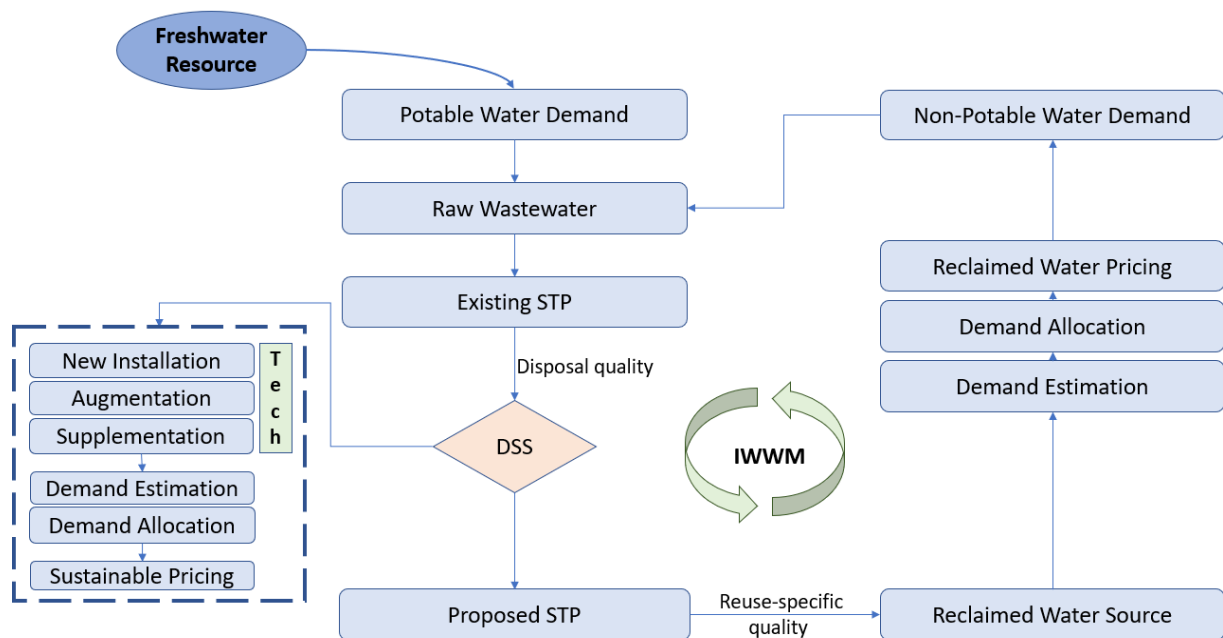


Following the integrated water and wastewater management approach, this study aims to develop a Decision Support System (DSS\_IWWM) to facilitate the selection of treatment technology combinations for upcoming sewage treatment plant installations, while keeping in mind the quality criteria for the effluents required, as per the desired reuse. Similarly, the DSS\_IWWM will also facilitate the selection of treatment technologies for the upgradation or supplementation of existing technologies, which are not able to satisfy the desired quality requirements through the current installations. Therefore, the technology selection using DSS\_IWWM is divided into three categories:

- i. New Installations: When setting up of a new STP is proposed for desired reuse purposes.
- ii. Augmentation/Upgradation: When new emerging or tertiary technologies or both in combination are suggested to be added to the existing technology installed at the concerned STP, to achieve the desired effluent quality.
- iii. Supplementation: When secondary technologies in combination with emerging or tertiary technologies or both in combination are suggested to be added to the existing technology installed.

The DSS\_IWWM will also facilitate the allocation of reclaimed water demands identified in the vicinity of the STP using a socio-economic approach, to satisfy both social obligations toward the poor communities and generate revenue to overcome costs incurred by the installing parties. Along the same lines, using proportional pricing approach, the DSS\_IWWM will make suggestions for water prices for the different groups of consumers, so that the cost burden is reduced from the part of low-income people while cost-recovery is also achieved. The following

Figure 3.1 represents the overall vision of this study in which the raw wastewater obtained from the community is treated through appropriate treatment technologies based on the desired reuse purpose and a reclaimed water source is created from the treated effluents. Thereafter, the reclaimed water demand existing in the vicinity of the STP is calculated, and then based on the socio-economic methodology developed, and reclaimed water prices recommended, the reclaimed water is distributed in the community for non-potable water demands. Therefore, this approach closes the human water-cycle loop and helps achieve circular economy in water management.



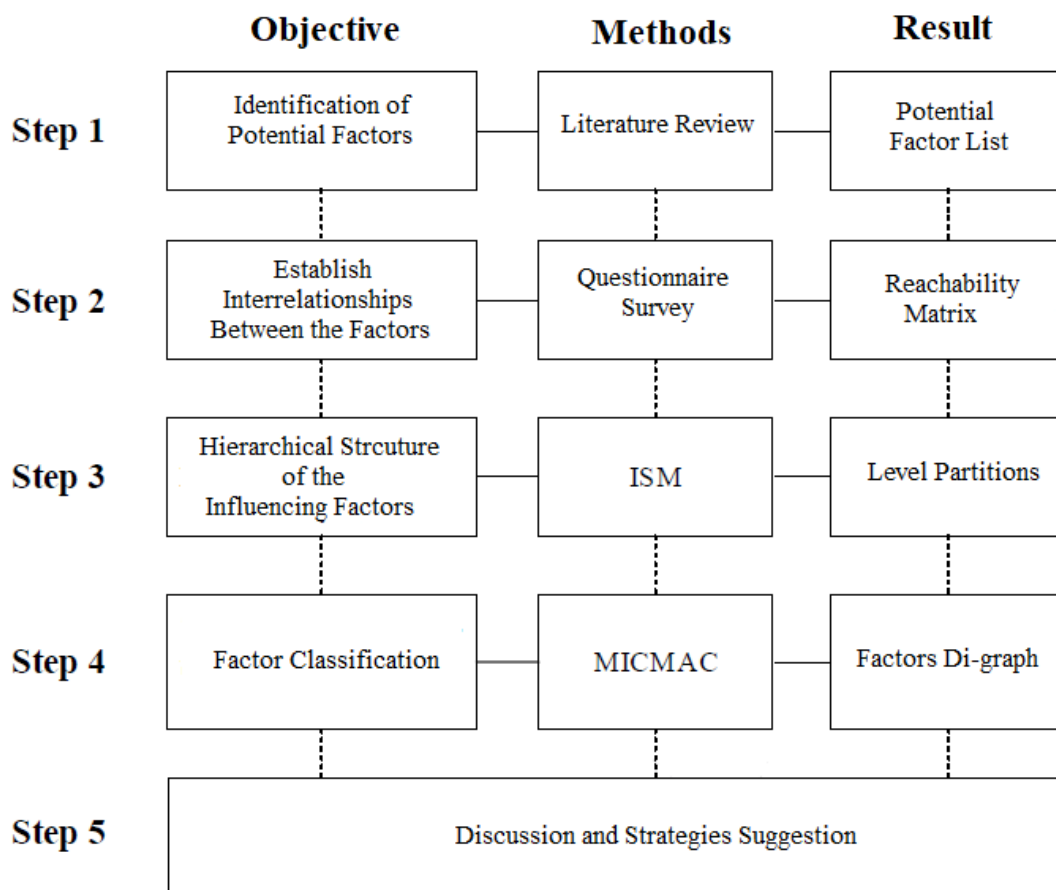
**Fig. 3.1. The schematic representation of the applicability of the DSS\_IWWM.**

### 3.1 Selection of Key Factors Affecting Reuse Focused IWWM

This study was conducted in five stages, as shown in Figure 3.2. Firstly, by in-depth literature review, potential factors influencing wastewater treatment and reuse were identified. Secondly, academicians and engineers from the concerned field were approached with a survey questionnaire to rate the factors and influencing capacity of each factor, based on their practical experiences. Using these responses, key influencing factors were identified, and their interrelationships were represented in the Reachability Matrix. Thirdly, Interpretive Structural

Modelling (ISM) was applied to identify the crucial factors and represented in a hierarchy structure using level partitions. Fourthly, MICMAC (Matrix of Cross Impact – Multiplications Applied to Classification) analysis was used to arrange the factors on a digraph representing the autonomous, dependent, driving, and linkage factors. Fifthly, strategies were suggested to implement an efficient IWWM network for wastewater reclamation.

In this study, Microsoft Excel software was used. No specific software is required for ISM. The application of ISM is completely based on the opinions of an optimum sample size of experts of a region and, their experiences and expertise are used as the primary data. No region-specific modification is required for conducting ISM except the data used.



**Fig 3.2. Research flow diagram for ISM and MICMAC**

### **3.1.1 Enlisting of Potential Factors, Questionnaire Survey and Expert Ratings**

A questionnaire survey (Annexure 2) was conducted to identify the key influencing factors for efficient Integrated Water and Wastewater Management (IWWM) and establish their interrelationships. It was sent to fifty academicians and engineers with expertise in wastewater engineering, and thirty responses were obtained. The sample size of 30 respondents was considered sufficient based on five considerations (Bryman, 2016). Firstly, only five survey responses identified additional factors; hence, data collection ceased due to "data saturation." Secondly, as stated by Shen et al. (2016), a large set of experts is not needed in ISM, and "minimum sample size" is not defined for rating factors in the ISM model (Lyu et al., 2016). Thirdly, since highly experienced experts working in wastewater engineering were invited, they covered most of the aspects of the concerned field and represented "adequate population heterogeneity". Fourthly, citing "theoretical underpinning of research", several studies were conducted which applied ISM for factor identification in different fields; the range of experts in such studies ranged from 5 to 30 (Xu and Zou (2020)). Lastly, since this study's "research scope" is limited to identifying potential influencing factors and establishing interrelationships between them, the sample size of 30 is considered sufficient. The objective of the study was explained to the experts, and they were requested to rate and correlate the factors. The background of the expert's approach for the survey is presented in the following Table 3.1.

**Table 3.1. Background of experts who responded to questionnaire survey**

No. of Experts	Organization	Occupation	Work Experience (years)
5	Academic Institution	Professor	>20
5	Academic Institution	Associate Professor	>10
2	Government Department	Deputy Chief Engineer	>30
5	Government Department	Deputy General Manager	>25
5	Government Department	Senior Engineer	>15
3	Government Department	Assistant Engineer	>7
5	Environment Consultancy	Consultant	>15

### **3.1.2 Finalization of Key Factors based on Expert Ratings**

A questionnaire survey (Annexure 2) was prepared to obtain the opinion of professionals and academicians. The experts were requested to rate the identified potential factors on a scale of 1 to 5, where 1 depicted least importance and 5 depicted high importance. The top twelve factors having higher scores were considered in this study. This filtration also reduced complexity in methodology as 12 or lesser factors are considered most suitable for applying ISM (Attri et al., 2013). The experts were also asked to suggest any potential factor they would add to the current list. Out of 50 invited responses, a response rate of 60 percent was obtained, and hence 30 responses were used for selecting final key factors. A similar number of responses (32) were taken for barrier identification in prefabricated construction, conducted by Tan et al. (2019). The experts were also requested to mention against each factor, all the factors that this factor can influence or get influenced by. Therefore, for each factor, a set of influencing factors were obtained. The occurrence of the factors in both influencing and getting influenced categories further led to formation of interrelationships using ISM.

### **3.1.3 Developing Importance Hierarchy of Key Factors Using Interpretive Structural Modelling (ISM)**

ISM technique was developed by Warfield (1974) to analyze the complexity and subjectivity of problems. The interrelationships and the hierarchical structure between the affecting factors within a system can be obtained using this method (Farris and Sage, 1975). ISM has seen wide application in different contexts. The following steps are included in this technique:

*Step 1:* Identification of relevant factors out of potential factors obtained through literature review.

*Step 2:* Establishment of interrelationships between the identified factors by using experts' opinions. The pairwise relationship between the identified factors is represented in a Structural Self-Interaction Matrix (SSIM) using A, O, X and V, each depicting interdependencies between the comparing factors.

The dependencies between factors *i* and *j* are marked by four symbols, which are:

- (a) W: if factor *i* directly affects factor *j* but factor *j* does not affect factor *i* directly
- (b) X: if factor *j* affects factor *i* directly but factor *i* does not affect factor *j* directly
- (c) Y: if both factors *i* and *j* affect each other
- (d) Z: if factors *i* and *j* are not related

*Step 3:* The SSIM is converted into a binary matrix called "Adjacency Matrix". In SSIM, each symbol is replaced by binary numbers as per the substitution rules shown in Table 3.2.

**Table 3.2. Substitution Rule in SSIM**

<b>SSIM</b>	<b>Reachability Matrix</b>	
	<b>(i,j)</b>	<b>(j,i)</b>
W	1	0
X	0	1
Y	1	1
Z	0	0

*Step 4:* The transitivity rule states that if factor i directly influences factor j and factor j directly influences factor k then factor i will also influence factor k, and thus establishes indirect relationships between the influencing factors (Xu and Zou, 2020). In this step, after checking transitivity rules in which apparent “1\*” is assigned in place of “0” to depict the indirect relationship between the considered factors. The Reachability Matrix has been prepared.

*Step 5:* Level Partitions are obtained in this step. Reachability and antecedent sets are obtained from the Reachability Matrix, which indicates influencing factors concerning each factor row-wise and column-wise, respectively (Ali et al., 2020). The intersection between the two sets is obtained and presented as an Intersection set. Levels are awarded starting from level 1 (least significant level) to highest level (most significant level) if the reachability set becomes equal to the intersection set (Tan, 2018). The top-level factors (level I, II) depict low significance while those at bottom levels are of higher significance.

*Step 6* The level partitions obtained in the previous step are used to present the identified relevant factors in the form of a hierarchy structure, where the most important level is represented at the bottom of the structure. Direct relationships or indirect relationships can be shown in this structure.

### **3.1.4 Classification (as Driver, Dependent, Autonomous and Linkage Groups) of Key Factors using MICMAC (Matrix of Cross Impact – Multiplications Applied to Classification)**

ISM method is applied in combination with MICMAC. MICMAC was developed to study the impact distribution of factors (Dupperin and Godet, 1973; Wang et al., 2008; Tan et al., 2019). MICMAC is used for the structural analysis of factors. The influencing factors are presented on a digraph based on their dependence and driving powers and divided into four groups (Shen et al., 2016). Lower dependence power indicates a lesser dependency on other factors. In contrast, a higher dependency will suggest that several other factors influence the considered factor, and their management is required before this factor (Attri et al., 2013). Under MICMAC, factors are classified into four groups:

- (1) Autonomous factors (low dependence and low driving power): they have less interdependencies and are less likely to influence or get influenced by other factors.
- (2) Dependent factors (high dependence power and low driving power): They have a lesser capacity to influence other factors while they get influenced by several other factors. These are accounted for automatically if its driving and linkage factors are addressed.
- (3) Driving factors (dependence power is low and driving power is high) significantly influence other factors but are less likely to be influenced by other factors.
- (4) Linkage factors (both dependence and driving powers are high): they have both high dependence power and driving power. These are most reactive, and any change in them will likely influence other factors (Mandal and Deshmukh, 1994; Xu and Zou, 2020).

### **3.2 Finalized Quality Criteria of Reclaimed Water for Reuse Purposes**

A list of potential reuse purposes was prepared along with the quality requirements of each reuse from the review of the scholarly literature (Table 3.3). 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. The quality criteria for identified fourteen reuse purposes are as shown in Table 3.3. Five quality parameters, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total nitrogen (TN) and faecal coliform (FC) are considered in this study. Some reuse purposes such as industrial cooling are very sensitive to total dissolved solid (TDS), hence consideration of more parameters is suggested in the future scope of the study.

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.

The quality criteria (each parameter) for the multiple reuse scenario will be as described below:

$$\text{BOD} = \text{Min} (\text{BOD}_{R1}, \text{BOD}_{R2}, \text{BOD}_{R3}, \text{BOD}_{R4}, \text{BOD}_{R5})$$

$$\text{COD} = \text{Min} (\text{COD}_{R1}, \text{COD}_{R2}, \text{COD}_{R3}, \text{COD}_{R4}, \text{COD}_{R5})$$

$$\text{TSS} = \text{Min} (\text{TSS}_{R1}, \text{TSS}_{R2}, \text{TSS}_{R3}, \text{TSS}_{R4}, \text{TSS}_{R5})$$

$$\text{TN} = \text{Min} (\text{TN}_{R1}, \text{TN}_{R2}, \text{TN}_{R3}, \text{TN}_{R4}, \text{TN}_{R5})$$

$$\text{FC} = \text{Min} (\text{FC}_{R1}, \text{FC}_{R2}, \text{FC}_{R3}, \text{FC}_{R4}, \text{FC}_{R5})$$

Where, R1, R2, R3, R4, R5, are multiple reuses applicable in a case.

### **3.3 Finalized WWTTs for DSS\_IWWM.**

#### **3.3.1 Performance Efficiencies of WWTTs**

After a comprehensive literature review, a total of 25 treatment technologies were identified, belonging to secondary, emerging, and tertiary categories. The performance efficiencies of each technology are compiled in Table 3.4.

#### **3.3.2 Land, Energy, Capital and O&M Costs of WWTTs**

Land, energy, capital cost and O&M cost are taken as the key decision criteria 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 the total energy required for the functioning of the STP throughout the design period of the plant. Capital costs are also distributed over the design period for technology selection. In this study, for technology selection, total O&M costs for the design period are considered.

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

This study does not include an elaborate sustainability assessment study. It comes in the future scope of this work. Land requirement, energy requirement, capital cost and O&M cost for each technology are tabulated in Table 3.5. For calculating requirement of these resources in different scenarios, such as, for new installations, upgradation of existing technology and supplementation of existing technology, following approach was utilized.

- *New installations:* The respective resource requirement obtained was taken directly.
- *Upgradation/Supplementation:* For upgradation/supplementation of existing technology, the land and capital cost requirements for the existing technology were subtracted from the total land and capital cost requirements respectively obtained for the combination (existing + upgradation/supplementation suggestions), as for upgradation, no new land or capital cost is incurred for the existing technology but only for the technologies required for augmentation while the energy and O&M costs were retained as they will be required for the functioning of the obtained combination.

**Table 3.3. Quality criteria for application of reclaimed water in various reuses**

S.N.	Desired Reuse	Source	COD (mg/l)	BOD (mg/l)	TSS (mg/l)	TN (mg/l)	FC (MPN/l)
1	Toilet Flushing (TF)	(Lyu et al., 2016)	-	10	10	10	200
2	Construction (C)	(Chen et al., 2017)	-	15	10	20	200
3	Road Cleaning (RC)	(Chen et al., 2017)	-	15	10	10	200
4	Landscape (L)	(Adewumi and Oguntuase, 2016)	-	20	10	20	2000
5	Industrial Cooling (IC)	(Lyu et al., 2016; Chen et al., 2017)	30	10	10	10	2000
6	Irrigation (I)	(Chen et al., 2017)	100	40	10	-	20000
7	Vehicle Washing (VW)	(Lyu et al., 2016; Chen et al., 2017)	-	10	20	10	2000
8							
	a. Inland Surface Water		250	30	100	100	10000

	b. Surface waters as a source of drinking water	(CPHEEO, 2013)	-	10	10	10	2300
9	Fire Protection (F)	(Lyu et al., 2016)	-	15	10	10	200
10	Laundry Washing (LW)	(Adewumi and Oguntuase, 2016)	-	10	10	-	250
11	Dust Control (DC)	(Lyu et al., 2016)	-	15	10	20	200
12	Snow Making (SM)	(State of California, 1994)	-	15	10	10	22
13	Outdoor Bathing (OB)	(BIS, 1992)	-	3	10	10	5000
14	Groundwater Recharge (GR)	(Adewumi and Oguntuase, 2016)	10	5		1	1

**Table 3.4. Performance Efficiencies of WWTs**

S. N.	Technology	Source/Reference	Removal (%)				
			BOD	COD	TSS	TN	FC
<b>Secondary Treatment Technologies</b>							
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)	82.19	90.00	85.15	10.00	90.00
8.	MBR	(Ajmi et al., 2018)	97.60	96.50	95.00	60.00	99.99
9.	Anaerobic lagoon + Stabilization Pond (AL+SP)	(CPCB, 2013)	70.00	51.33	70.00	10.00	90.00
10.	SAFF	(Tare and Bose,	96.67	87.50	76.40	10.00	99.99

11.	BIOFOR-F	2009)	97.00	95.40	92.00	70.00	99.99
13.	BIOFOR	(Tare and Bose, 2009; Sharma and Singh, 2013)	95.20	93.40	90.00	70.00	99.99
14.	Oxidation Pond (OP)	(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
<b>Emerging Technologies</b>							
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
<b>Tertiary Treatment Technologies</b>							
23.	Coagulation+ Flocculation+ Rapid Sand Filters (C+F+RSF)	(Hamoda et al., 2004)	65.00	53.34	52.14	30.00	80.00
24.	Ultra-filtration (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

**Table 3.5. Land, energy, capital and O&M costs WWTs**

S.N.	Technology	Source	Land (ha/ MLD)	Energy (KWh/ ML)	CC (Cr Rs/MLD)	O&M Cost (Cr Rs/MLD)	Avg. Annual Inflation <sup>#</sup> (%)	Projected Capital Cost (2021) (Cr Rs/ MLD)	Projected O&M Cost (2021) (Cr Rs/year/ MLD)
<b>Secondary Treatment Technologies</b>									
1	ASP	(Tare and Bose, 2009; GRBMP, 2010)	0.200	202.5	1.08	0.12	6.02	2.05	0.24
2	MBBR		0.055	220.0	1.08	0.13	6.02	2.05	0.24
3	SBR		0.055	150.0	1.15	0.09	6.02	2.20	0.17
4	WSP		0.610	2.0	0.63	0.10	6.02	1.20	0.19
5	UASB		0.110	120.0	1.08	0.12	6.02	2.05	0.23
6	DPS		4.000	2.0	0.30	0.02	6.02	0.57	0.04
7	MBR		0.045	300.0	3.00	0.05	6.02	5.70	0.10
8	A2O	(Park and Dho, 2018)	0.060	170.0	1.00	0.10	6.02	1.90	0.19
9	AL+SP	(Tare and	0.335	18.0	0.25	0.03	6.02	0.47	0.07

10	SAFF	Bose,	0.050	390.0	0.70	0.12	6.02	1.32	0.22
11	BIOFOR	2009;	0.040	277.5	0.73	0.09	6.02	1.38	0.35
12	BIOFOR-F	GRBMP,	0.080	180.0	0.52	0.02	6.02	1.00	0.03
14	C.Tech	2010)	0.150	175.0	1.10	0.01	6.02	1.10	0.27
15	Trickling Filter		0.500	180.0	0.45	0.05	6.02	0.45	0.09
16	Oxidation Pond	(CPCB, 2013)	0.150	2.0	0.25	0.02	5.11	0.37	0.04
17	CW	(Ramachan dra et al., 2017)	0.315	4.0	0.50	0.05	4.51	0.58	0.06
18	SBT	(Stefan et al., 2017)	0.030	121.0	2.00	0.02	4.51	2.34	0.02
<b>Emerging Technologies</b>									
19	MLE	(USEPA,	0.040	120.0	1.20	0.06	6.85	2.71	0.13

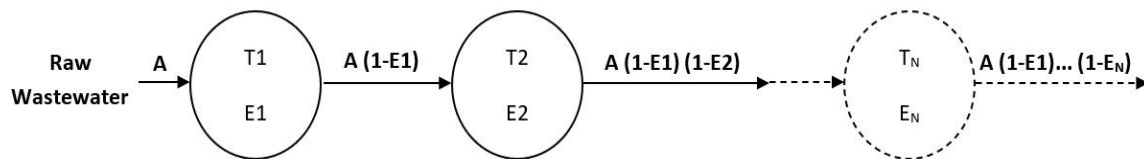
20	Step-Feed BNR	2013)	0.040	135.0	1.70	0.02	6.85	3.84	0.04
21	Bardenpho		0.090	150.0	2.80	0.02	6.85	6.32	0.04
22	WP		0.040	120.0	1.40	0.06	6.85	3.16	0.14
<b>Tertiary Treatment Technologies</b>									
23	C+F+RSF	(Hamoda et al., 2004)	0.100	140.0	0.50	0.05	6.83	1.20	0.12
24	UF + RO	(Pizzichini and Russo, 2001)	0.050	180.0	2.00	0.06	6.21	6.41	0.20
25	MF + RO		0.080	150.0	1.80	0.06	6.21	5.77	0.20

\*1 United States Dollar (1 USD) = 73.44 Indian Rupees (2021), # Source: IMF 2021

### 3.4 Framework for Selection of Appropriate Wastewater Treatment Technologies (WWTTs)

#### 3.4.1 Prediction of Final Effluent Quality in a Chain of Treatment Processes

The procedure for obtaining contaminant concentration in the effluent obtained after passing through a treatment technology train is as shown in Figure 3.3. The removal efficiency of one technology compounds with that of the other technology to obtain the effective contaminant concentration in the treated effluent (Metcalf et al., 1991).



\*A: Initial contaminant concentration; T<sub>1</sub>, T<sub>2</sub>....T<sub>N</sub>: Treatment Process; E<sub>1</sub>, E<sub>2</sub>....E<sub>N</sub>: Efficiency of respected treatment process.

**Fig. 3.3. Estimation of effective contaminant concentration in a train of treatment processes**

#### 3.4.2 Finalization of Decision Criteria for Selection of Appropriate WWTTs

Out of the 12 key factors identified in this study, factors relevant to the selection of WWTTs were further identified. The identification was done by analysing the direct technical and economic role of factor for selection of technologies.

#### 3.4.3 Weightage Calculation for Decision Criteria using Full Consistency Method (FUCOM)

FUCOM (Pamucar 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 pair-wise comparisons, that is,  $n-1$  ( $n$ = number of criteria), whereas AHP requires  $(n(n-1)/2)$  and BWM requires  $2n-3$  pairwise-comparisons (Stevic et al., 2020).

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.

$$C_1 > C_2 > C_3 > \dots > C_n$$

(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 to 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 to 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:

(i) Ratio of weights should be equal to comparative priorities of respective criteria.

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

(ii) 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:

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

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

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

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

### 3.4.4 Sensitivity Analysis for Weightage of Decision Criteria

The appropriate selection of WWTTs depends very much on the importance weightages provided by the user and it is reasonable to assume that some percentage of error may be present in the assumptions made by the user (Saisana and Saltelli, 2008). Hence, sensitivity analysis was done to investigate how the output factor will vary with change in input weightages applied on the chosen decision criteria (Pianosi et al., 2016).

### 3.4.5 Least Weighted Cost for WWTTs using 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:

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

$W_j$ = 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.

The 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.

#### **3.4.6 Ranking of WWTTs**

Eighteen technologies for secondary treatment, four emerging technologies and three combinations for tertiary treatment 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. Examples of the combinations of technologies are illustrated in Table 3.6.

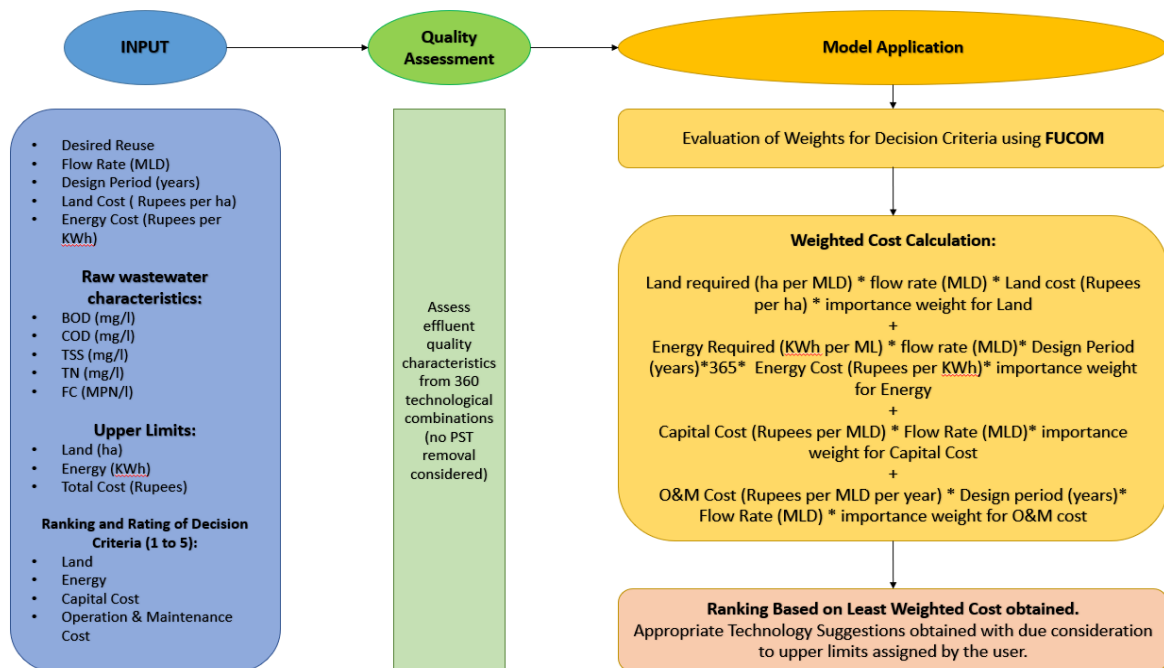
Similarly, for upgradation and supplementation scenarios, same combinations were run through to identify the most appropriate treatment technologies. Therefore, for new installation, a total of 360 combinations are checked for application and for existing technology case, again 360 combinations are checked in addition to the existing technology's performance and resource characteristics.

**Table 3.6. Examples of wastewater treatment technology combinations**

<b>Technology Combinations (Total No. 360)</b>	
Base Technology (18)	
Base Technology + Emerging Technology (18 x 4)	
Base Technology + Tertiary Technology (18 x 3)	
Base Technology + Emerging Technology + Tertiary Technology (18 x 4 x 3)	
<b>ASP and its combinations</b>	
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	

As shown in Table 3.6., 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 Figure 3.4.



**Fig. 3.4. Flow-chart representing procedure for ranking of WWTs based on least weighted cost**

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 weightages to obtain final weighted costs. The resulting technological combinations are further sorted out 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 the least weighted cost.

### 3.5 Demand Estimation for Reclaimed Water

The demand for reclaimed water in a city is the most crucial factor for setting up a treatment facility targeted for different reuse purposes. It was identified as one of the driving factors in the previous section. For demand calculation, formulas for respective reuse purposes were developed for evaluations in the immediate vicinity of STP. The formulas for different reuse purposes are shown in Table 3.7.

**Table 3.7. Formula for reclaimed water demand estimation**

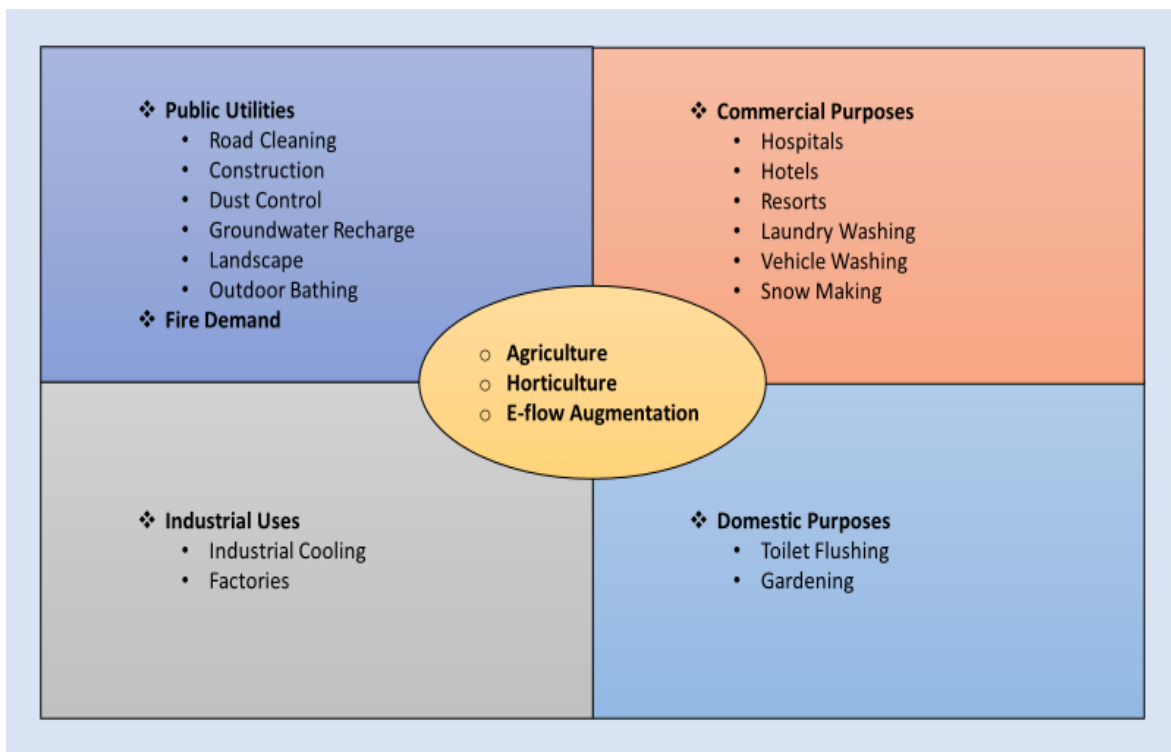
S.N.	Reuse Purpose	Equation for Demand (l)	Parameters
1	Industrial Cooling (IC)	$D = N * W * C$	N= Number of Industries; C=Capacity (MW); W= Water requirement per Industry per month (Avg. requirement= 3.5 cu m per h per MW) (MoEF, 2019)
2	Dust Control (DC)	$D = A * W$	A= Area in sq. m; W= Water required per area of dust control (Assumed, 4 liters per sq m)
3	Fire Protection (F)	$D = 100 * \text{sqrt}(P)$	P= Population of city in thousands (CPHEEO, 2013)
4	Toilet Flushing (TF)	$D = DD * P * W$	DD= Domestic water supply in lpcd; P= Population; W= Toilet flushing percentage (IS Code 1172:1993)
5	Rail Washing (RW)	$D = WG * T * p +$	WG= Water per carriage per day for BG/MG; T= number of trains

		$WC * P * ST * p +$ $P * A * WP * p +$ $NP * WD * u$	terminating/originating; p= probability of washing; WC=Water for cleaning carriage at platform; P= number of platforms; ST= number of stopping trains; A= average area of platform/apron; WP= water required for platform and apron; NP= Number of passengers; WD=average water demand; u= probability of use (IRWM, 2005)
6	Vehicle Washing (VW)	$D = N * T * W$	N = Number of vehicles; T= Type of vehicle; W = Average Water requirement per vehicle (Monney, et al., 2020)
7	Construction (C)	$D = N * W$	N = Number of construction sites; W = Average Water requirement per site
8	Laundry Washing (LW)	$D = N * W * n$	N = Total Number of Dhobi-ghats; W= Average water required for each laundry; C= Average Number of Clothes per day
9	Road Cleaning (RC)	$D = L * B * W * P$	L= Length of road; B= Width of road; W= Average water required per area; P= Probability of washing
10	E-flow Augmentation (EF)	$D = N * Q * 0.3$	Q = Avg. Drain capacity (Assuming 30% excess); N = Number of drain for augmentation
11	Hotels	$D = N * P * A$	N= Number of hotels; P= Number of people in hotel; A= Allocation per head as per IS code (IS 1172:1993)

12	Hospitals	$D = N * B * A$	N= Number of hospital; B= Number of beds; A= Allocation per head as per IS code (IS 1172:1993)
13	Resorts	$D = N * P * A + S * F + G * W$	N= Number of resorts; P= Number of people; A= Allocation per head as per IS code; S= Swimming pool volume; F=frequency of water change; G=gardening area; W= water per garden area
14	Landscape (L)	$D = A * W$	A= Area in sq. m; W= Water required per area
15	Groundwater Recharge (GR)	$D = V * (1 + L\%)$	V= Volume of aquifer; L= Loss factor (%)
16	Outdoor Bathing (OB)	$D = N * W$	N = Number of people; W = Average Water requirement per person
17	Factories	$D = N * W * A$ or $D = P * C$	N= Number of factories; W= water required per activity; A= Number of activities; P= Number of people; C=Allocation as per IS code
18	Gardening/ Agriculture/Horticulture (H)	$D = A * W$	A= Total area; W= Water required based on plant/ crops

### 3.6 Competitive Uses and Procedure for Demand Allocation and Pricing

Due to the nature of growing economies, competitive uses of water have emerged leading to significant increase in water demand. In a country like India, which is largely a socialist economy, the demand allocation should be done using a socio-economic approach, in which the social priorities of the region are satisfied before obtaining the related economic benefits. To address the socio-economic requirements, in this study, the demands are further classified into five categories based on the end-use of water. This is done to levy appropriate costing as well as prioritize users based on their social conditions. The categorization of the demand is as shown in Figure 3.5.

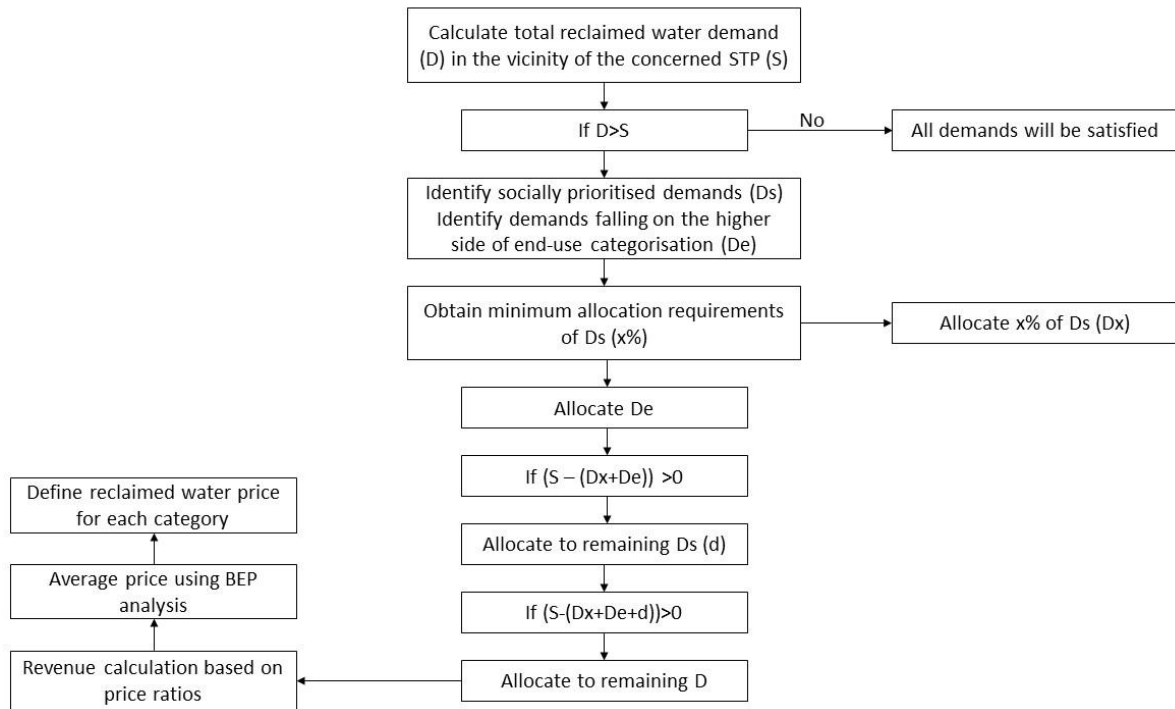


**Fig. 3.5. Categorization of reuse purposes based on end-user income group**

The demand allocation will be primarily done in two rounds, in first round, the water allocation for the prioritized end-users will be done and in the second round, after the demand satisfaction of prioritized sections, water will be allocated to those end-users from whom

larger revenue will be earned.

The methodology for demand allocation is as shown in Figure 3.6.



**Fig. 3.6. Flowchart representing demand allocation methodology**

This methodology suggests localized demand allocation. The first step in this process is the selection of STP in the vicinity of which the demands are to be satisfied. The capacity of STP is to be entered into the DSS\_IWWM. It is followed by the identification and estimation of water demands. The DSS facilitates entering multiple water demands. The water demands are already classified into different categories based on end-users to include the paying capacity of the end-users. The DSS itself classifies the demands. The agriculture and public utilities demand are considered socially prioritized in this study. A minimum allocation percentage is asked from the user to decide how much minimum percentage of imposed demand is mandatory to be satisfied. After satisfaction of minimum socially prioritized demand, the demand for high-income end-users is allocated so that the revenue stream from

the allocation is assured. After the satisfaction of demand of high revenue generating end-users, the methodology goes back to satisfaction of rest of the demand which is distributed equally among all prioritized and non-prioritized categories.

This concept of demand allocation is very much dependent on the proportional pricing approach, that is, imposing per unit price of water per volumetric consumption. However, this method is different from the usual pricing approach in the sense that the average cost of water to be recovered from the total allocation of water is proportionately divided into the different categories. The method for arriving at per unit prices for all the categories is discussed below.

Firstly, a variable cost ratio as per the discretion of the user is assigned to the different categories based on how much burden of cost is to be levied on each category. As an example, we may assume a certain water price to be levied for agriculture and public utilities categories, and then proportionately thrice higher price for domestic demand, five times higher for industrial and seven times higher for commercial demands respectively. This gives a unit price per volumetric consumption basis in the ratio of 1:1:3:5:7 for agriculture/horticulture/e-flow augmentation, public utilities/fire demand, domestic purposes, industrial purposes, and commercial purposes respectively.

The average cost to be recovered from the total allocation is obtained using the break-even point (BEP) analysis. It is on the user to decide the break-even point number of years. Therefore, this method of pricing will facilitate cost recovery as well as reduce the burden of payment from prioritized end-users.

Based on BEP analysis, the minimum feasible average price is chosen for per unit of reclaimed water, as per the target year by which the total cost is to be recovered.

$$\text{Cumulative Recovery} = \sum(\text{Annual Revenue} - \text{Annual O\&M Cost})$$

$$\text{Annual Revenue} = \text{Units per day} * 365 * \text{Price per unit}$$

$$\text{Annual O\&M Cost (n}^{\text{th}} \text{ year)} = \frac{\text{Initial O\&M Cost} * (1 + \text{Inflation Rate})^{(n-1)}}{\text{Design Period}}$$

$$\text{BEP achieved when, } \frac{\text{Total Capital Cost}}{\text{Cumulative Recovery}} = 1$$

The assumptions for calculating the minimum feasible average price are:

- It assumes annual O&M cost inflates at 5% every year.
- There is no change in the capacity of the plant at the beginning or at the end of the period.
- The price of reclaimed water is assumed to be constant over design life (due to low inflation rate).

The benefits of imposing a proportionate pricing structure based on type of end user and volumetric consumption is that the burden of payment from low-income groups will be alleviated and the wasteful use of water will be reduced, domestic consumption will be metered with proportionate and reasonable pricing. Higher cost will be imposed on high profit generating sectors, so that the cost recovery is ensured, and private players will be more interested in becoming a stakeholder.

### **3.7 DSS for IWWM (DSS\_IWWM)**

The study is conducted to develop a Decision Support System for selection of an appropriate treatment technology for integrated water and wastewater management. The application is named DSS\_IWWM in this study. The development of the application was done using Streamlit and written in Python. Streamlit is an open-source web application framework.

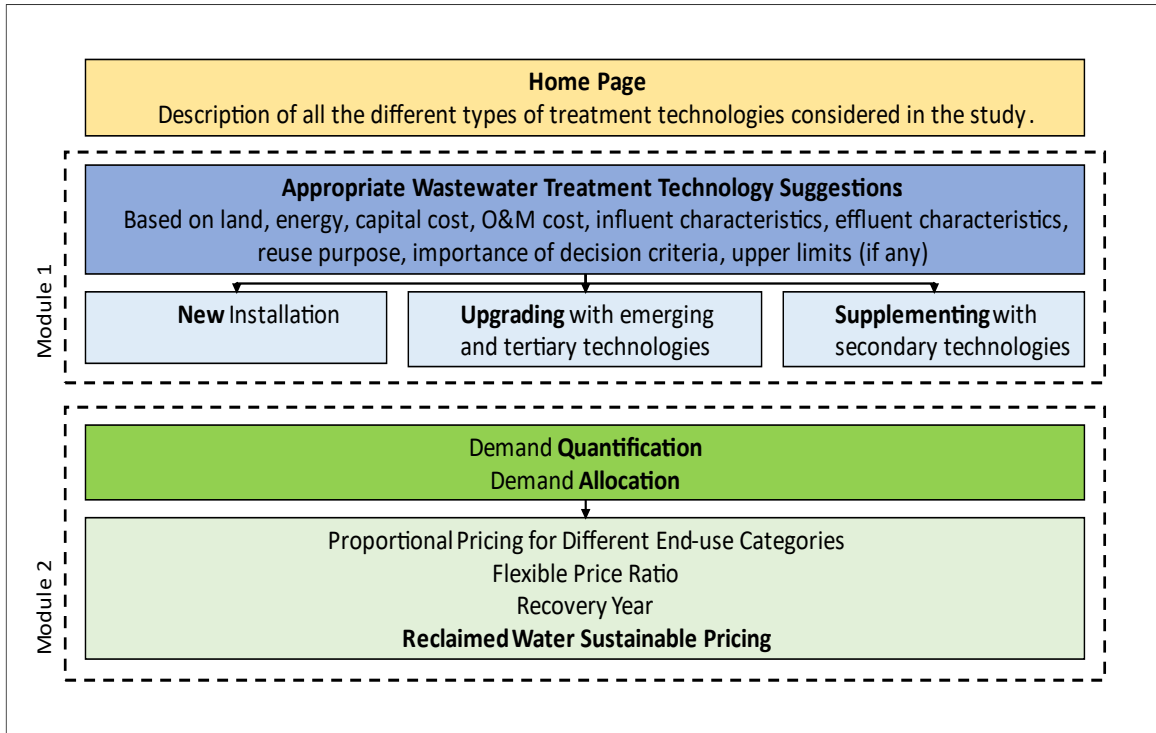
The DSS\_IWWM is hosted on GitHub which is a web hosting service.

The DSS\_IWWM is developed to facilitate appropriate treatment technology selection based on target reuse purpose and local conditions, such as the raw wastewater characteristics, the target reuse quality criteria, the land cost, electricity cost, capital cost, O&M cost, and the importance of each criterion. The DSS\_IWWM consists of a library of treatment technologies along with their treatment efficiencies and resource requirements and a list of reuse purposes and quality criteria associated with each. It provides the user the choice to select one or multiple reuses out of all the reuse purposes. The DSS\_IWWM can suggest technology for a new installation and even for upgrading or supplementing an existing STP.

The DSS\_IWWM gives an array of reuse purposes and requests for water demand for each of the selected reuse purposes. Based on the social prioritization of the end-users, DSS\_IWWM suggests a suitable demand allocation pattern that will address needs of prioritized end-users and suggest sustainable water costs to be imposed on each category. It gives the user the flexibility to select different average costs for cost recovery and to change the price ratio for different categories of end-users. The DSS\_IWWM will be very useful for policymakers, engineers, companies, and government for putting in place an efficient STP which safely provides the water for target reuse purpose and even tells how the water should be distributed in the community and what prices should be imposed.

The DSS\_IWWM consists of two modules. The first module is for appropriate treatment technology selection and the second module is for demand allocation and sustainable pricing.

The structure of the DSS\_IWWM is as shown in the following Figure 3.7.



**Fig. 3.7. The structure of the DSS\_IWWM**

### 3.7.1 Working Principle of DSS\_IWWM Application

A web-based Decision Support System (DSS\_IWWM) for selection of an appropriate treatment technology for integrated water and wastewater management is presented in this chapter. The application was designed using python language in streamlit which is an open-source app framework. It is hosted on GitHub which is a cloud-based hosting service provider. Python language is simple and transparent. It is reliable and suitable to be used in the back-end development of the application (Shukla et al., 2021). Streamlit provides an environment framework for app development. It is easier to deploy codes written in Streamlit

(Khorasani et al., 2022). Git refers to a **distributed version control system** that enables availability of the whole code set on computers of all developers (Munaiah et al., 2017). GitHub is a cloud-based service for hosting Git so that it becomes easy for developers to manage Git for their applications.

The DSS\_IWWM can be accessed by creating an account on GitHub and using the url [https://github.com/maxDeCoder/water\\_reclamation](https://github.com/maxDeCoder/water_reclamation). The user will have to login to the account and request for access to the code by the developers and then use the application, after the approval of request.

On the home page (Figure 3.8), a brief description of all the types of treatment technologies considered in the study is provided as shown in Figure 3.9.



**Fig. 3.8. Home page of DSS\_IWWM**

### Secondary Treatment Technologies

These sewage treatment technologies depend on biological processes for the decomposition of suspended and dissolved organic matter present in wastewater. They employ cultured micro-organisms to decompose organic matter and aid reproduction. Therefore, more populations of microbes become available for carrying out the biological decomposition of organic matter and obtaining treated wastewater. The oxygen required by microorganisms to carry out this process is referred to as Biochemical Oxygen Demand (BOD). These treatment processes can take place in the presence or absence of oxygen, known as, aerobic decomposition and anaerobic decomposition respectively. The associated microorganisms are also categorized as aerobic and anaerobic bacteria respectively. The aerobic process is suitable for the treatment of low strength wastewater (bCOD<1000mg/l) while the anaerobic process is considered suitable for high strength wastewater (bCOD>4000 mg/l). Various treatment technologies considered in this tool, are discussed in this section.

Activated Sludge Process (ASP) +

Sequencing Batch Reactor (SBR) -

SBR technology is a modified version of ASP. SBR operates in batch mode and all the physical and biological processes take place in the same basin in a time-sequenced manner. This process takes place in four phases: filling, in which raw wastewater is filled in the basin in batch mode; reaction, in which, the air is supplied and mixed with the wastewater in the basin; settling, the solid and liquid phases are left to separate via settling, and; decanting, in which, the treated wastewater is drawn from the basin. A minimum of two basins are required for the operation of SBR, such that while one basin is in reaction phase, the other basin is in the settling phase and decanting. The process has higher efficiency due to better sludge settling characteristics.

**Fig. 3.9. Description of technologies provided on home page of DSS\_IWWM**

### 3.7.2 Basic Data Requirements

The DSS\_IWWM contains a library of data related to performance efficiency, land, energy, capital cost and O&M cost of the WWTs considered in this study. It also comprises of a list of 14 potential reuse purposes and associated quality criteria that must be strictly satisfied. The user needs to enter the raw wastewater characteristics for the city he wants to run the DSS for. The quality parameters of wastewater for BOD, COD, TSS, TN and FC are required to be fed into the DSS. A link to the CPCB site is provided for abstraction of input characteristics by the user in case of non-availability of primary data. The user needs to enter his priority for four decision criteria: land, energy, capital cost and O&M cost on a scale of 1 to 4 with unique value assigned against each decision criteria. The DSS\_IWWM itself calculates the weightages based on user's ratings. To help the user calculate the reclaimed water demand for reuse purposes, formulae are provided in the DSS to help user approximate the value. The links to the latest government guidelines for demand approximation are also provided in the section. The DSS\_IWWM enables an integrated water and wastewater

management in the city by suggesting appropriate treatment technologies, by localizing the STP planning and demand estimation and allocation and also by setting up a pricing mechanism so that a judicious costing is applied. In the next chapter, the developed DSS is applied on different cities.

The inputs required to be entered into the DSS\_IWWM are tabulated in Table 3.8. These inputs can be found in CPCB (2013) for Indian cities.

**Table 3.8. Inputs required for DSS\_IWWM**

<b>DSS_IWWM</b>	
<b>First Module</b>	<b>Second Module</b>
<b>Appropriate WWTTs Selection</b>	<b>Reclaimed Water Demand Allocation and Pricing</b>
1. Raw wastewater characteristics: BOD (mg/l), COD (mg/l), TSS (mg/l), TN (mg/l), FC (MPN/l)	1. Number of reuses
2. Decision Criteria Weightage (1 indicating highest priority to 4 indicating lowest priority): Land, Energy, Capital Cost and O&M Cost	2. Demand for each reuse (MLD)
3. STP Capacity (MLD)	3. Select Technology: Select suitable WWTTs from the dropdown for calculations.
4. Land Upper Limit (ha)	4. Price ratio for categories: Agriculture, Public Utilities, Domestic Demand, Industrial Demand and Commercial Demand
5. Power Upper Limit (kWh/day)	5. Minimum Allocation for Prioritised Uses (%)
6. Land Cost (Rs.)	6. STP Capacity (MLD)
7. Electricity Cost (Rs. Per kWh)	7. Average Cost (Rs per kl)
8. Target Reuse Purpose(s)	8. Inflation rate (%)
9. Existing Technology (if any)	

The input pages in DSS\_IWWM are as shown in Figure. 3.10 – 3.12

**Fig. 3.10. The input page for Module 1 of DSS\_IWWM**

**Fig. 3.11. Input page showing selection of multiple reuse purposes in Module 1 of**

**DSS\_IWWM**

### Reclaimed Water Demand Allocation & Pricing

**Technology Selection**

Select technology

SBR + MLE v

**Price ratio for categories**

Public Utility

1 - +

Agriculture

1 - +

Domestic

3 - +

Industrial

5 - +

Commercial

## Reclaimed Water Demand Allocation & Pricing

Number of Reuse

4 - +

Reuse Purpose	Demand (MLD)
Road Cleaning <span style="float: right;">v</span>	8 <span style="float: right;">- +</span>
Reuse Purpose	Demand (MLD)
Vehicle Washing <span style="float: right;">v</span>	9 <span style="float: right;">- +</span>
Reuse Purpose	Demand (MLD)
Factories <span style="float: right;">v</span>	10 <span style="float: right;">- +</span>
Reuse Purpose	Demand (MLD)
Resorts <span style="float: right;">v</span>	44 <span style="float: right;">- +</span>

**Total demand: 71 MLD**

**Fig. 3.12. The input page for Module 2 of DSS\_IWWM**

### 3.7.3 Output of DSS\_IWWM

The DSS\_IWWM suggests the appropriate WWTs for three cases, i. new installation, ii. Upgradation of existing technology, and iii. Supplementation of existing technology. The suggested technologies are ranked based on the weighted costs obtained by each technology combination. For each technology suggestion, DSS\_IWWM defines the total land requirement, energy requirement, capital coat and O&M cost requirements as shown in Figure 3.13 – 3.17.

#### STP Parameters

STP capacity(MLD)

30 - +

Land upper limit(ha)

8 - +

Power upper limit(KWh)/day

70000 - +

**Costs**

Land Cost (Rupees per Ha)

1700000 - +

Electricity cost (Rupees per kWh)

7 - +

Is there an already installed STP?

**Available options:**

1 - BIOFOR-F + WUHERMAN -

show in plot and save for next step

	Secondary Tech	Emerging Tech	Tertiary Tech	Total Weighted Cost (cr Rs)	Land (ha)	Power (KWh)	Capital Cost
0	BIOFOR-F	WUHERMAN	None	159,060,299.9000	3.6000	9,000.0000	

2 - SBT + WUHERMAN + Coagulation&Flocculation&RSF -

show in plot and save for next step

	Secondary Tech	Emerging Tech	Tertiary Tech	Total Weighted Cost (cr Rs)	Land (ha)	Power (KWh)
0	SBT	WUHERMAN	Coagulation&Flocculation&RSF	183,722,001.0000	5.1000	11,430.

**Fig. 3.13. Output page for new installation appropriate WWTs suggestions (Module 1)**

**STP Parameters**

STP capacity(MLD)  
30 - +

Land upper limit(ha)  
8 - +

Power upper limit(KWh)/day  
70000 - +

**Costs**

Land Cost (Rupees per Ha)  
1700000 - +

Electricity cost (Rupees per kWh)  
7 - +

Is there an already installed STP?

Select your technology  
ASP

Since you have opted for an upgrade, the land and power upper limit will not be considered

**Upgrade options:**

1 - ASP + WUHERMAN + mf&ro +

2 - ASP + WUHERMAN + uf&ro +

**Supplementing with secondary technologies:**

1 - SBT + WUHERMAN +

**Fig. 3.14. Output page showing appropriate WWTs for upgradation/supplementation case (Module 1)**

**Technology Selection**

Select technology  
SBR + WUHERMAN

**Price ratio for categories**

Public Utility  
1 - +

Agriculture  
1 - +

Domestic  
3 - +

Industrial  
5 - +

**Total Demand: 38 MLD**

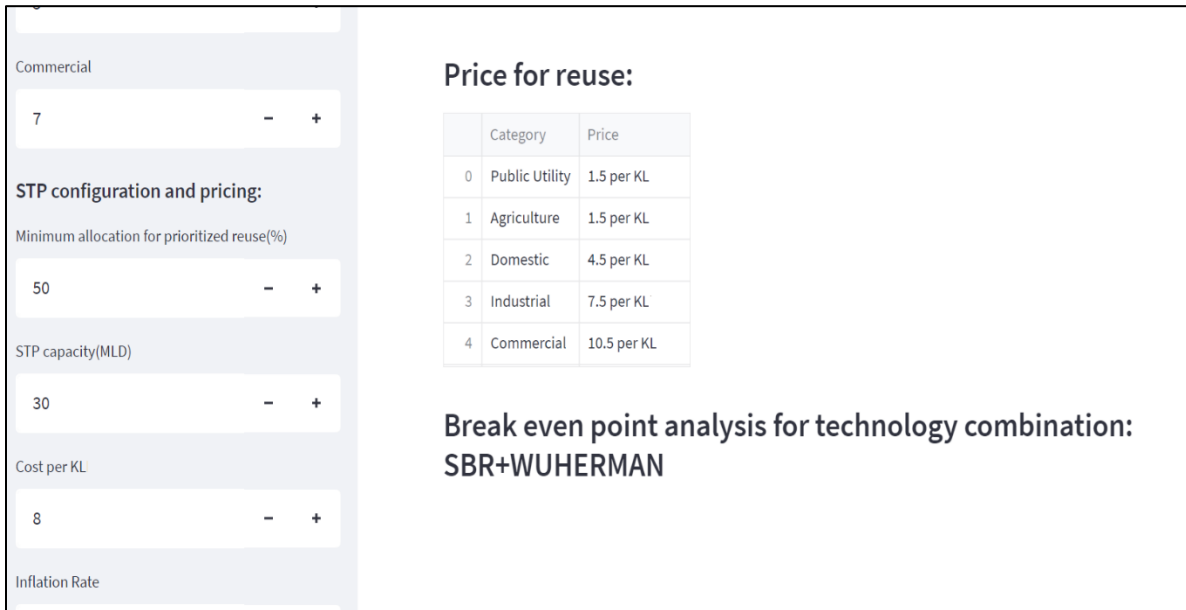
The total demand is greater than the STP capacity

	Capital Cost	O&M Cost/year
56	61.2900	2.7600

**Reclaimed Water Demand Allocation**

	Reuse	Category	Dem	Final Allocation	Revenue Factor
0	Horticulture	Agriculture	5	2.5000	2.5000
1	Road Cleaning	Public Utility	3	1.5000	1.5000
2	Toilet Flushing	Domestic	8	4.0000	12.0000
3	Factories	Industrial	5	5.0000	25.0000
4	Resorts	Commercial	17	17.0000	119.0000

**Fig. 3.15. Output page for final demand allocated (Module 2)**



**Fig. 3.16. Output page for water prices (Module 2)**



**Fig. 3.17. Output page showing breakeven analysis for average cost assumed (Module 2)**