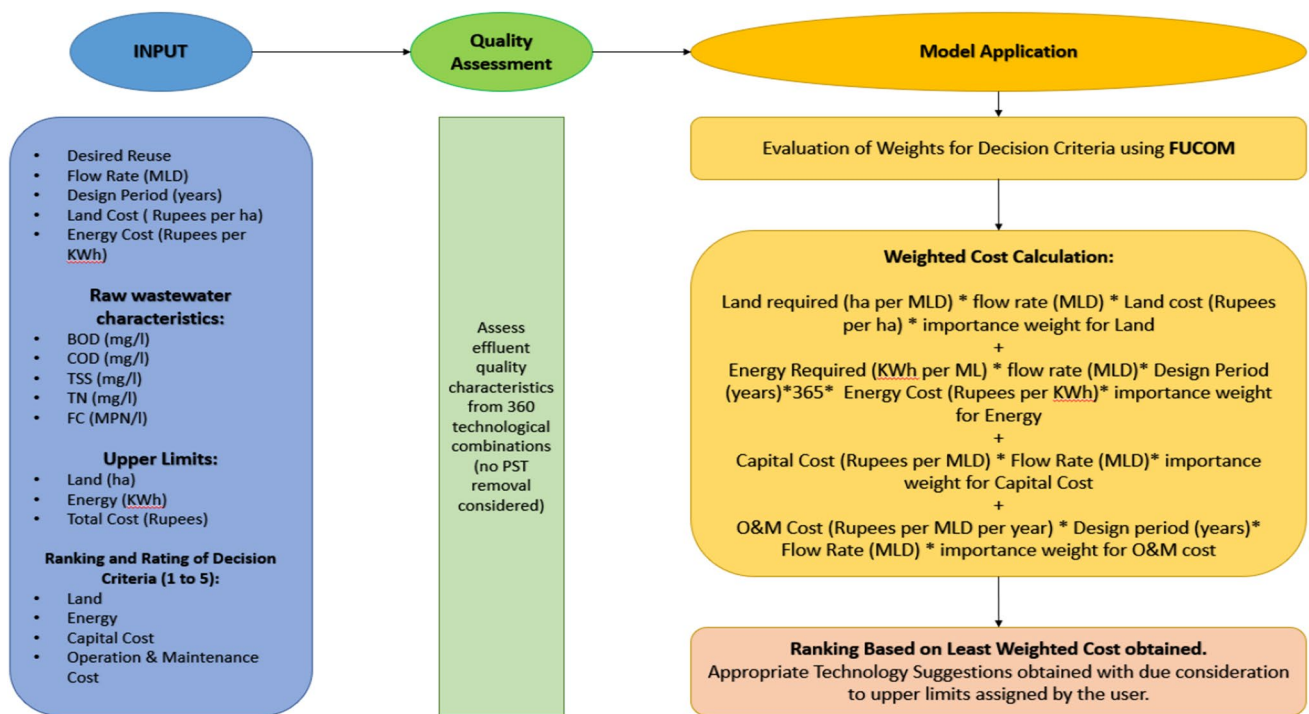
**Table 4** Examples of waste water treatment technology combinations

*Technology Combinations (Total No. 360)*

Base Technology (18)  
 Base Technology + Emerging Technology (18×4)  
 Base Technology + Tertiary Technology (18×3)  
 Base Technology + Emerging Technology + Tertiary Technology (18×4×3)

*ASP and its possible combinations with other technologies*

ASP + MLE	ASP + Step-Feed BNR + Coagulation + Flocculation + Rapid Sand Filters
ASP + Step-Feed BNR	ASP + Step-Feed BNR + UF + RO
ASP + Bardenpho	ASP + Step-Feed BNR + MF + RO
ASP + UF + RO	ASP + Bardenpho + Coagulation + Flocculation + Rapid Sand Filters
ASP + WP	ASP + Bardenpho + UF + RO
ASP + Coagulation + Flocculation + Rapid Sand Filters	ASP + Bardenpho + MF + RO
ASP + MF + RO	ASP + WP + Coagulation + Flocculation + Rapid Sand Filters
ASP + MLE + Coagulation + Flocculation + Rapid Sand Filters	ASP + WP + UF + RO
ASP + MLE + UF + RO	ASP + WP + MF + RO
ASP + MLE + MF + RO	



**Fig. 2** Flow-chart representing procedure for appropriate technology selection to meet reuse quality

downstream of Kanpur. The city has undertaken serious attempts to enhance its sewage treatment infrastructures and consequent value addition in the Ganga river water quality improvements in recent years.

Kanpur has a population density of about 6900 persons per sq km (Kanpur JNNURM 2006); thus, the land is a critical factor in this city. Based on preliminary analyses of agricultural land rates in Kanpur, land cost is assumed as 20

million rupees per hectare and the prevailing electricity rate is taken as 6 rupees per kWh.

**Desired wastewater reuse quantity estimation**

Kanpur is a large metropolitan city and has huge potential for utilizing treated wastewater. Out of 14 reuse applications considered in this study, Kanpur can meet considerable water

demand in eight applications, such as toilet flushing in residential buildings, commercial buildings or railway stations and locomotives, construction activities, road cleaning, industrial cooling, landscape development, vehicle washing including railway locomotives, fire protection and dust control.

There are five operational STPs in Kanpur city (Fig. 3), out of which three are located in the Jajmau: 5 MLD (UASB), 130 MLD (ASP) and 36 MLD (UASB). The treated effluents from 130 MLD (ASP) and 36 MLD (UASB) STPs are used by farmers in land irrigation, while the treated effluent from 5 MLD (UASB) joins the

the added technology will be treated effluent from existing STPs. Accordingly the existing STPs can be augmented with a newer technology combination to meet the desired reuse objectives as per the availability of resources.

**Industrial cooling** Panki Thermal Power Plant is an upcoming 660 MW coal-based power plant in Kanpur which derives water directly from the river Pandu. As per MoEF notification (MoEF 2019), in a cooling tower of a thermal power plant,  $3.5 \text{ m}^3$  of water is required per 1 MWh of electricity generation.

Water required for Cooling (MLD)

$$= \left[ \frac{3.5 * 1000 * \text{Power Plant Capacity (MWh)} * 24}{1000000} \right] = 55.44 \text{ MLD}$$

river Ganga through open drain. Bingawan STP is based on UASB technology and has an installed capacity of 210 MLD where only 80–90 MLD is utilized. Sajari STP (42 MLD ASP based) is also devoted to municipal wastewater treatment (STP 2021). The treated effluents from Bingawan and Sajari STPs are reportedly discharged into river Pandu which ultimately joins river Ganga after traveling around 70 km along the course.

For the present study, municipal wastewater characteristics of Jajmau STP is considered with BOD 314 mg/l, COD 572 mg/l, TSS 969 mg/l, ammoniacal-nitrogen 19.2 mg/l, and fecal coliform 94,000,000 MPN/l (CPCB 2013).

For testing the applicability of the model developed in the present study, industrial cooling in Panki Power House and non-potable domestic reuse in the colony or neighboring area have been considered as desired reuse objectives.

The suggested technology chain is for new installations. If existing STPs need to be supplemented, the feed water to

Considering a loss factor of 20%, a gross demand of 70 MLD is obtained for the said power plant.

**Non-potable domestic water demand** There exists a gap of 215 MLD in the water demand and supply scenario of Kanpur city (Bassi et al. 2019). In order to bridge the gap, it is proposed to meet 70 MLD water demand for non-potable domestic purpose through reclaimed water. The target effluent quality for this application must satisfy the quality criteria required for toilet flushing and laundry washing.

The inputs taken for appropriate technology selection in Kanpur city are as shown in Table 5.

#### Evaluation of weights for decision criteria using FUCOM

The priorities of the decision-maker in terms of resource availability are assessed and used for evaluation of weights using FUCOM as shown in Table 6. The decision-maker



Fig. 3 Location of STPs in Kanpur city



**Table 5** Local resource scenario, raw wastewater characteristics, and target effluent quality characteristics for assumed reuse purposes in Kanpur city (India)

Local resource scenario (based on available primary data)								
Desired reuse	Quantity (MLD)	Design period (years)	Land Cost (Rupees per hectare)	Electricity cost (Rupees per kW-h)	Land (ha)	Energy (MWh)	Capital cost (Rupees)	O&M cost (Rupees)
Industrial cooling	70	15	20 Million	6.00	8	50	–	–
Non-potable Domestic reuse	70	15	20 Million	6.00	8	50	–	–
Raw wastewater characteristics (CPCB 2013)								
Source	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)			
Municipal	314	572	969	19.2	$9.4 \times 10^7$			
Target quality characteristics (Table 1)								
Desired reuse	BOD (mg/l)	COD* (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)			
Industrial cooling	10	30	10	10	2000			
Non-potable domestic reuse	10	30	10	10	200			

\*Due to the absence of quality standards for COD parameter, a BOD/COD ratio of 0.3 is considered for the treated effluent in model application to represent average COD concentration

**Table 6** Weightage calculation of criteria for Kanpur city (India) using FUCOM

Total number of criteria = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Land	Energy	Capital Cost	O&M Cost
Rank	1	3	2	4
Criteria (according to rank)	Land	Capital Cost	Energy	O&M Cost
Criteria comparisons	1	2	3	4
$\phi_{1/2}$	$\phi_{2/3}$	$\phi_{3/4}$	$\phi_{1/3}$	$\phi_{2/4}$
2.00	1.5	1.33	3.00	2.00
	Land	Capital cost	Energy	O&M cost
Weights	0.480	0.240	0.160	0.120

\*Weights were obtained by using above data and applying linear programming model in Eqs. (1) and (2)

is asked to rank the decision criteria based on importance and perform a pairwise comparison and rate each decision criteria in terms of significance with respect to the previous criteria on a scale of 1 to 5 where 1 represents maximum importance, while 5 indicates the minimum importance.

**Model application for appropriate technology selection**

Fecal coliform concentration separates the effluent quality required for industrial cooling and non-potable domestic reuse (toilet flushing and laundry washing). After applying the inputs and respective weights, based on required quality and least weighted cost, the following wastewater treatment technology combinations are suggested for industrial cooling and non-potable domestic reuse in Kanpur city in increasing order of weighted cost (Table 7).

The cost figures are for comparative purpose only. It is observed that for reuse in industrial cooling application MBR treatment method with Wuhrmann process (WP) is suggested to be the most appropriate combination. After MBR process, the BOD, COD, TSS, TN, and FC in secondary effluent is expected to be 7.5 mg/l, 20.5 mg/l, 48.4 mg/l, 7.7 mg/l, and 9400 MPN/l, respectively. This effluent when passed through single-stage post-denitrification process, that is, WP, the resulting effluent will have BOD 0.2 mg/l, COD 16.53 mg/l, TSS 0.3 mg/l, TN 0.85 mg/l, and FC 940 MPN/l. Meeting the effluent quality requirements as well as adherence to land resource-constraint and least cost option makes MBR followed by WP the most preferred technology for the purpose.

For non-potable reuse, UF and RO combination preceded by A2O gives the most preferred combination, very closely to be followed by SBR or MBR as supportive pretreatment.

**Table 7** Appropriate WWTs combinations based on the least weighted cost for industrial cooling (70 MLD) and non-potable domestic reuse (70 MLD) purposes under resource-restraint condition in Kanpur city (India)

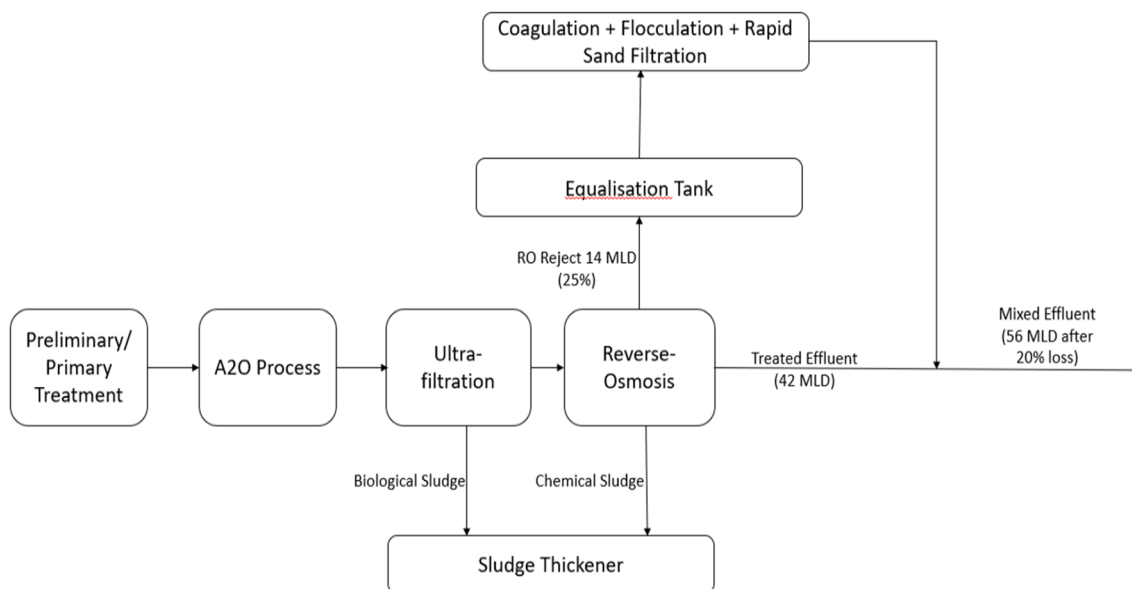
Rank	Technology combination	Weighted cost (million Rupees)	Total absolute cost (million Rupees)	Land (ha)	Energy (MWh per day)	Absolute capital cost (million Rupees)	Absolute O&M cost (million Rupees)
<i>Industrial cooling</i>							
1	MBR + WP	1990.6	9704.5	5.95	29.40	6204.8	2415.0
2	A2O + UF + RO	2090.8	10,873.6	7.70	24.50	5819.8	3071.2
3	SBR + UF + RO	2105.3	10,820.6	7.35	23.10	6029.8	3885.0
4	MBR + UF + RO	2647.3	12,814.1	6.65	33.60	8479.8	3097.5
<i>Non-potable domestic reuse</i>							
1	A2O + UF + RO	2090.8	10,873.6	7.70	24.50	5819.8	3071.2
2	SBR + UF + RO	2105.3	10,820.6	7.35	23.10	6029.8	3885.0
3	MBR + UF + RO	2647.2	12,814.1	6.65	33.60	8479.8	3097.5

Thus, under land constrained and adequate energy availability conditions, such as shown in Kanpur city of India, a combination of UF and RO preceded by either of A2O, SBR or MBR may be a good choice for both industrial cooling and non-potable reuse purpose. Schematic diagram representing A2O + UF + RO-based plant system is as shown in Fig. 4.

In the A2O + UF + RO-based system, the effluent will be firstly treated in A2O bioreactor and then solid–liquid separation will be achieved through membrane filtration. The expected contaminant concentration in the permeate will be BOD 5 mg/l, COD 15 mg/l, TSS 5 mg/l, TN 10 mg/l, and FC 1222 MPN/l. This water after passing the RO system will produce tertiary-treated effluent with BOD, COD, TSS, TN, and FC as < 5.0 mg/l, < 10.0 mg/l, < 5.0 mg/l, < 0.3 m

g/l, and < 12.22 MPN/l, respectively, derived using effective contaminant concentration formula shown in Fig. 1 and treatment efficiencies summarized in Table 2.

Management of RO reject is a challenge and needs to be addressed. Assuming 25% rejection rate, the volume of RO reject will be 14 MLD (taking over all loss to be 20%). This water will have the BOD, COD, TSS, TN, and FC as 20 mg/l, 60 mg/l, 20 mg/l, 40 mg/l, and 4888 MPN/l, respectively. This effluent may be collected in an equalization tank and further treated by chemical coagulation leading to production of chemical sludge. The expected BOD, COD, TSS, TN, and FC of treated reject water after coagulation–flocculation–rapid sand filtration is expected to be 7 mg/l, 32 mg/l, 9.4 mg/l, 28.0 mg/l, and 733 MPN/l, respectively. Therefore, for RO reject management, all the suggested technology train

**Fig. 4** Schematic diagram showing combination of A2O + UF + RO systems with reject treatment and reuse

will need coagulation–flocculation–rapid sand filtration. The suggested technology combination options will remain same.

The treated reject water can be mixed with the effluent from WWTP. This effluent will still satisfy the quality criteria and the expected BOD, COD, TSS, TN, and FC of mixed effluent will be < 5.0 mg/l, 6.1 mg/l, 4.0 mg/l, < 10 mg/l, and < 200 MPN/l, respectively.

The volume of biological sludge produced from the membrane filtration should be mixed with the obtained chemical sludge and thickened in a sludge thickener. This thickened sludge is further dewatered using a centrifuge decanter before disposal. The supernatant from the sludge thickener is sent back to the equalization tank discussed earlier.

Due to very high BOD, COD, TSS, TN, and FC concentrations, as reported for Kanpur, advanced tertiary treatment technologies are suggested in this case study. It shows that influent quality of wastewater plays a significant role in defining the degree of treatment required for obtaining the desired quality characteristics for reuse. Membrane filtration processes (MF/UF/RO) are high-performing, low-maintenance, but costly technologies (Tables 1 and 2). The sustainability of RO process is often questioned due to high reject ratio (Zhang and Liu 2020). Therefore, application of this combination is suggestive for places where adherence to stringent quality standards is required.

## Varanasi City

Varanasi is said to be one of the oldest living cities in the world. It is located at 25.31° N latitude and 82.97° E longitude on the left-crescent-shaped bank of the mighty river Ganges in the state of Uttar Pradesh in India (Varanasi JNNURM 2006). Population density of Varanasi city is 2400 inhabitants per sq km indicating better land availability. A design period of 15 years is taken for this study with land rate at Rs 14 million per hectare and Rs 6 per KWh of electricity.

Currently, there are four operational STPs in Varanasi, including Goithaha STP (120 MLD), Bhagwanpur STP (10 MLD), Dinapur STP (220 MLD) and DLW STP (12 MLD) as shown in Fig. 5. Two new STPs, one at Ramna (50 MLD) and Ramnagar (10 MLD), are also under construction. The raw wastewater characteristics for Varanasi is taken from Bhagwanpur STP which gives BOD 101 mg/l, COD 289 mg/l, TSS 198 mg/l, TN 12 mg/l, FC  $1 \times 10^7$  MPN/l (CPCB 2013).

## Reclaimed wastewater reuse potential estimation

Out of the fourteen reuse applications considered in this study, Varanasi can use significant amount of reclaimed wastewater in eight purposes such as toilet flushing (in community wash rooms near railway stations, markets, etc.), construction activities, road cleaning, landscape development, vehicle washing including washing at railway stations

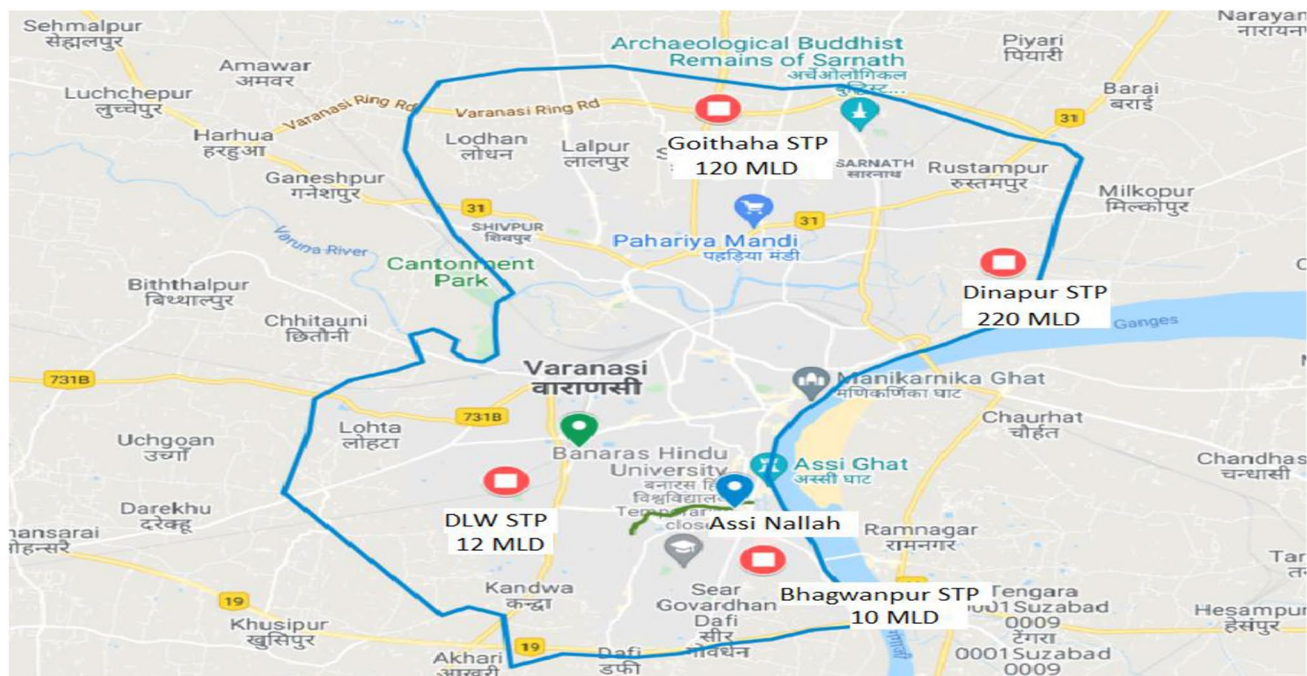


Fig. 5 Varanasi city map and location of different STPs



and airports, fire protection, recreation and environmental flow augmentation of rivers Assi or Varuna in city zone.

**Vehicle washing (railways and multi-model transportation hub)**

As per Indian Railway Works Manual (IRWM 2005), in a railway station, for apron and platform washing, 10 l and 5 l of water is required per sq m per day. For washing of carriages on washing lines, 3600 l and 2600 l of water is required per carriage per day for broad gauge (BG) and meter gauge (MG), respectively. For cleaning of carriages on platform, 500 l of water is required per carriage per day. For Varanasi railway station, total number of passengers is about 363,000 per day. Also, the number of platforms is 9, of approximately 200 sq m area each. About 40 trains originate or terminate at this station, and more than 250 trains stop at this station every day. For assessing non-potable reuse options around Varanasi, water demand from railways is considered from platform, apron, and carriage washing works only. A probability of 0.57 is taken considering four washing days in a week.

Thus, Water Demand for washing operations in railways:

$$\begin{aligned}
 &= (\text{Water per carriage per day for BG/MG} * \text{number of trains terminating/originating} * \text{probability of washing}) \\
 &+ (\text{Water for cleaning carriage at platform} * \text{number of platforms} * \text{number of stopping trains} * \text{probability of washing}) \\
 &+ (\text{Number of platforms} * \text{average area of platform/apron} * \text{water required for platform and apron} * \text{probability of washing}) \\
 &+ (\text{Number of passengers} * \text{average water demand} * \text{probability of use})
 \end{aligned}$$

$$\begin{aligned}
 &= (3600 * 40 * 0.5 + 500 * 9 * 250 * 0.7 + 9 * 200 * (10 + 5) * 1 + 363,000 * 45 * 0.6) \\
 &= 10.68 \text{ MLD}
 \end{aligned}$$

Therefore, for washing operations in railways, around 11 MLD water is required. Considering 20% losses, 20 MLD plant is considered enough to meet this water demand.

**E-flow augmentation (inland surface water)**

River Assi has taken the form of almost a nallah, which has flow of around 24 MLD of sewage discharge in its stream (Varanasi CDP 2015). Similar is the condition of river Varuna water quality once it enters the city area. It has been thought that augmenting their flows using treated effluents from the nearby STPs can lead to dilution of pollution and may help revive the sick rivers. The quality criteria for e-flow augmentation are taken from CPHEEO manual which has defined quality standards for inland surface waters (CPHEEO 2013). Appropriate technology selection for this purpose is performed in two ways: (1) considering installation of a new STP, and (2) augmenting an existing ASP-based STP.

Accordingly, the inputs taken for appropriate technology selection for waste water treatment with desired reuse purpose of treated effluent are as shown in Table 8. These are primarily obtained data from field experts and engineers.

**Evaluation of weights for decision criteria using FUCOM**

The priorities of the decision-maker in terms of resource availability are assessed and used for evaluation of weights using FUCOM as shown in Table 9. The decision-maker was asked to rank the decision criteria based on importance

**Table 8** Represents local resource scenario, raw wastewater characteristics, and target effluent quality characteristics for respective desired purposes in Varanasi city

Local resource scenario (primary data)								
Desired reuse	Quantity (MLD)	Design period (years)	Land cost (Rupees/hectare)	Electricity cost (Rupees/KW-h)	Land (ha)	Energy (MWh)	Capital cost (Rupees)	O&M cost (Rupees)
Vehicle Washing	20	15	14 million	6.0	6.0	6.0	–	–
E-flow	40	15	14 million	6.0	6.0	12.0	–	–
Raw wastewater characteristics (CPCB 2013)								
Source	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)			
Municipal	101	289	198	12	10,000,000			
Target wastewater characteristics (Table 1)								
Desired reuse	BOD (mg/l)	COD (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)			
Vehicle washing	10	30*	20	10	2000			
E-flow augmentation	30	250	100	100	10,000			

\*Due to the absence of quality standards for COD parameter, a BOD/COD ratio of 0.3 is considered for the treated effluent in model application

**Table 9** Weightage calculation of criteria for Varanasi city (India) using FUCOM

Criteria number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of criteria	Land	Energy	Capital cost	O&M cost
Rank	2	1	3	4
Criteria (according to rank)	Energy	Land	Capital cost	O&M cost
Criteria comparisons	1	2	4	5
$\phi_{1/2}$	$\phi_{2/3}$	$\phi_{3/4}$	$\phi_{1/3}$	$\phi_{2/4}$
2.00	2.00	1.25	4.00	2.50
	Energy	Land	Capital cost	O&M cost
Weights	0.513	0.256	0.128	0.103

\*Weights were obtained by using above data and applying linear programming model in Eqs. (1) and (2)

and perform a pairwise comparison and rate each decision criteria in terms of significance for the previous criteria on a scale of 1 to 5, with 1 as the most important and 5 as least important.

### Model application for appropriate technology selection

The reuse purposes considered in this case, vehicle washing and e-flow augmentation (inland surface water), require very strict effluent characteristics. After applying the required inputs and weights, based on required quality and least weighted cost, the following wastewater treatment technologies are suggested as shown in Table 10.

Thus, the developed methodology suggests BIOFOR-F as the most appropriate technology for vehicle washing operations in railways and multi-model transportation hub of Varanasi, followed by SBR. After BIOFOR-F, the expected BOD, COD, TSS, TN, and FC concentrations in the secondary effluent are expected to be 3 mg/l, 13 mg/l, 15 mg/l,

3.5 mg/l, 1000 MPN/l, respectively. Due to high capital and O&M costs, SBR ranks lower than BIOFOR-F, which has comparable land and energy requirements but lower capital and O&M costs. While BIOFOR ranks third, MBR ranks fourth in the suggested options due to high energy and very high capital cost requirements with them, as observed through FUCOM weights.

For **E-flow Augmentation (Inland surface water)**, BIOFOR-F and Soil Bio-Technology (SBT) are ranked as the top two suggested technologies. The quality standards for this reuse are more relaxed than vehicle washing scenario. SBR has better performance than SBT but since SBT has less land and energy requirements and very less O&M costs, SBT is preferred over SBR. Currently, one STP (Ramna: 50 MLD) in river Assi catchments and another (Goithaha: 120 MLD) in river Varuna catchments are SBR technology-based installations. Thus, the analyses suggest that although these planned setups might not be the least cost options at the time of installation, their effluents can beneficially use

**Table 10** Appropriate Technology combinations based on the least weighted cost for Vehicle washing (20 MLD) and E-flow (Inland surface water) (40 MLD) under energy resource-restraint condition in Varanasi

Rank	Technology combination	Weighted cost (million Rupees)	Total absolute cost (million Rupees)	Land (ha)	Energy (MWh per day)	Absolute capital cost (million Rupees)	Absolute O&M cost (million Rupees)
<i>Vehicle washing</i>							
1	BIOFOR-F	102.5	442.7	1.60	3.60	200.0	102.0
2	SBR	163.3	1064.0	1.10	3.00	440.0	510.0
3	BIOFOR	240.3	1523.5	0.80	5.55	277.0	1053.0
4	MBR	279.6	1634.7	0.90	6.00	1140.0	285.0
5	A2O + MLE	323.4	2115.9	2.00	5.80	922.4	975.0
<i>E-flow augmentation (inland surface water)</i>							
1	BIOFOR-F	205.0	885.3	3.20	7.20	400.0	204.0
2	SBT	219.9	1249.8	1.20	4.84	936.0	138.0
3	SBR	326.7	2127.9	2.20	6.00	880.0	1020.0
4	C. Tech	359.6	2344.0	6.00	7.00	440.0	1590.0
5	Oxidation Pond + WP	396.1	2706.3	7.60	4.88	1413.6	1026.0

for inland surface water flow augmentation of rivers Assi and Varuna.

In order to suggest technology combinations for up gradation of ASP-based 10 MLD Bhagwanpur STP in Varanasi to meet effluent suitable for Inland surface water augmentation, as shown in Table 11.

The effluent produced from ASP is generally of very low quality and requires costly tertiary treatment technologies to produce water for desired reuse. It is observed that in addition to the existing ASP-based system, WP, which is one of the emerging technology, supported with membrane-based treatment methods (MF/UF) and RO may be required to meet the quality criteria for inland surface water augmentation. Membrane filtration processes have lesser land and O&M requirements, but very high capital cost and relatively higher energy needs. These are not suitable for projects having restraint of fund-availability. RO is also not sustainable for all applications due to very high reject value (Zhang and Liw 2020), which further requires another set of processes for treatment of reject water. This combination is only suitable at places which have stringent quality criteria.

### Sensitivity analysis

Sensitivity analysis is performed to assess the reliability of results obtained through the application of any model (Hamby 1994). Weights of prioritized criteria are increased and decreased by 25% each, respectively, and the variations in the result are analyzed (Castillo et al. 2017). Since all the case studies follow the same pattern, sensitivity analysis for case 1, i.e., reuse of 70 MLD treated effluent in industrial cooling in Kanpur city is only presented. The sensitivity analysis is performed without considering restraint on resources for better analysis.

The changes in weights of all four decision criteria are illustrated in Table 12. A 25% increase or decrease in prioritized criteria is accompanied by proportionate changes in the rest of the criteria.

Modified weights were applied for industrial cooling reuse in Kanpur city (70 MLD) in the designed model. An increase of 25% in weight of land criteria will cause lesser accessibility to land resources and higher land cost components in weighted cost. The weighted costs obtained in this

**Table 12** Effects of change in weightage of considered criteria

Water reuse in Industrial Cooling in Kanpur city (India) Resource Prioritization: Land Availability (Constrained) > Capital Cost > Energy Availability (Liberal) > O&M Cost				
S. No	Resource	Original weight assigned	With 25% increase in weight	With 25% decrease in weight
1	Land	48	60	36
2	Energy	16	12	20
3	Capital cost	24	18	30
4	O&M cost	12	10	14

case are lesser in comparison with the first case due to the lower weight of capital cost and O&M costs. In the case of a 25% decrease in land cost criteria, more relaxation in acquiring land is given and higher weight to capital cost is given leading to higher costs. Relatively newer technologies such as BIOFOR, BIOFOR-F, A2O, and SBR are found under higher preferences because of their optimum land and energy use reported efficiencies and higher performance.

### Conclusion

The objective of the present study is to develop a methodology for selection of the appropriate technology chain in municipal wastewater treatment which meets water quality criteria for the defined reuse. Availability of land, energy, capital cost, and O&M cost have been considered as the decision criteria. Thus, the selection of an appropriate chain of WWTs becomes a multi-criteria decision-making process with multiple alternatives and sensitivity to local resource-constraints. Full Consistency Method (FUCOM) for evaluating the weights for decision criteria provides credible and consistent prioritization, and Weighted Sum Method (WSM) helps in ranking technologies with sensitivity to resource-availability. The developed methodology is user-friendly and flexible. With suitable modifications in terms of performance efficiency based on climatic conditions, socio-economic, environment, and cost variations and required quality criteria for selected reuse, the methodology

**Table 11** Appropriate Technology suggestion for up gradation of ASP-based 10 MLD Bhagwanpur STP based on the least weighted cost for Inland Surface Water augmentation

Rank	Technology combination	Weighted cost (million Rupees)	Total absolute cost (million Rupees)	Land (ha)	Energy (MWh per day)	Absolute capital cost (million Rupees)	Absolute O&M cost (million Rupees)
1	WP + MF + RO	215.9	1501.6	1.20	2.70	893.6	503.3
2	WP + UF + RO	228.1	1571.5	0.90	3.00	957.8	503.3

\*The costs presented in above table do not include costs associated with ASP technology





can be used as a decision support tool for technology chain selection toward defined reuse purpose. Application of the developed methodology for two cities in India namely, Kanpur and Varanasi, for selection of most preferred combination of technology for defined reuses or supplementation of technology chain to an existing STP has been examined and explained. Relatively newer and emerging technologies, such as BIOFOR-F, Wuhrmann process, and membrane-based systems, such as MF/ UF/RO, are found preferable for meeting reuse quality criteria. Sensitivity analysis checks the robustness of the suggested chain of technologies and gives the effect of the uncertainties involved in assigning the weights to the chosen criteria. Ranking of the technologies based on the least weighted cost, out of a total 360 combinations for 14 defined reuses makes the developed methodology a very good decision-making tool for selection of appropriate technology chain in reused focused wastewater treatment scheme to bridge the gap between water demand and supply.

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## Declarations

**Conflict of interest** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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