water

Supplementary Materials

Development and Application of a Multi-Objective-Optimization and Multi-Criteria-Based Decision Support Tool for Selecting Optimal Water Treatment Technologies in India

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S1. Database on Drinking Water Treatment Technology Selection Tool

There are two classes of technologies within this database: i. Water treatment unit processes (large/medium scale) and ii. Packaged drinking water purification systems (small scale). Both classes are evaluated against similar criteria and indicators. Each technology or unit process occupies one worksheet, which is divided into eight sections. Each section provides a range of information which is used in the process of technology selection and decision making.

S1.1. Section 1: Technology description

This section gives an overview of each unit process/package (see Figure S1). This starts with the name of technology, treatment capacity, and lifespan. There are some other questions, e.g., level of treatment and source of influent which can be purified by this particular technology; this information can be used for narrowing down the decision. At the end of this section, a list of the published literature, brochures, images, and technical reports on the technology is provided.

1. TECHNOLOGY DESCRIPTION		
		Comments
Name of technology	APEC Light Commercial Reverse Osmosis Water Systems (RO-LITE-360 with UV)	
Total volume of treated water the technology can produce (m^3 per day)?	1.36	
Technology lifespan (years)?	2 (1 ≤ x < 5 years)	
Which sources of water can be treated with this technology?	All	
Does the technology need post-treatment? If so, please indicate here	No	
Does the technology address physical contamination?	Yes	
Does the technology address chemical contamination?	Yes	
Does the technology address biological contamination?	Yes	
Is the technology suitable for rural/urban areas?	Both	
Does it require frequent monitoring?	No	
Is there any published literature, brochures, images, technical reports available?	Yes	
If so, please provide sources	http://www.freedrinkingwater.com/light-commercial-detail.htm	

1st Stage
High-Grade 5 micron 20" high-capacity polypropylene sediment filter—removes dust, particles, and rust. (US Made) More Info
2nd Stage
Premium Extruded Carbon Block 5 micron 20"—removes chlorine, odour, organic contaminants, pesticides, and cysts. (US Made) More Info
3rd Stage
Premium Extruded Carbon Block 5 micron 20"—removes residual chlorine and VOC, extends membrane life. (US Made) More Info
4th Stage
Select Filmtec (Dow Chemical) High Rejection TFC Reverse Osmosis Membranes— Remove up to 99.9% of most chemicals, dissolved solids, metals, bacteria, and viruses. (US Made) More Info
5th Stage
Advanced Coconut Shell Refining TCR (Total Contamination Removal) Carbon 12"—removes any residual impurities and odours from the tank. (US Made)
Tank-14
Premium 14 gallon pressurized tank. More Info
RO System Components
Standard with system: Lead-Free, long reach faucet, Food Grade tubing, and Complete Installation Hardware which includes Wrench, feed water valve, drain saddle valve, teflon tape and instruction manuals.

Figure S1. Worksheet Section 1: Technology Description.

S1.2. Section 2: Technology installation

This section provides fundamental information on installation or construction of the technologies (see Figure S2). For instance, it is asked if the technology needs installation or construction, whether skilled workers are required, and how easy the technology can be installed or constructed. In addition, a question regarding land requirement is included in this section.

2. TECHNOLOGY INSTALLATION		
		Comments
Does the technology require construction/installation?	No	
Does its construction/installation require skilled labour?	No - end-user can install it	
Is the technology easy to install?	5 (Very easy)	
Indoor or outdoor installation?	Indoor	
How long does the installation/construction take (days)?	0	
How many hours of labour in total is required to install/construct?	0	
Area of land required to install the technology including storage tanks (m^2)?	0.25	

Additional information on technology installation:

Figure S2. Worksheet Section 2: Technology installation.

S1.3. Section 3: Technology Operation and Maintenance (O&M)

This section (Figure S3) may be considered as the most important section of the technology library, since the information provided here is associated with a range of indicators (e.g., O&M costs, energy consumption, degree of automation, and process maturity) influencing the final decision. To ease and speed up the process of completing the questions, drop-down lists are provided.

3. TECHNOLOGY OPERATION AND MAINTENANCE		
		Comments
Technical ability required to operate the technology (ease of operation)?	5 (No/low skilled personal necessary)	
Technical ability required to operate the technology (ease of maintenance)?	5 (No/low skilled personal necessary)	
Degree of automation	5 (Fully automated operation)	
Process maturity	Operational at target capacity	
Total amount of waste produced (kg per m3)?	- Non-toxic	
Does the technology need external power source?	Yes-please indicate in the comment box	Electrical/Solar
How much energy (net energy) is required to produce 1 m3 of treated water (kWh/m3)?	2 ($10 < x \leq 100$ kWh/m^3)	
Availability of spare parts and consumables	3 (Most key spare parts only available abroad)	
Additional information on technology operation:		

Figure S3. Worksheet Section 3: Technology Operation and Maintenance.

S1.4. Section 4: Maintenance Activities

This gives an overview of the activities that should be undertaken for maintaining a technology (Figure S4). In this section, maintenance activities (e.g., changing filters, desludging, and topping up chemicals) and the frequency of each activity are identified.

4. MAINTENANCE ACTIVITIES (please add rows for additional activities if required)			
Maintenance activity	Frequency of maintenance activity	Time required for activity (hours)	Annual cost of each activity (INRs)
Activity 1 (toping up disinfectant)			
Activity 2 (e.g. maintenance of pumps etc	Annually	1	[redacted]
Activity 3 (e.g. desludging)			
Activity 4 (e.g. changing filters)	Annually	1	6500
Activity 5			
Additional information on maintenance activities:			

Figure S4. Worksheet Section 4: Maintenance activities.

S1.5. Section 5: Chemical Requirement

This section provides a list of chemicals that must be used for operating and maintaining the technology (Figure S5). Similar to the previous section of the worksheet (Figure S4), in some cases and for some chemicals, no information on costs is available. In addition, the level of availability of chemicals (e.g., local, regional, or national) is identified; this helps identify how accessible the chemicals are in the area of interest.

5. CHEMICAL REQUIREMENT FOR OPERATION & MAINTENANCE			
Name of chemical and purpose	Quantity required (g/m3 of treated water)	Unit cost (Rps./kg)	On which level is it available?
Chemical 1 anti-scalant dosing	?	?	National
Chemical 2 lime stone re-mineralization (post-treatment)	e.g. trickling filter	lime 70 €/tn = 5 INR/kg	Local
Chemical 3 flocculant dosing e.g. FeCl3 (eventual pre-treatment)	2-5	250 €/tn = 18 INR/kg	Regional
Additional information on chemical requirements:			

Figure S5. Worksheet Section 5: Chemical Requirement for Operation and Maintenance.

S1.6. Section 6: Cost of Technology

This section provides total and annualized costs of technologies. In this table, both capital and O&M costs are broken into small elements; for example, for CAPEX, the costs of land, equipment, and construction/installation are included (Figure S6). Some parameters, such as land costs and labor costs, are scenario-based, which means that the questions will be asked in the user interface (tool) and will be answered by the end-user.

6. COST OF TECHNOLOGY	Total cost (Rps.)	Cost/m3 of tretaed water (Rps.) (life span consideration)	Comments
CAPEX	₹688,000	3 (10 < x ≤ 100 INR/m³)	1000 l/h operational 12h/d
Land (Not required here - but captured via user interface)			excluded
Equipment	INR 355000		included
Construction and Installation	[redacted]		included
OPERATIONS AND MAINTENANCE	₹0.047/L (≈$0.75/m3).	3 (10 < x ≤ 100 INR/m³)	1000 l/h operational 12h/d
Energy (Not required here - but captured via user interface)			included
Labour costs (Not required here - but captured via user interface)			included
Chemicals (total of Section 5)			included
Waste disposal			excluded
Maintenance activities (total of Section 4)			included
Additional information of technology cost:			

Figure S6. Worksheet Section 6: Chemical Requirement for Operation and Maintenance.

S1.7. Section 7: Social aspects

Social aspects (see Figure S8) and their indicators are mainly addressed in the user interface, due to the divergences between end-users in India due to differences in the styles and standards of living in different regions.

7. SOCIAL ASPECT		
Indicators	Rate	Comments
Technology affordability (Not required here - but captured via user interface)		
Social acceptance (Not required here - but captured via user interface)		
Willingness to pay (Not required here - but captured via user interface)		
Additional information on social aspects:		

Figure S7. Worksheet Section 7: Chemical Requirement for Operation and Maintenance.

S1.8. Section 8: Contaminant removal

This section provides information on the effectiveness and efficiency of each unit process or packaged technologies in the removal of different contaminants (Figure S8). If the effluent quality for a package does not meet the Indian standards for drinking water, the package cannot be listed for further evaluation.

More than 60 water quality parameters/contaminants are listed in this table; however, due to lack of data for many of the contaminants, we only included the following contaminates in the tool: i. Arsenic, ii. Faecal coliform, iii. Fluoride, iv. Iron, v. Lead, vi. Nitrate, vii. pH, viii. Total dissolved solids, and ix. Turbidity.

8. TECHNOLOGY PERFORMANCE (please fill in as much as possible for the relevant unit process)

Parameter	Unit	Influent quality this technology can treat:		Effluent quality	Removal performance (efficiency) (%)	Does the effluent quality meet the drinking water standards in India? (Not required here – but captured via user interface)	Comments
		Minimum	Maximum				
Treatment flow rate	m3/day						
Microbiological parameters							
Enterococci	no./100ml					Yes	
Escherichia coli	no./100ml					Yes	date available
Faecal coliform	**no./100ml**					**Yes**	**date available**
Coliform bacteria	no./100ml					Yes	date available
Clostridium perfringens	no./100ml					Yes	
Colony counts	no./100ml					Yes	
Cryptosporidium parvum	Avg no./101					Yes	date available
Physical parameters							
Colour	mg/l Pt/co					Yes	
Turbidity	**NTU**					**Yes**	
Taste (Dilution)	3 at 25 C					Yes	
Odour (Dilution)	3 at 25 C					Yes	
pH	**6.5–10.0**					**Yes**	
Conductivity	µS/cm					Yes	
Total dissolved solids	**mg/l**					**Yes**	
Hardness	**mg/l as $CaCo_3$**					**Yes**	
Chemical parameters							
Aluminium	µg/l					Yes	date available
Antimony	µg/l					Yes	
Arsenic	**µg/l**					**Yes**	**date available**
Boron	µg/l					Yes	date available
Cadmium	µg/l					Yes	date available
Chromium	µg/l					Yes	date available
Copper	µg/l					Yes	date available
Iron	**µg/l**					**Yes**	**date available**
Lead	**µg/l**					**Yes**	**date available**
Manganese	µg/l					Yes	date available
Mercury	µg/l					Yes	date available

Figure S8. Worksheet Section 8: Technology performance in terms of contaminant removal.

S2. Overview of the Main Forms in WETSUiT

WETSUiT is a multi-device application which can be run on any MS Windows, Android, and iOS devices. WETSUiT is designed in a way that suits any user with basic knowledge on decision making processes and/or computer science. The main tabs/pages on WETSUiT are described below:

S2.1. Welcome to WETSUiT

This tab (Figure S9) provides a brief introduction to the WETSUiT Tool and gives some information about the project Water4India funded by the European Commission under FP7 Programme (W4I 2016). On the lower right side of the tab, there is a button which takes the user to the next tab (WETSUiT user Information).

Figure S9. Main tabs on WETSUiT: Welcome to WETSUiT.

S2.2. User Information Tab

As can be seen in Figure S10, the user is asked to input their title, name, affiliation, and job title. The user also needs to answer a question regarding the interface; there are a number of message boxes, tips, and alerts which improve the user's experience in working with WETSUiT. By answering 'No' to the question "Would you like to use tips, alerts, and other help messages while using WETSUiT?", no help boxes, messages, or tips will be shown to the user.

The last question on this tab is on the user type, where the user will log in as either a "Standard user" or "Expert user". The standard user will be presented with information on the tabs that does not require them to be a water treatment expert. The expert user will be presented with extra options that allow additional control of the unit processes, evaluation criteria, and contaminant levels to be edited.

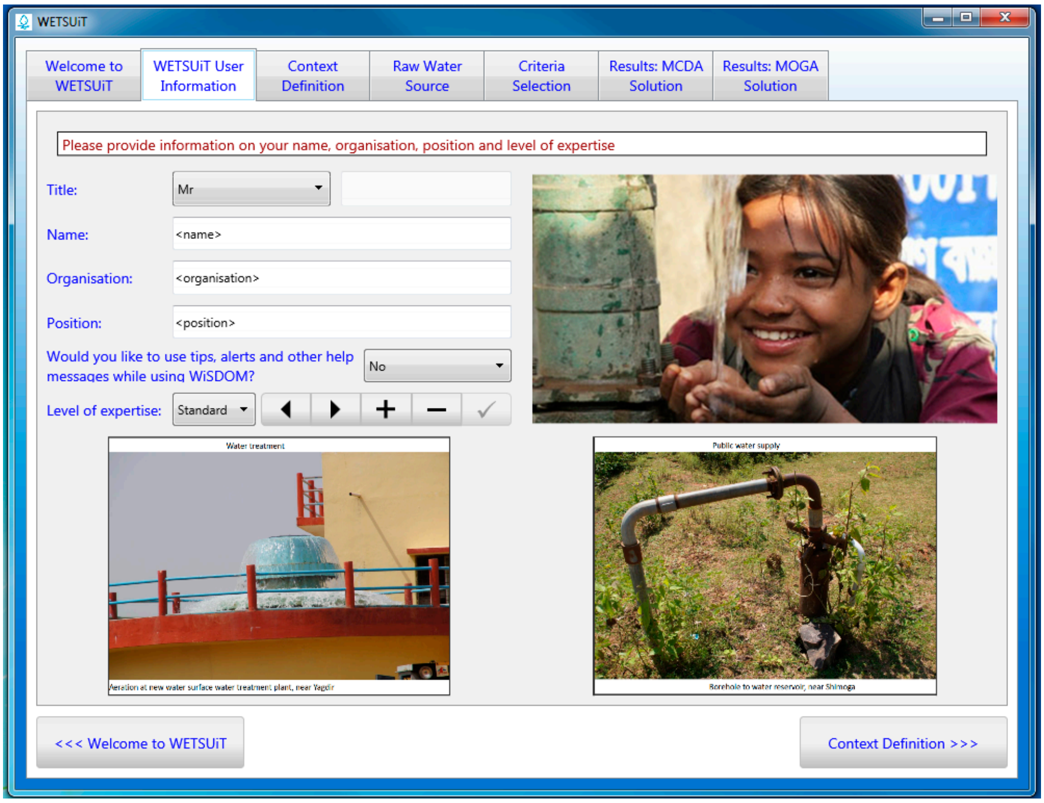


Figure S10. Main tabs on WETSUiT: User Information.

S2.3. Context Definition

This tab enables the users to define/create a new scenario. As illustrated in Figure S11, this tab asks the user to provide information regarding the geographical location of the case study, e.g., state/region and city/town. Population, per capita water consumption, land availability, leakage, and possible amount of investment are the other factors that should be input on this page. The user is also required to clarify the targeted type of solutions (full-scale, community, or household systems). The other focus of this tab is the operation and maintenance implications (e.g., O&M annual costs, electricity supply continuity, availability of spare parts, and technical availability for running and maintaining the systems in the area). The list of saved projects in WETSUiT is provided in "List of projects" at the bottom right-hand side of the tab.

There are a number of navigator tools in the different tabs of WETSUiT. Different buttons of the navigator tool are illustrated in Figure S12. Each button provides a different function.

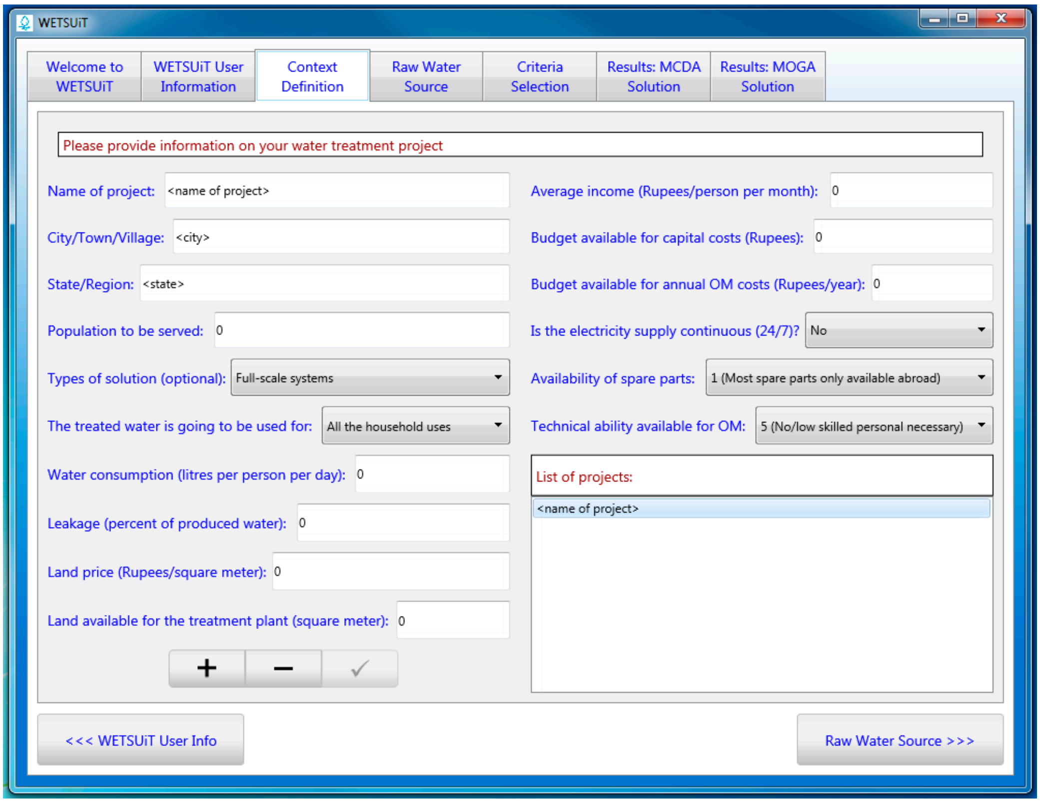
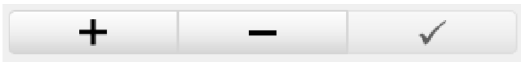


Figure S11. Main tabs on WETSUiT: Context Definition.



(a) (b) (c)

Figure S12. Navigator tool on WETSUiT. Button (**a**): create a new record, (**b**): delete/remove a record and (**c**): save changes.

S2.4. Raw Water Source

On this tab, the user is required to input information on available raw water sources. As can be seen in Figure S13, the first question is on the type of water source (namely: river water, groundwater, or tap water (for household packages only)). It is noteworthy that in each project (created in the context definition tab), several water sources can be defined. However, only one water source will be considered for evaluation and optimization at a time. This tab allows the user to provide all the information on the raw water source required to perform calculations in WETSUiT, including the maximum, minimum, and average (concentration) values on different contaminants and water quality parameters. On the right-hand side of the tab (Figure S13), a table (i.e., grid) is presented that shows the pollutant data to be considered in the evaluation process. This table includes some default values for pollutant concentrations. The table at the bottom of the tab presents the Indian standards on drinking water.

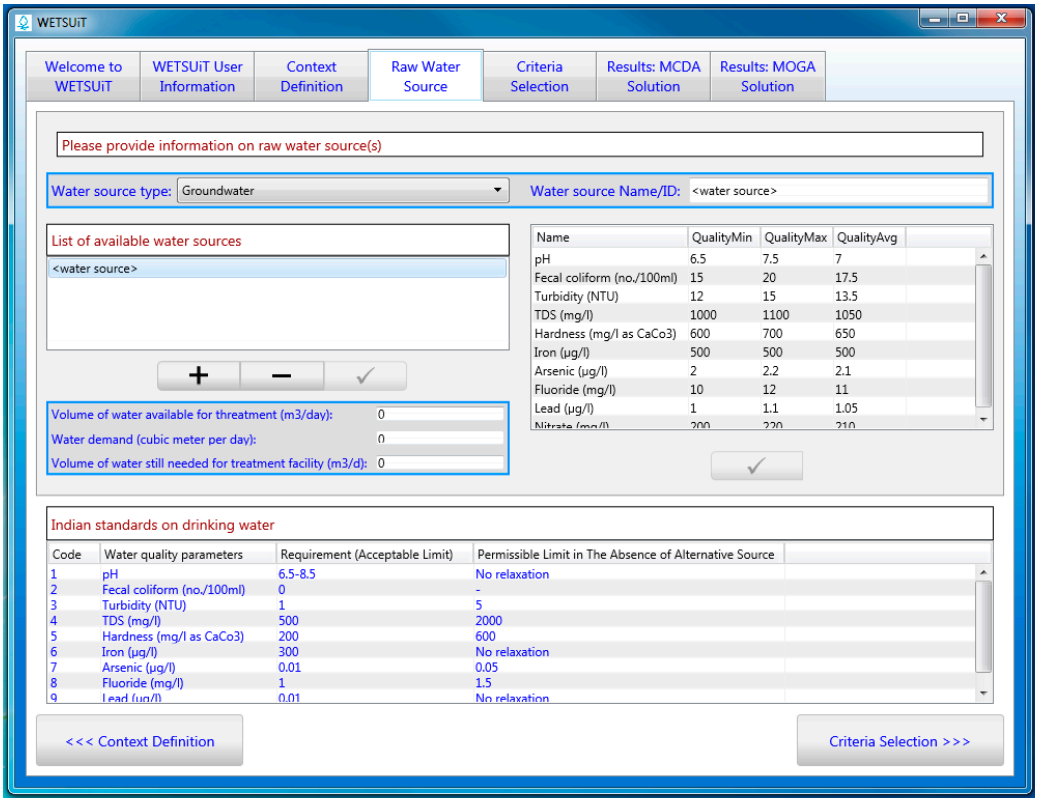


Figure S13. Main tabs on WETSUiT: Raw Water Source.

S2.5. Criteria Selection/Evaluation

On this tab, the most important criteria are presented in a table and the user (of any type/class) can select or deselect any of the criteria for the optimization process based on their preferences (see Figure S14 and Figure S15). On this particular page, expert users can see an additional question at the bottom of the tab: “Would you like to modify criteria/indicators?” (Figure S15). If the answer is “No”, the user can press the Calculate MCDA button to see the multi-criteria results (for the packaged technologies) or click the Optimise—GA button to start the evaluation process by multi-objective genetic algorithm optimization (for the centralized systems). If the answer is “Yes”, a flow chart with all criteria and sub-criteria will be shown (Figure S16). On this tab flow chart, the connections and relations between different criteria and sub-criteria (i.e., indicators) are shown. This would assist the user in the process of selecting/deselecting criteria and setting weights to the selected criteria. In addition to the flow chart (diagram), a tick-box is included on the top of this tab; by unticking this tick-box, a table including all criteria and sub-criteria will be shown (Figure S17).

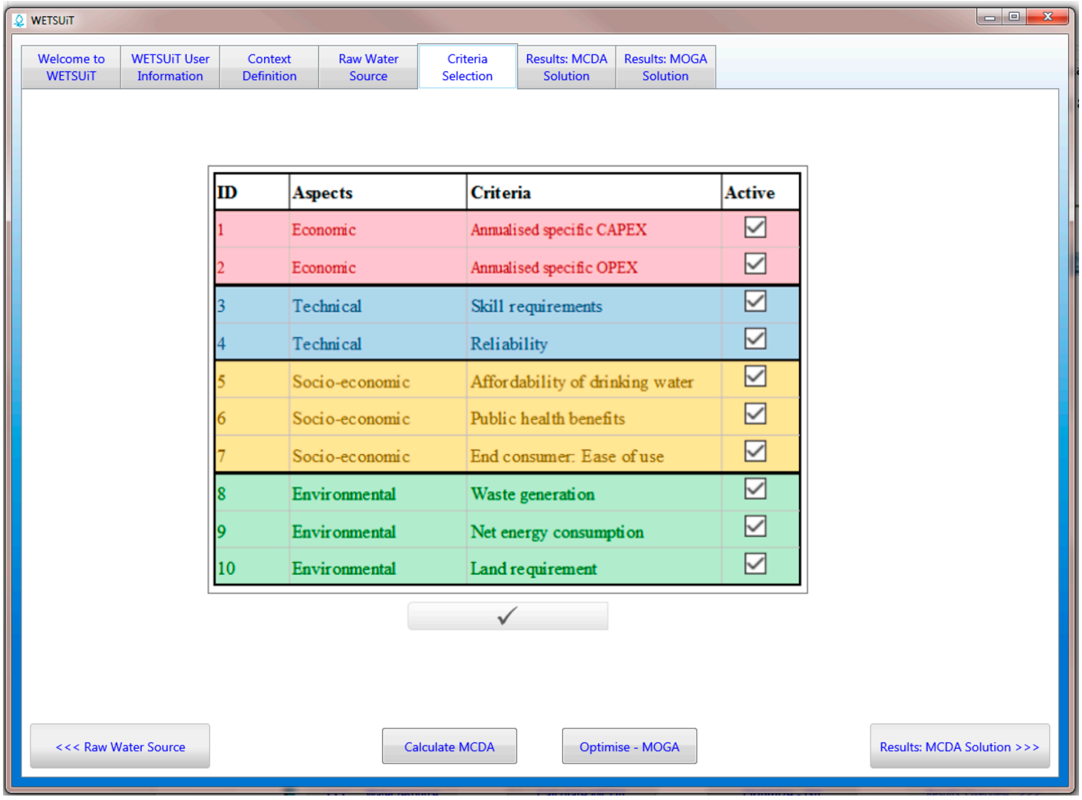


Figure S14. Main tabs on WETSUiT: Criteria Selection/Evaluation—first form (standard users ONLY).

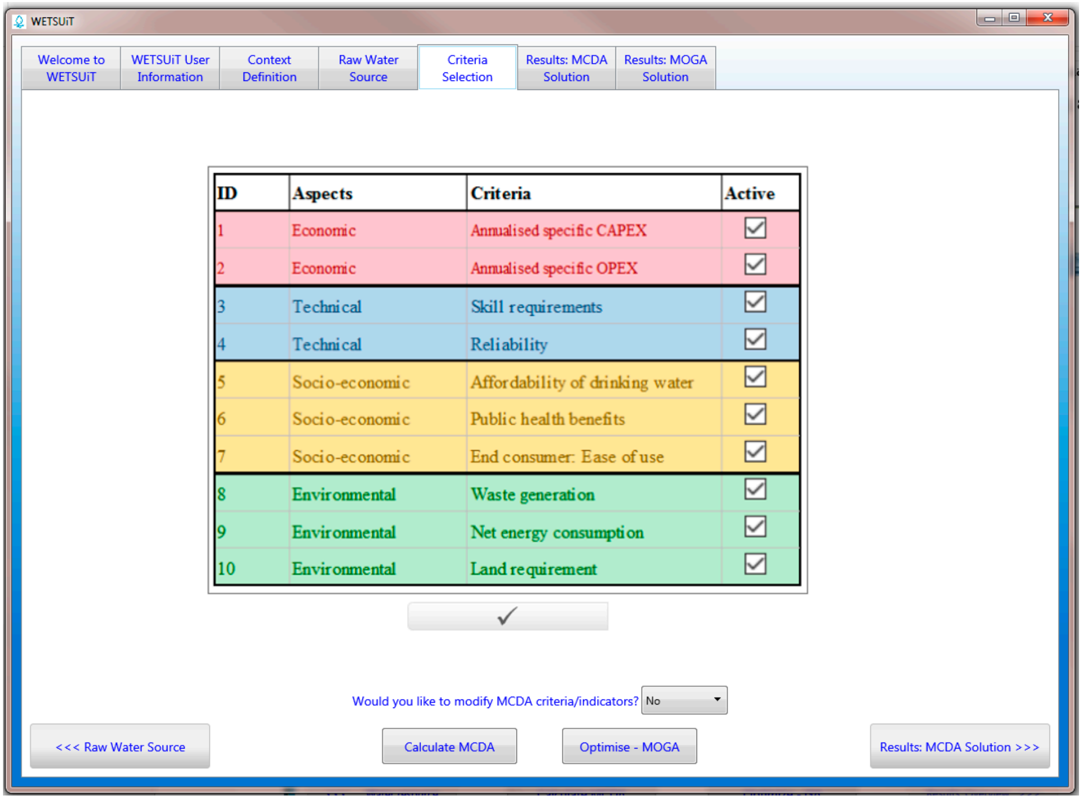


Figure S15. Main tabs on WETSUiT: Criteria Selection/Evaluation—second form (expert users ONLY).

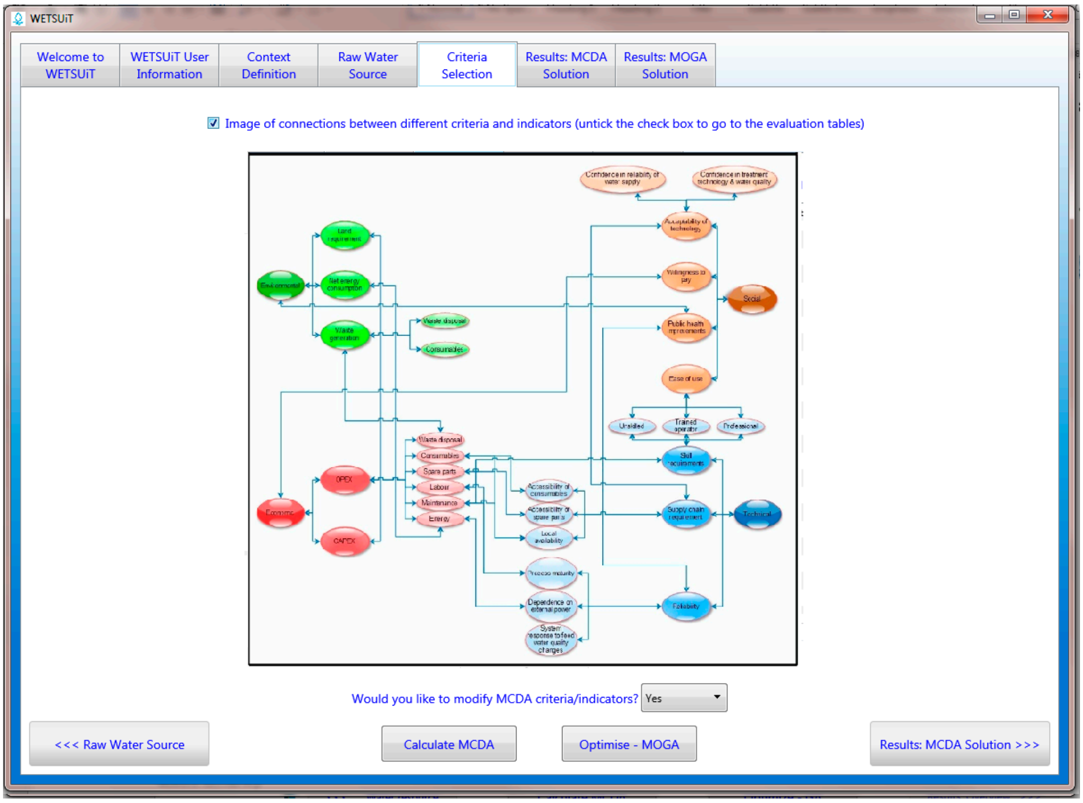


Figure S16. Main tabs on WETSUiT: Criteria Selection/Evaluation—third form: table presenting all criteria and sub-criteria (expert users ONLY).

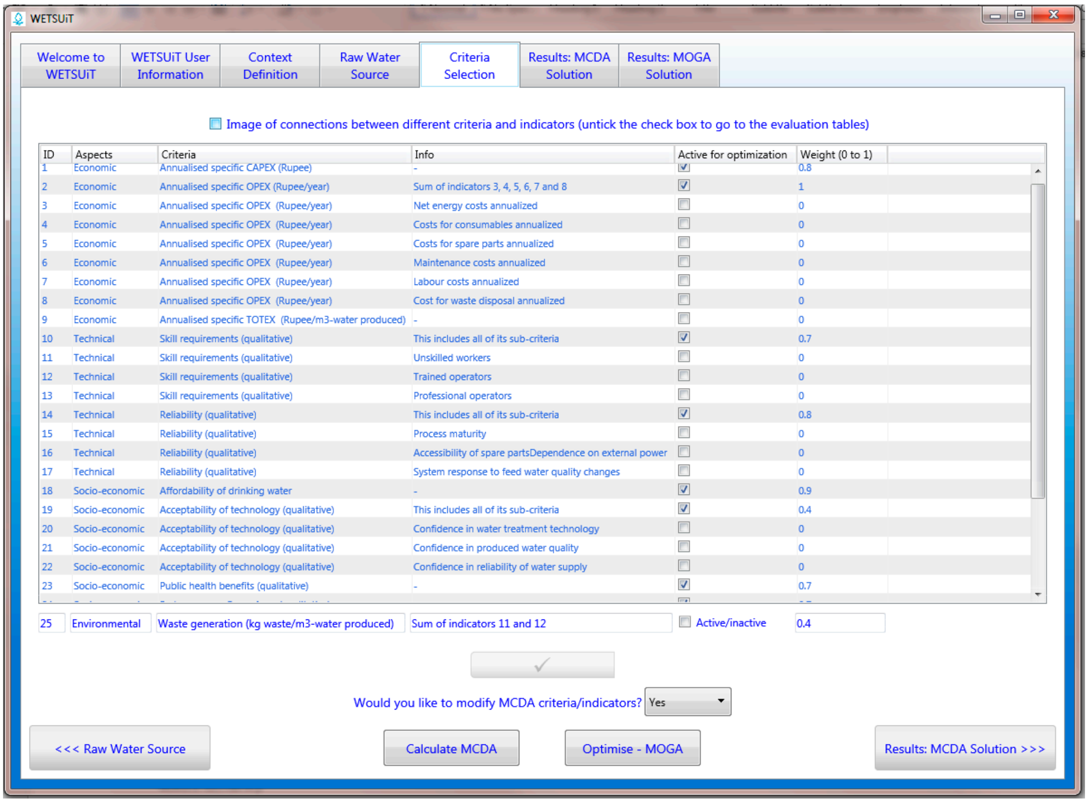


Figure S17. Main tabs on WETSUiT: Criteria Selection/Evaluation—fourth form: diagram on the criteria and sub-criteria (expert users ONLY).

On the fourth form of this tab (Figure S17), the expert user can express their preferences by ticking (enabling) any criteria. The list of ticked criteria and sub-criteria is used for the optimization process by multi objective genetic algorithm optimization. In the next column (to right), the user can select a weight assigned to each of the selected (enabled) criteria. The weights are used in the treatment train evaluation calculations by the multi-criteria decision analysis to determine the overall score on which different treatment trains can be compared. Although WETSUiT is designed to operate with up to 10 criteria for optimization, a trade-off may exist between potentially each and every pair of criteria. Therefore, computational load will increase combinatorically as the number of criteria increases. The number of active criteria should, therefore, be limited and the user should select ONLY the most important criteria/sub-criteria that they would wish to prioritize. This will shorten the period of simulation/run. In order to facilitate criteria selection, "group criteria" have been created for technical, financial, environmental, and social criteria groups. By using these group criteria, all sub-criteria in each group will be aggregated and used. In this way, many criteria can be covered under the four independent headings. When WETSUiT is first installed, these four "group criteria" are included in the list of recommended (default values) criteria that have been pre-selected. When the preferred criteria are selected and weighed (see Figure S17), the user can click the Calculate MCDA button to see the results on MCDA or press the button "Optimise – GA" to start the optimization process via MOO/GA.

S2.6. Results: MCDA Solutions

This tab is designed to present the MCDA results. As mentioned in the previous section, once the user presses the "Calculate MCDA" button (see Figure S14, Figure S15, Figure S16, and Figure S17), the tab is going to be updated and the user will be directed to the "Results: MCDA Solution" tab (Figure S18). The stacked chart (in Figure S18) is used to compare the performance of different water treatment trains/systems based on different criteria to the overall performance (considering all the selected criteria). On the top right-hand side of the tab, there is a component by which the user can change the number of solutions to be displayed. There is also a table (Figure 12) that shows the composite unit processes (treatment trains) or the name of packaged technologies and their overall ranks and performances. For cases/scenarios that focus on centralized systems, this tab will not be accessible until the MOO/GA is complete. The user can save the MCDA results on a local disk or an external memory by pressing the "Save chart" button (to save the stacked chart) and the "Save results" button (to save the MCDA results displayed in the table).

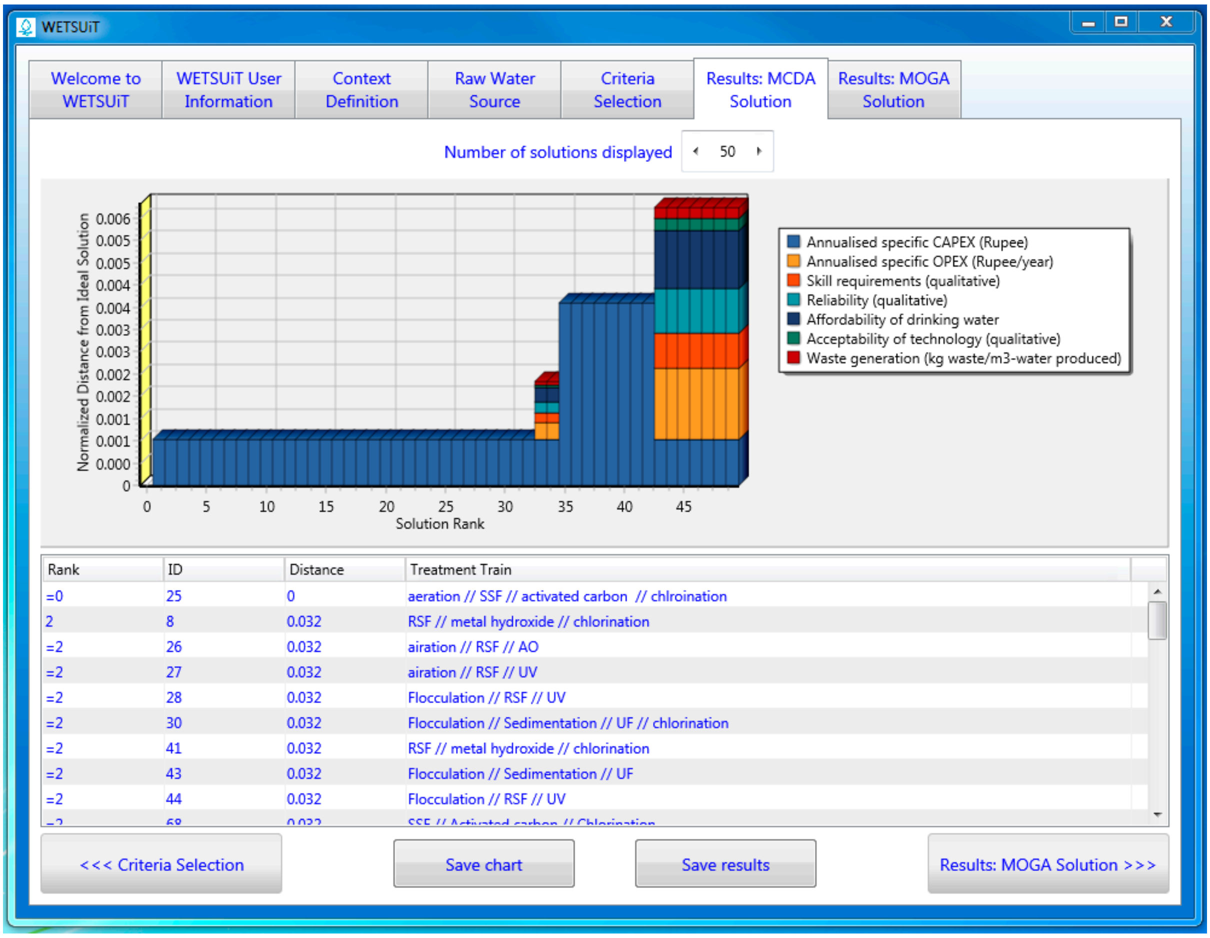


Figure S18. Main tabs on WETSUiT: Results: MCDA Solution.

S2.6. Results: MOO/GA Solutions

Figure S19 illustrates the tab of optimization results. As mentioned earlier in this document, and in the main text, MOO/GA is only utilized for centralized systems (not packaged technologies). Once the user clicks the "Run MOO/GA" button (on the top left side of the "Results: MOO/GA Solutions" tab), the optimization process will start. The optimization may take up to a few minutes depending upon mainly the number of selected objectives/criteria and constraints. The optimization/genetic algorithm displays the obtained solutions in the form of a grid containing values of age, rank, objectives/criteria, and constraints/infeasibility/penalty. When the algorithm is running, it displays all the abovementioned variables reflecting its progress (Figure S20). This table also shows the performance of each solution with respect to water quality and contaminant removal.

Upon completion, the final population of solutions are displayed in three scatter plots (see Figure S20), providing the user with a visual representation of the trade-offs between the three primary objectives (namely: CAPEX, OPEX, and Energy). This can aid the user in understanding the objective space in order to make more informed decisions.

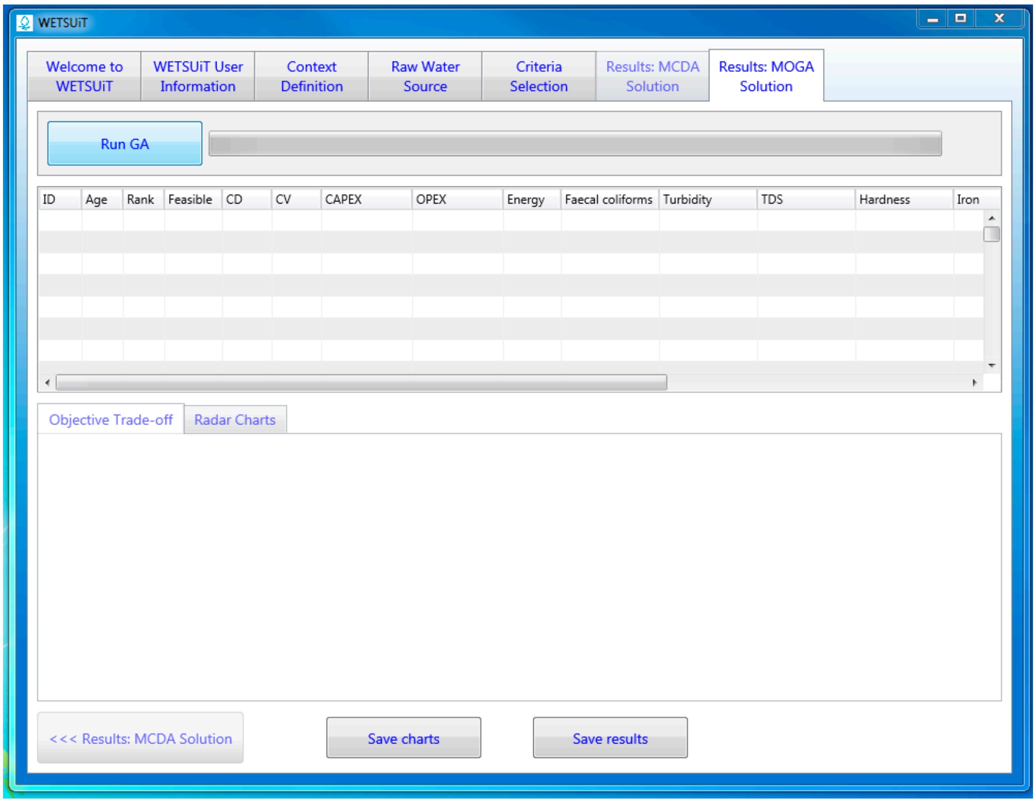


Figure S19. Main tabs on WETSUiT: Results: MOO/GA Solution (before running MOO/GA).

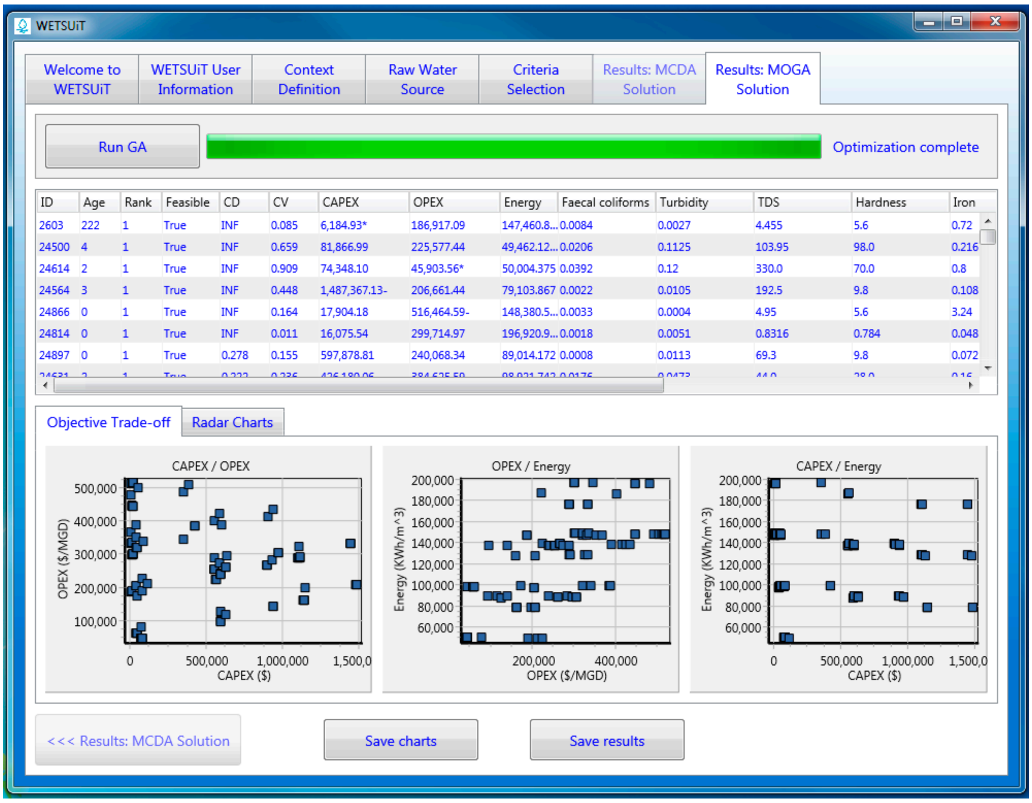


Figure S20. Main tabs on WETSUiT: Results: MOO/GA Solution (after running MOO/GA) with scatter plots.

To analyze the results in detail, optimal treatment trains can be visually represented on two "radar charts" (Figure S21). Each alternative employs a different color data point and line on the radar charts. The radar chart on the left shows the performance of different solutions (in different colors) with respect to the three objectives: CAPEX, OPEX, and Energy consumption. Objectives are represented by the axes. If an alternative data point on an axis is low, it implies the alternative performs well in that objective and vice versa. The radar chart on the right illustrates the performance of the selected solutions with respect to the water quality parameters (i.e., pollutants): i. Fecal Coliform; ii. Nitrate; iii. Lead; iv. Fluoride; v. Arsenic; vi. Iron; vii. Hardness; viii. Total Dissolved Solids (TDS); ix. Turbidity. The number of solutions to be displayed on the radar chart can be selected/altered by changing the "Add/Remove Solutions" component (see Figure S22). The user can add a new solution to the radar charts by clicking (selecting) a solution from the table above (in Figure S21) and pressing the "+" button on the "Add/Remove Solutions" component (Figure S22). The "−" button is to remove any selected solutions (in different colors). The "C" button is to clear both radar charts from all the displayed solutions.

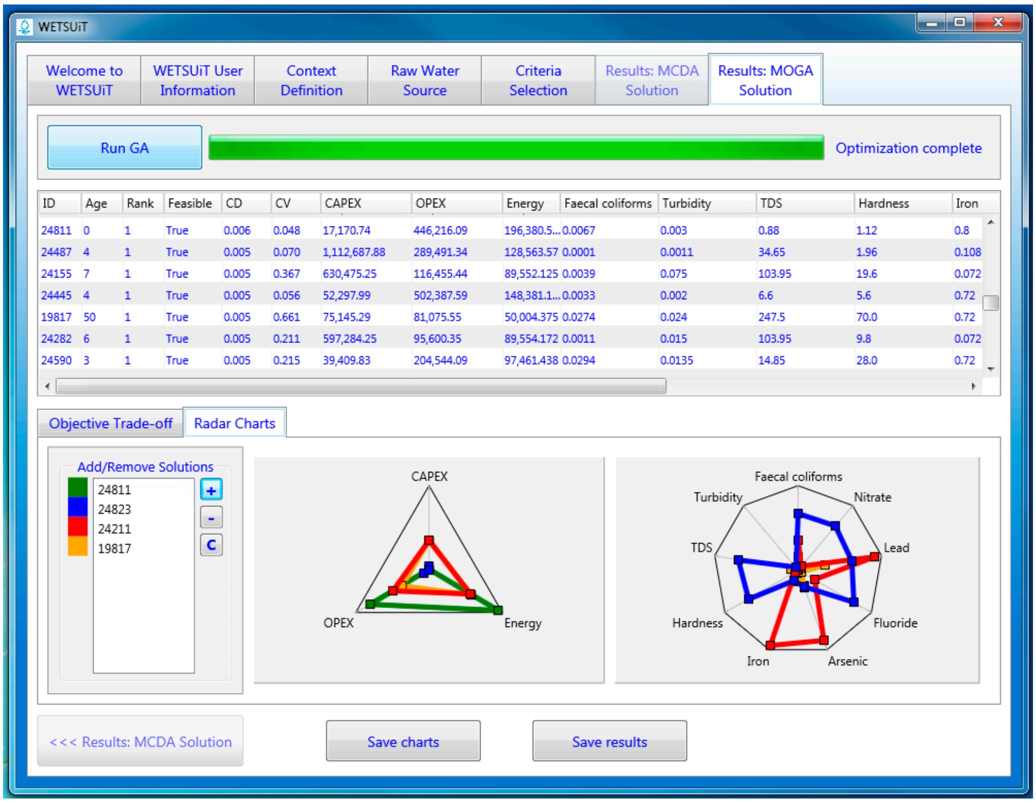


Figure S21. Main tabs on WETSUiT: Results: MOO/GA Solution (after running MOO/GA) with radar charts.

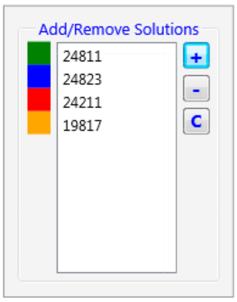


Figure S22. The component "Add/Remove Solutions" on the main tab of: Results: MOO/GA Solution with radar charts.

Similar to the "Criteria evaluation" tab, the results presented in the table (showing the whole population of the optimal solutions) and in the radar charts can be saved on a local disk or an external memory by pressing the "Save results" and "Save charts" buttons, respectively.

S3. Criteria and Sub-Criteria Identified in this Study

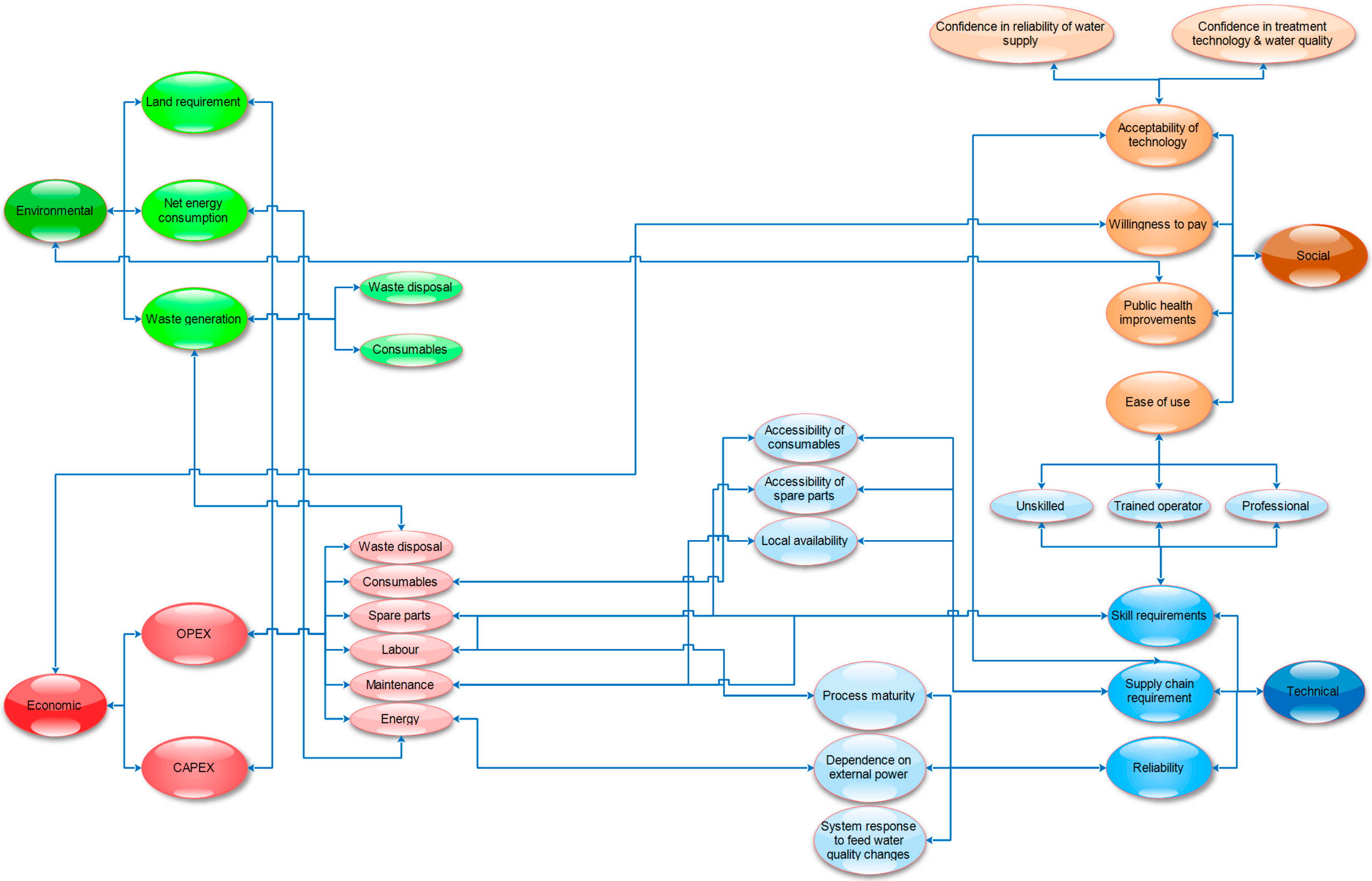


Figure S23. Aspects, criteria, and sub-criteria (sustainability indicators) identified in this study and used in the DSS.

S4. Analytic Hierarchy Process (AHP) Ranking System and Example

Table S1. Ranking system of the AHP (adopted from Saaty, (1987)).

Intensity of Criteria	Definition	Explanation
1	Equal Importance	The activities contribute equally to the objective
3	Slight Importance	Experience and judgement slightly favor one activity over another
5	Strong Importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	One is clear favored and dominance has been demonstrated in practice
9	Vital Importance	The evidence favoring the one activity is of the highest order and has been proven in practice numerously
2,4,6,8	Intermediate values between the two adjacent values	Compromise is needed between intensities

Table S2. Pair-wise comparison of criteria for the selection of decentralized small-scale systems in a low-income household scenario (see Section 3.2.2).

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	Total Score $TS=\sum_{j=1}^{n} C_{i,j}$	Weight (W_i)
C1	1.00	0.20	0.17	2.00	0.25	0.25	3.00	0.50	0.25	7.62	0.06
C2	5.00	1.00	0.50	4.00	3.00	2.00	5.00	3.00	2.00	25.50	0.19
C3	6.00	2.00	1.00	3.00	3.00	2.00	3.00	3.00	2.00	25.00	0.18
C4	0.50	0.25	0.33	1.00	0.33	0.33	4.00	0.33	0.33	7.42	0.05
C5	4.00	0.33	0.33	3.00	1.00	2.00	5.00	4.00	3.00	22.67	0.16
C6	4.00	0.50	0.50	3.00	0.50	1.00	5.00	0.33	2.00	16.83	0.12
C7	0.33	0.20	0.33	0.25	0.20	0.20	1.00	0.33	0.25	3.10	0.02
C8	2.00	0.33	0.33	3.00	0.25	3.00	3.00	1.00	2.00	14.92	0.11
C9	4.00	0.50	0.50	3.00	0.33	0.50	4.00	0.50	1.00	14.33	0.10
									SUM	88.53	1.00

C_1	Reliability	C_6	Energy Consumption
C_2	Capital Cost	C_7	Availability of Spare parts
C_3	Annual O&M costs	C_8	Water treatment Capacity
C_4	Ease of Installation	C_9	Land requirement
C_5	Ease of O&M		

S5. References

Saaty, R. W. 1987. 'The Analytic Hierarchy Process—What It Is and How It Is Used'. Mathematical Modelling 9(3): 161–76.

W4I. 2016. 2016 '(Smart, Cost-Effective Solutions for Water Treatment and Monitoring in Small Communities in India. Decision Support System Integration.) | Report Summary | WATER4INDIA | FP7-ENVIRONMENT'. CORDIS | European Commission. https://cordis.europa.eu/project/rcn/104190/reporting/en.