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

Seyed M. K. Sadr [1,*], Matthew B. Johns [1], Fayyaz A. Memon [1], Andrew P. Duncan [1], James Gordon [1], Robert Gibson [1], Hubert J. F. Chang [1], Mark S. Morley [1,2], Dragan Savic [1,2] and David Butler [1]

1 Centre for Water Systems, College of Engineering, Mathematics and Physical Sciences, University of Exeter, North Park Road, Exeter EX4 4QF, UK; M.B.Johns@exeter.ac.uk (M.B.J.); f.a.memon@exeter.ac.uk (F.A.M.); andrew.paul.duncan@mail.com (A.P.D.); jamesccgordon@gmail.com (J.G.); rw23gibson@gmail.com (R.G.); cjf.hubert@gmail.com (H.J.F.C.); mark.morley@kwrwater.nl (M.S.M.); dragan.savic@kwrwater.nl (D.S.); d.butler@exeter.ac.uk (D.B.)

2 KWR Water Cycle Research Institute, Groningenhaven 7, 3433 PE Nieuwegein, The Netherlands

* Correspondence: S.M.K.Sadr@exeter.ac.uk

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Abstract: Despite considerable efforts to improve water management, India is becoming increasingly water stressed due to multiple factors, including climate change, increasing population, and urbanization. We address one of the most challenging problems in the design of water treatment plants: how to select a suitable technology for a specific scenario or context. The process of decision making first requires the identification of feasible treatment configurations based on various objectives and criteria. In addition, the multiplicity of water quality parameters and design variables adds further complexity to the process. In this study, we propose a novel Decision Support Tool (DST), designed to address and support the above challenges. In this user-friendly tool, both Multi-Criteria Decision Analysis (MCDA) and Multi-Objective Optimization (MOO) methods are employed. The integration of MCDA with MOO facilitates the generation of feasible drinking water treatment solutions, identifies optimal options, and ultimately, improves the process of decision making. This implemented approach has been tested for different contexts, including for different types of raw water sources and system implementation scales. The results show that this tool can enhance the process of decision making, supporting the user (e.g., stakeholders and decision makers) to implement the most suitable water treatment systems, keeping in view the trade-offs.

Keywords: drinking water; water treatment unit processes and packaged systems; multi-objective optimization; multi-criteria decision analysis; WETSUiT

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1. Introduction

Water scarcity is becoming a major issue in today's world, affecting every continent in different aspects [1]. Statistics from The Water Project showed that one out of every five children under the age of five died due to a water-related disease and 1 in 9 people worldwide have no access to potable drinking water [2]. In developing countries, around 80 percent of diseases are associated with poor water and sanitation conditions [2]. India, the focus of this paper, with about 16 percent of the world's population, has access to only 4 percent of the world's freshwater supply, of which only 60 percent is easily accessible due to geographical and topographical reasons [3]. With a population of around 1.37 billion people [4,5] and a rapid Gross Domestic Product (GDP) growth rate of around 6.7% per annum [6], India faces multiple challenges regarding this scarce resource. At present, only 88% of the population has access to an improved water source [7]. In addition, it is estimated that 21% of communicable diseases in India are related to unsafe water [8]. To counteract this, India requires an improved water infrastructure system and utilization of available water treatment systems to ensure the population receives sufficient potable water.

There are an insufficient number of water treatment plants in operation in India and those are close to maximum capacity or falling into disrepair due to poor management [9,10]. The need for new water treatment infrastructure is especially apparent in more remote communities where financial, socioeconomic, and technical constraints hinder development. These constraints need to be taken into account when designing and selecting water treatment systems. The scale of a water treatment system can differ drastically depending on the size of the population being served; this can range from a large settlement to a single dwelling. Commonly, a large settlement will require a centralized water treatment system, which is considered as an effective water supply solution, providing the most efficient way of generating large quantities of drinking water for the population, given their economies of scale [11]. In the case of smaller scale settlements, a decentralized water treatment system offers the possibility of clean reliable water to urban, rural, or remote settlements where centralized systems are not economically or technically feasible [12,13]. With three types of systems, Point-of-use (POU) supply, Point of entry (POE), and Small-scale system (SSS) [11,14], a solution can be tailored to meet context-specific needs.

There are many water treatment options (unit processes and packaged technologies) available to a decision maker (e.g., water authorities and engineers), making the task of formulating the optimal solution for a given context extremely difficult. The number of potential treatment train configurations for most scenarios result in a search space greater than that which can be fully evaluated in polynomial time. Techniques such as metaheuristics are able to traverse these large solution spaces and arrive at a near optimal solution. Such a technique is the Genetic Algorithm (GA), which has been applied to a large number of engineering optimization problems including water systems and has demonstrated the ability to generate high quality solutions. There is often more than one objective to consider, resulting in a set of solutions where no single solution is worse than its counterparts in a scenario. In addition, both centralized and decentralized systems have a large number of factors that influence the selection of optimum technology combination. This is where Multi-Criteria Decision Analysis (MCDA) can play a prime role in decision making. MCDA is a broad method or discipline which deals with decisions involving the choice of best alternatives from several potential candidates, subject to several conflicting criteria [15].

Utilizing a Decision Support System (DSS) can help decision makers select the optimal technologies in different situations. In the last four decades, a number of projects and studies focused on the development of models and tools to help decision makers select suitable treatment options. The first (key) example was done by Rossman in 1979 and 1980 [16,17]; in this study, he explored the synthesis of wastewater treatment trains and developed a model to generate a set of alternatives for wastewater treatment considering eight stages/processes. The main strength of this model was the implementation of an implicit enumeration approach to system synthesis which operated on a discrete set of candidate unit processes with fixed specifications. However, very few unit processes were considered for each stage of treatment, and simple assembly rules were used. The other pioneering water/wastewater treatment technology selection model was developed by Tang et al. [18], in which an Analytic Hierarchy Process (AHP) model compared different syntheses of wastewater treatment processes, but the main limitation of this model was lack of a screening process to decrease the number of solutions based on the user's preferences. This aspect was better addressed in the model developed by Chen and Beck [19], who developed a Monte Carlo-based approach to synthesize treatment trains and identify more sustainable treatment options. This model, however, was designed with fixed values for each unit process and indicator without flexibility to adapt to local conditions and/or to consider altered assumptions [20]. In other words, the model could not be applied to different contexts.

More recently, Economopoulou and Economopoulos [21] developed a MCDA-based model, which they called the "expert system", to select small and medium scale systems in Greece and focused mainly on water quality parameters. Finney and Gerheart [22] developed a DST for the selection of suitable water and wastewater treatment technologies. The tool contained information on different processes and each process was assessed based on several factors. However, the main drawback of this tool was related to the process of generating treatment trains, which was very time consuming and required users' experience and familiarity with treatment processes. In addition to the above, Joksimovic et al. [23], Bottero et al. [24], Adewumi [25], Kalbar et al. [26,27], Loo et al. [28], Garrido-Baserba et al. [29], and Sadr et al. [30–32] developed decision support tools in different contexts. The most recent decision support tool developed is called "Poseidon" [33]; the tool considers over 30 processes and 12 water quality parameters. However, almost all the aforementioned tools/models focused on wastewater treatment and/or water reuse scenarios or considered a very limited number of water treatment options.

This paper presents a novel decision support system, WETSUiT (WatEr Treatment decision SUpport software Tool), which employs a hybrid model with a Genetic Algorithm-based Multi-objective Optimization process (GA-MOO) to generate feasible solutions (for centralized systems only) and Multi-Criteria Decision Analysis (MCDA) as a method of selecting the optimal centralized systems or decentralized packages based on a given context. To the best of the authors' knowledge, there is no such decision support model/tool for (drinking) water treatment technology selection integrating MOO with MCDA whilst considering about 30 water treatment unit processes and 35 packaged technologies.

The tool is substantiated and tested using theoretical case studies in the context of India, with data collected during the Water4India project (EU FP7 Grant Agreement Number: 308496). The second section of this paper discusses the methodology proposed in this piece of research and describes the main components of the DSS. Section 3 first gives an overview of each scenario defined in this study; it also shows the results and discusses how the results could be interpreted and aid the stakeholders in making an informed decision. Finally, Section 4 summarizes the conclusions and implications of this study.

2. Materials and Methods

The selection of potable water treatment technology/feasible solution is a complex process involving multiple criteria of fitness, choices of technology, and constraints. This makes unaided manual selection a challenging task [34]. As mentioned earlier, the demand for decision making and technology selection systems is high in India as there are many villages and towns which have underdeveloped water infrastructure [7,35]. The result of this is that inhabitants living in these locations do not receive safe drinking water. This study proposes a decision support system called WETSUiT (WatEr Treatment decision SUpport Tool) to assist decision makers in selecting a suitable drinking water solution. In this increasingly complex world, especially in developing countries, such a decision support tool is required to validate the chosen technologies based on specific regulations to assess whether the potential technologies or solutions meet the drinking water standards or guidelines. The WETSUiT consists of several interconnected components, as shown in Figure 1. The key components are briefly described below:

- **Technology library**: This is a database containing information on approximately 30 unit processes and 35 packaged water treatment systems and their respective sustainability indicators (such as waste generation, greenhouse gas emissions, net energy consumption, and land requirement); the list of all indicators considered in this study are shown in Section 2.3 in Table 1. The technology library (i.e., database) is divided into eight main tables: i. Technology Description; ii. Technology Installation; iii. Operation and Maintenance (O&M); iv. Maintenance Activities; v. Chemicals required for O&M; vi. Cost of Technology; vii. Social Aspects; and viii. Technology Performance in Terms of Contaminant Removal. Each table contains several questions aiding the process of decision making. The details of the questions in each table of the database are provided in the SM, Section S1 (Figures S1–S8). One of the advantages of the database is that its contents can easily be augmented if the user wants to add information on a new technology and/or to improve/update details of an existing process or a packaged system.

- **Graphical user interface:** This has been built using C++ builder in Rad Studio and facilitates processing the user-defined context information for which water treatment is required (e.g., system scale, raw water source and quality, budget, and availability level of skills and power supply). WETSUiT is a multi-device application which can be run on any MS Windows, Android, and iOS devices. The WETSUiT user interface contains eight tabs (namely: Welcome to WETSUiT, User Information, Context Definition, Raw Water Information, Criteria Selection, MCDA Results, and MOO results) to facilitate context definition data input, setting constraints, simulation automation, results analysis, and visualization. The details of each tab are provided in the Supplementary Materials (SM), Section S2 (Figures S9–S22).
- **Optimization engine**: This generates optimal treatment trains using an evolutionary algorithm based on the Non-dominated Sorting Genetic Algorithm-II (NSGA-II), which is a genetic algorithm driven by Pareto dominance [36]. NSGA-II evaluates the fitness of each solution in relation to an entire population of candidate solutions. More details on the optimization and selection process are provided in Section 2.1.
- **Solution evaluator**: This enables the user to assess solutions generated by the optimization engine and small household packaged treatment technologies by employing Multi-Criteria Decision Analysis (MCDA), showing the performance for each candidate solution (i.e., water treatment technologies) with respect to each of the criteria. The details on the solution evaluator are discussed in Section 2.2.

One of the advantages of the WETSUiT Tool is its replication feature: it can easily be applied to other projects or case studies in different contexts. The proposed tool can be used by stakeholders or decision makers at the start of the design procedure, for identifying feasible and appropriate drinking water treatment or desalination alternatives, and for estimating important project parameters such as capital cost, O&M costs, energy consumption, and contaminants removal.

2.1. Multi-Objective Optimization

For the Multi Objective Optimization (MOO) approach, the Fast Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II) [36] was employed to optimize treatment train configurations. NSGA-II employs a fast non-dominated sorting process to sort each individual (solution) into a front based on Pareto non-dominance. The algorithm filters out all non-feasible unit processes and/or treatment trains based on a number of constraints: e.g., influent and effluent quality and quantity, budget availability, reliability of electricity, availability of land for the water treatment plant/system. Potentially feasible solutions (unit processes for centralized systems or packaged technologies for decentralized systems) then become candidates for the optimization process (if centralized systems are required) which mixes and matches treatment technologies at each required stage in the treatment train (Duncan et al., 2015). The approved list (solutions) of the final generation is then analyzed by MCDA techniques described in the following section (see Section2.2).

2.2. Multi-Criteria Decision Analysis

Multi-Criteria Decision Analysis (MCDA) is a decision making method which can be used to make a comparative assessment of alternatives based on multiple evaluation criteria [30]. MCDA is a method for resolving decision problems with many alternatives, which are evaluated based on user weighted criteria [31,37]. A large (growing) number of MCDA methods have been developed. The growth in MCDA methods is attributed to several factors [38]: (1) existence of many different types of decision problems which fit a broad spectrum of MCDA techniques; (2) the complexity and time required to process data and to carry out analysis; and (3) amount and type of data required by different MCDA techniques. In this study, two distinct MCDA methods are applied in order to aid in translating the user decisions/weights for a better outcome.

Table 1. The 30 criteria included in WETSUiT.

	Economic		**Technical**
1	CAPEX	10	Skill requirements—Total
2	OPEX	11	Skill requirements—Unskilled workers
3	Net energy costs annualized	12	Skill requirements—Untrained workers
4	Costs for consumables annualized	13	Skill requirements—Professional operators
5	Costs for spare parts annualized	14	Reliability—Total
6	Maintenance costs annualized	15	Reliability—Process maturity
7	Labor costs annualized	16	Reliability—Accessibility of spare parts—Dependence on external power
8	Cost for waste disposal annualized		
9	TOTEX	17	Water treatment capacity
	Socioeconomic		**Environmental**
18	Affordability of drinking water	25	Waste generation (kg/m^3-water produced)—Total
19	Acceptability of technology—Total	26	Waste generation (kg /m^3-water produced)—non-toxic
20	Acceptability of Technology (AoT)—Confidence in water treatment technology	27	Waste generation (kg waste/m^3-water produced)—toxic
21	AoT—Confidence in produced water quality	28	Green-house emissions (kgC/m^3-water produced)
22	AoT—Confidence in reliability of water supply	29	Net energy consumption (kwh/m^3-water produced)
23	Public health benefits	30	Land requirement (m^2)
24	End consumer: ease of use		

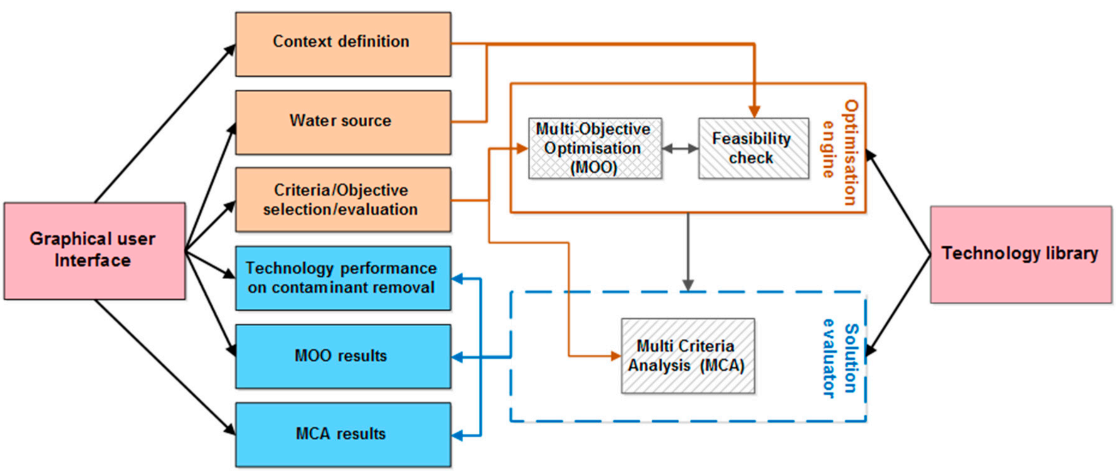


Figure 1. Overview of WETSUiT (WatEr Treatment decision SUpport Tool) Structure and main components of this tool.

2.2.1. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) involves the construction of a decision hierarchical structure, whereby a decision problem is broken down into simpler constituents. In the first place, the problem should be structured into a hierarchical model. In other words, the problem should be decomposed into elements based on their common characteristics and forming a hierarchical model at each level [39,40]. The uppermost level represents the aim of the problem, while the lowest level corresponds to the alternatives. The intermediate level(s) represent evaluation aspects, criteria, and sub-criteria. It also involves determination of relative weights based on a pair-wise comparison between criteria represented in the hierarchical structure for the purpose of ranking alternatives [41].

Pair-Wise Comparison

Pair-wise comparison, based on different aspects, determines the relative weights of the considered criteria for a scenario of water treatment [32,42]. The definitions and explanations for the ranking system of the AHP are presented in Table S1 in the Supplementary Materials (S), where 1 represents equal importance of two criteria and 9 denotes an extreme importance of one criterion over the other. Here, the pair-wise comparison of criteria for selection of decentralized small-scale systems in an emergency situation is shown in Table S2, in the SM. In this table, the criteria in rows (C_i) are compared to criteria in columns (C_j) and matrix element C_{ij} denotes the comparison between C_i and C_j. It is important to mention that matrix elements C_{ij} and C_{ji} are in inverse ratio (C_{ij} = 1/C_{ij}). The other assumption is that when i equals j (diagonal elements), $C_{ij} = C_{ji} = 1$. Further to the above assumptions, the total score for the ith row (TS_i) can be calculated by Equation (1) [32]:

$$TS_i = \sum_{j=1}^{n} C_{ij} \tag{1}$$

where n is the number of criteria. To calculate the sum of scores of all rows (SUM), Equation (2) can be used.

$$SUM = \sum_{i=1}^{n} TS_i \tag{2}$$

Now, the weight of each criterion (W_i) can be determined using Equation (3) [32]:

$$W_i = \frac{TS_i}{SUM} \tag{3}$$

Weighted MCDA of Technology/Solution

First, a multi-criteria scoring matrix is prepared by assigning the water treatment system (T) a score from within a normalized range. The scores are determined from the traits of the individual unit process that comprise these systems. Subsequently, the selected treatment trains are assessed against the weightings of the various criteria. The weighted values or total scores of TS are obtained by Equation (4):

$$TS = \sum_{i=1}^{n} W_i S_{ki} \tag{4}$$

where n is the number of criteria and S_{ki} are the scores corresponding to kth water treatment technology and ith criteria.

2.2.2. Compromise Programming

Compromise programming (CP) is an MCDA approach [43] used to identify the optimal solution [43,44]. It consists of obtaining weightings from AHP. This contributes to the overall performance index (OPI) of a water treatment system [45]. CP uses the equation below to rank the various potential technologies in accordance with their overall score, where the optimal solution consists of the highest score. These overall scores are all relative to each other, with the optimal solution a point of reference to the decision maker [44]. The total score for each treatment train is obtained by Equation (5) [45]:

$$TS = \left\{ \sum_{i=1}^{n} \left[w_i^p \left(\frac{f_i - f_i^w}{f_i^b - f_i^w} \right) \right] \right\} \quad (5)$$

where TS is the total score of a treatment system, w_i is weight of a criterion, f_i^b is the best criterion score, f_i^w is the worst criterion score, and f_i is the actual score.

2.3. Identification of Evaluation Criteria and Optimization Objectives

WETSUiT considers three objectives for GA-based optimization (only for the centralized solutions), namely: i. Capital expenditure (CAPEX); ii. Operational and maintenance expenditure (OPEX); and iii. Energy consumption. Additionally, it covers a large number of criteria (see Table 1), and the user is asked to select a number of these criteria based on their preferences for the decision making process (see more details in the SM, Section S2.5). As mentioned in the previous section, weights should be assigned to the selected criteria for the MCDA evaluation process. To ease the process of criteria weighing, a diagram showing the relation between different criteria is presented in the user interface (see Figures S16 and S23, in the SM). Thus, it is impractical and not user-friendly to utilize a pair-wise comparison of all 30 criteria. Therefore, for any cases where the user selects more than 10 evaluation criteria, CP (without pair-wise comparison of the criteria) is applied.

2.4. WETSUiT Application

The WETSUiT tool was applied to identify treatment solutions for four different scenarios. These and the resulting technology mix are discussed in the following sections.

3. Results and Discussion

The defined scenarios can be divided into two categories, involving: i. Centralized water treatment trains (Section 3.1) and ii. Small decentralized water treatment packages (household level) (Section 3.2). The main information/assumptions on both centralized and decentralized scenarios are presented in Tables 2 and 3, respectively. These have been collected from published reports and water treatment technology providers or assumed based on a series of discussions with the stakeholders.

3.1. Evaluation of Centralized Drinking Water Treatment Trains via WETSUiT

Two centralized scenarios (for two Indian towns, Srirangapatna and Bilikere) underwent the MOO and MCDA. Ten and thirteen evaluation criteria are utilized for Scenarios 1 and 2, respectively. The main assumptions of both centralized scenarios are summarized in Table 2. For detailed analysis into the effect the criteria have upon the MCDA, the selected criteria were banded into three groups. The first group (the control group) was centered on the establishment and operation of the treatment plant and consisted of: CAPEX (the capital cost criteria), OPEX (the operating cost criteria), the skill requirements of the plant and the reliability of the treatment plant. The second group referred to the ease of use—affordability, the acceptability of the technology used, the public health benefits and the ease of use for the end consumer. The third group was centered on environmental concerns and consisted of the amount of waste generated, greenhouse emissions, availability of spare parts, energy consumed in the process, and the land required for the plant. As mentioned above, the first group (focused on the establishment and operation of the treatment plant) was kept as the control as it is largely based upon economic incentives and therefore, would be of high importance for both towns. A summary of the weights given to the two centralized scenarios are presented in Table 4. It is noteworthy that the assumptions were made and criteria weights were assigned (in each scenario) with help from a number of stakeholders in India.

Table 2. Main information/assumption on the centralized scenarios.

Name and ID of Scenario	**Srirangapatna TP DW Treatment (Scenario 1)**			**Bilikere TP DW Treatment (Scenario 2)**		
City/District	Srirangapatna/Mandya District			Bilikere/Mysorae		
State	Karnataka			Karnataka		
Population to be served	30,000			10,000		
Types of solution	Full-scale systems			Full-scale systems		
Water consumption	200			200		
Leakage (% of produced water)	0.15			0.15		
Urban or Rural	Rural			Urban		
continuous electrical supply	No			No		
Availability of spare parts	All spare parts available on regional/national market			Some spare parts available on regional/national market		
Technical Ability for O&M	Training; personal with basic education			Training; personal with basic education		
Water Quality Parameters	**Min Value Occurring**	**Max Value Occurring**	**Current Value**	**Min Value Occurring**	**Max Value Occurring**	**Current Value**
pH	6.7	8.2	7.3	6.9	8.1	7.2
Fecal coliform (no./100mL)	0	0	0	0	0	0
Turbidity (NTU)	1	21.2	5.64	2	24	6.45
Total Dissolved Solids (mg/L)	25	320	153.23	30	350	160.2
Hardness (mg/L as $CaCO_3$)	34	160	140.69	30	155	135.4
Iron (µg/L)	3.69	4.52	3.9	3.5	4.72	4.01
Arsenic (µg/L)	0	0	0	0	0	0
Fluoride (mg/L)	0	0	0	0	0	0
Lead (µg/L)	0.0291	0.0402	0.031	0.03	0.052	0.037
Nitrate (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

3.1.1. Centralized Scenario 1—Srirangapatna (Scenario 1)

The first centralized scenario is based on the town of Srirangapatna, which lies on the Kaveri River and is located in the State of Karnataka. The data required for the scenario came from a study conducted by the University of Mysore on the Kaveri River's water pollution content [46]. The data were taken before, during, and after the monsoon season and therefore, show the full range of contaminants in the river, in a calendar year. The maximum and minimum values were obtained from this and compared against the Indian drinking water standards [47]. The lead content and turbidity were found to exceed the standards and as such, were the offending contaminants in this scenario. Some demographics were required for the compilation of this scenario, and these were sourced from the 2011 census data [48,49]. Other information required was assumed from the authors' experience of the town. Srirangapatna is a tourist town and as such, has a higher emphasis on the environment to encourage further tourism and therefore, is expected to have greater weightings in the corresponding criteria. Based on MOO results, several water treatment trains were generated and found to be suitable. Here in this paper, the best eight solutions are presented.

WETSUiT first calculated the performance of the generated water treatment trains on contaminant removal to check that all technologies meet the Indian drinking water standards [50]. Looking into the details of contaminant removal, it was observed that all technologies sufficiently remove turbidity.

However, T54 (aeration, Slow Sand Filtration (SSF), chlorination with hypochlorite (ClO^-)), T56 (aeration, Rapid Sand Filtration (RSF), ultrafiltration (UF), ClO^-), T66 (aeration, SSF, microfiltration (MF), ClO^-), and T80 (aeration, chemical precipitation, sedimentation, UF, chlorination) sufficiently remove the lead content to acceptable standards only under high operational conditions. T55 (aeration, SSF, RO: Reverse Osmosis, ClO^-), T59 (aeration, Sediment filter (5µm), adsorption with GAC: Granular Activated Carbon, chlorination), T65 (aeration, sediment filter (5µm), adsorption with

GAC, chlorination), and T79 (aeration, MF, RO, ultraviolet (UV)) all bring the contaminants in line with the required standards, and as such, are placed on the shortlist, to be evaluated further via MCDA in WETSUiT.

All the eight treatment trains are feasible solutions and their performances are not always noticeably different. The results are illustrated in Figure 2a (displaying a star chart) where the performance of treatment trains based on each criterion can be compared and analyzed; however, in this figure, the weight given to each criterion has not been taken into consideration. There are two types of criteria considered in this study: i. cost (e.g., CAPEX, OPEX, energy consumption, land requirement, waste generation, and carbon emission) and ii. benefit (e.g., reliability, ease of use, and spare part availability). This, for the cost criteria, implies that the smaller the value calculated for a solution is (with respect to a cost criteria), the higher its performance will be. As can be seen in Figure 2a, whilst T54 is rarely the best in any given criteria, its performance is consistently high in all of the criteria, leading to its high overall score. Figure 2b shows the performance of optimal water treatment systems. Based on the WETSUiT results, Optimal Treatment Train T54 and T59 are the best solutions for the given scenario, as they have the highest overall scores (3.92 and 3.90, respectively). T79 and T80 are the least preferred treatment trains with scores of 3.41 and 3.27, respectively.

Table 3. Main information/assumption on the decentralized scenarios.

Name and ID of Scenario	**Small-Scale System for an Emergency Situation (Scenario 3)**			**Effect of Income in an Urban Household Package (Scenario 4)**		
State	Srirangapatna/Mandya District			Bilikere/Mysorae		
Population to be served	Karnataka			Karnataka		
Types of solution	500			a family with 4–6 members		
Water consumption (Liters per person per day)	Community systems			Household systems		
Household earning	50			200		
Urban or Rural	Not Applicable			Scenario 4a: <5000 INRs [1] Scenario 4b: >5000 INRs		
Is the electrical supply continuous (24/7)	Rural			Urban		
Availability of spare parts	No			No		
Technical Ability available for O&M	N/A			Some spare parts available on regional/national market		
State	N/A			Training; personal with basic education		
Water Quality Parameters	Min Value	Max Value	Current Value	Min Value	Max Value	Current Value
pH	6.7	8.2	7.3	6.9	8.1	7.2
fecal coliform (no./100mL)	0	0	0	0	0	0
Turbidity (NTU)	1	21.2	5.64	1	2	1.43
Total Dissolved Solids (mg/L)	25	320	153.23	30	350	160.2
Hardness (mg/L as $CaCO_3$)	34	160	140.69	30	155	135.4
Iron (μg/L)	3.69	4.52	3.9	3.5	4.72	4.01
Arsenic (μg/L)	0	0	0	0	0	0
Fluoride (mg/L)	0	0	0	0	0	0
Lead (μg/L)	0.0291	0.0402	0.031	0.03	0.052	0.037
Nitrate (mg/L)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

[1] INRs—Indian Rupees.

Table 4. Importance weights given to criteria in Scenarios 1 and 2.

Criteria ID	Criteria	Normalized Weights for Scenario 1 (Srirangapatna)	Normalized Weights for Scenario 2 (Bilikere)
C1	CAPEX	0.131	0.103
C2	OPEX	0.131	0.128
C3	Skill requirements	0.116	0.09
C4	Reliability	0.104	0.09
C5	Ease of use	0.116	0.09
C6	Waste generation	0.078	0.077
C7	Green-house emissions	0.091	0.064
C8	Spare parts availability	0.091	0.051
C9	Energy consumption	0.091	0.09
C10	Land requirement	0.051	0.077
C11	Affordability	-	0.051
C12	Acceptability	-	0.038
C13	Public health benefits	-	0.051

Figure 2b also shows the contribution of each criterion to the performance of different technology combinations, where each color is assigned for a criterion. If a technology receives high contributions from all or most criteria, it is most likely to perform well in that scenario and vice versa [31]. Furthermore, the effect of the weightings on the groups can be seen from this. Whilst all eight treatment trains have high scores from the environmental grouping, T54 had the highest score, and as a result, the highest score overall.

The results also offer evidence of the effect of individual unit processes from the treatment trains on the overall results of WETSUiT. For instance, in this scenario, T54 and T55 have similar treatment trains. The only difference is T55 also has an extra unit process, reverse osmosis. The change in the end results is significant however, as T54 has a much higher score than T55, a difference of 0.49; see Figure 2b. In this scenario, therefore, reverse osmosis has an effective cost of 0.49 on the overall score. T54 was incapable of removing the contaminants to a high level, in contrast to T55, which is among the solutions with the best performance in removing the contaminants. This demonstrates that in a scenario where cost is prioritized, a worse performing (feasible) solution can score higher than that of a better performing solution with higher cost.

T56 and T66 consisted of almost identical unit processes, but rapid sand filtration was used for T56, and slow sand filtration was used instead for T66. As these two unit processes themselves are similar, the results of the scores might have also been close. However, there was a significant difference between the two, with T56 having a higher score by 0.15. This shows that in the case of this scenario, using rapid sand filtration instead of slow sand filtration improved the overall score. As such, rapid sand filtration could be seen as the less expensive unit process. However, similarly to the comparison made between T54 and T55, the overall treatment train with the higher score decreased the contaminant levels in the water the least. It would therefore appear that for similar treatment trains, the overall score and the effectiveness of the treatment train at removing contaminants are inversely related. Whilst it should be noted this only appears to be the case for similar trains, WETSUiT has shown that it is capable of finding the optimal middle ground between different conditions.

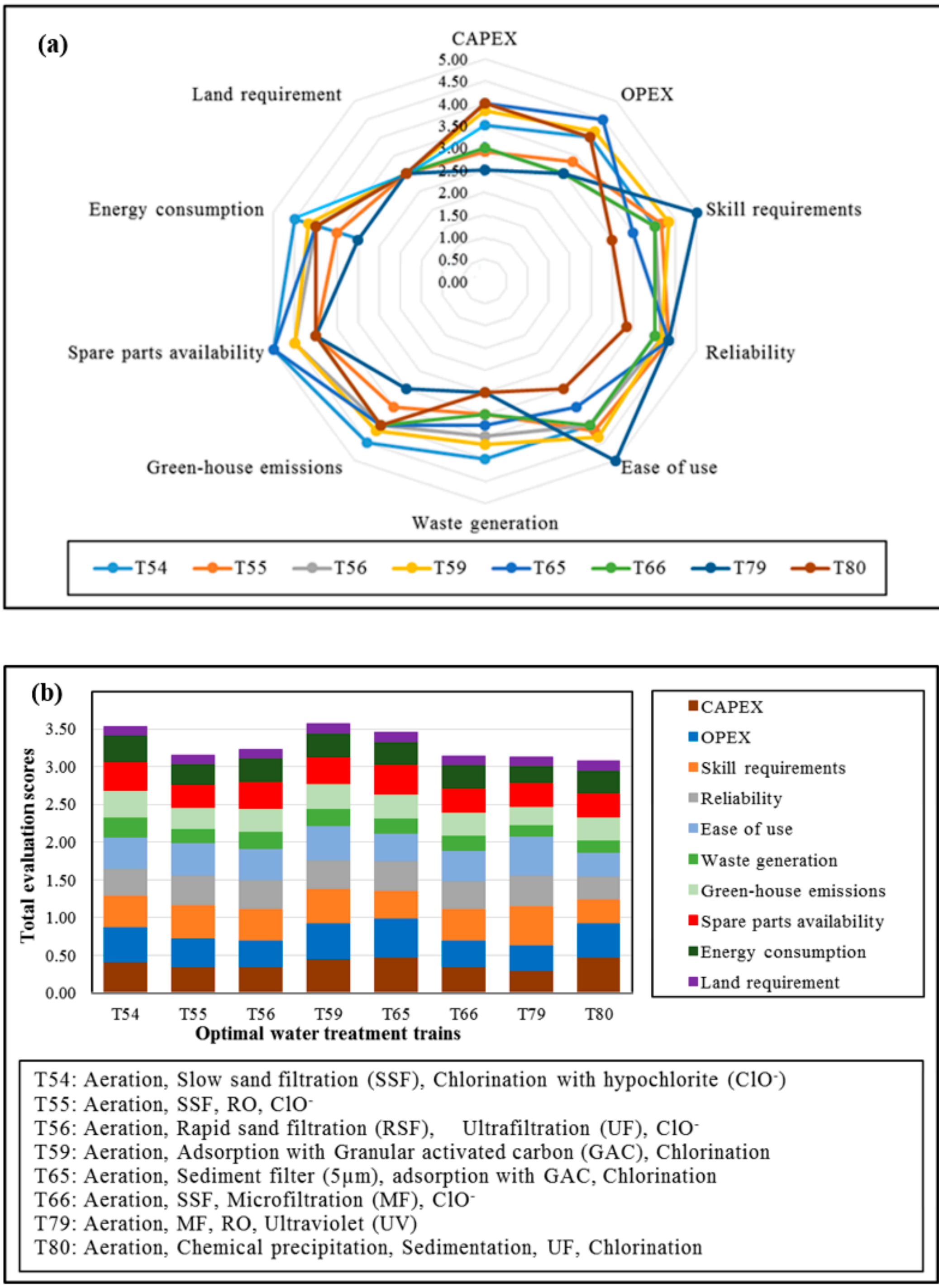


Figure 2. Results of Scenario 1—drinking water treatment systems for Srirangapatna: (**a**) Criteria/objective contribution star chart; (**b**) Stacked column on performance of water treatment systems.

3.1.2. Centralized Scenario 2—Bilikere (Scenario 2)

The second scenario was located in a smaller town (compared to Scenario 1) called Bilikere. Bilikere is part of the State of Karnataka and only about 20 kilometers from the River of Kaveri. The town requires a new water treatment facility. As a very small town, its focus will be on financial and operational criteria due to limited funds [51] and lack of education [52,53]. The weights of the evaluation criteria and assumptions of this scenario are summarized in Tables 2 and 4.

Figure 3a illustrates the star diagram comparing the performances of the best solutions with respect to all selected criteria (the weights assigned to each criterion have not been applied in this figure). It is shown in Figure 3a that the treatment technology configuration (i.e., treatment solution) T61 (in blue) and T62 (in green) perform well under most criteria. Whilst operational indicators are not the deciding factor for its overall score being highest, it had a significant impact upon the result. Based on the results illustrated in Figure 3a, T15 (in light blue) and T46 (in light grey) have not performed well under several criteria. The treatment processes in each solution (discussed in this section) are shown in Figure 3b.

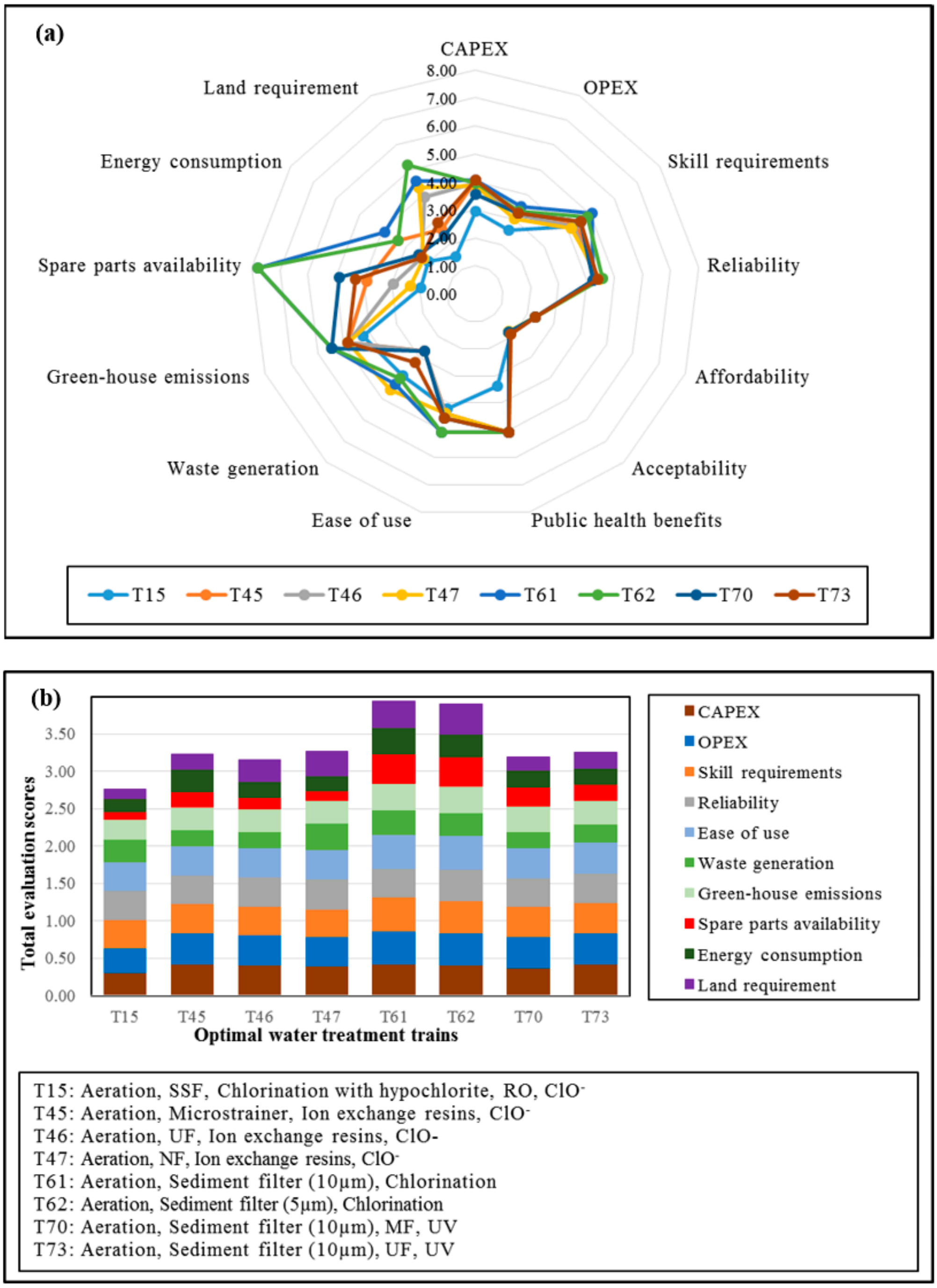


Figure 3. Results of Scenario 2—drinking water treatment systems for Bilikere: (**a**) Criteria/objective contribution star chart; (**b**) Stacked column on performance of water treatment systems.

Similar results can be seen in Figure 3b, where T61 has the highest overall score, whereas T15 has the lowest overall score. However, T61 did the least to reduce the contaminant level, although it meets the requirements in the Indian Drinking Water Quality Standards [50]. This can also be seen with T61 and T70. T61 had a much higher score than T70 but performs lower in contaminant removal. It therefore seems there is a significant trade-off between removing the amount of contaminant and having a high scoring technology.

3.2. Evaluation of Decentralized Drinking Water Treatment Systems (Self-Contained Packages) via WETSUiT

Two scenarios have been considered to evaluate decentralized water treatment packages. Thirty-three drinking water treatment packages of different sizes are available in the database. The database is expandable at any time by the user. Evaluation is considered, coinciding with the Indian Water Standards for drinking purposes [50]. Scenarios were developed to represent contrasting situations, allowing decentralized packages to be fully evaluated. Since the preference options and importance weights of criteria are likely to be different, in this study for each scenario, an altered pairwise comparison of criteria is conducted. In other words, the change of numerical values within the pair-wise comparison of criteria is subjective. The main assumptions and weights of criteria in both scenarios of decentralized water treatment systems are summarized in Tables 3 and 5, respectively.

Table 5. Importance weights given to criteria in Scenarios 3 and 4.

Criteria ID	Criteria	Normalized Weights for Scenario 3 (Srirangapatna)	Normalized Weights for Scenario 4a (Bilikere)	Normalized Weights for Scenario 4b (Bilikere)
C1	Reliability	0.05	0.06	0.18
C2	Capital Cost	-	0.19	0.14
C3	Annual O&M costs	-	0.18	0.15
C4	Ease of Installation	0.26	0.05	0.06
C5	Ease of O&M	0.16	0.16	0.11
C6	Energy Consumption	0.14	0.12	0.09
C7	Availability of Spare parts	0.08	0.02	0.02
C8	Water treatment Capacity	0.25	0.11	0.21
C9	Land/Area requirement	0.06	0.10	0.05

3.2.1. Selection of Decentralized Small-Scale System for an Emergency Situation (Scenario 3)

In the first decentralized water treatment scenario, the best small–scale systems for an emergency situation is investigated, whether it be after a natural disaster or in the case of water supply failure. Populations of developing countries are more affected by natural disasters than anywhere else in the world due to lack of physical and financial resources and infrastructure [46]. In the case of a natural disaster, such as an earthquake, a tsunami, or any other hydrological disasters, the water supply is often contaminated [47]. Small-scale systems/technologies are required to provide sufficient potable water and use varying power sources in case of unreliable electrical infrastructure. CAPEX and OPEX are not considered in this scenario, as small-scale systems are typically owned by rescue operations [49], acquired through government funds or charitable donations, and therefore, no cost is applied to the community. The system is immediately needed and should be installed as quickly as possible; therefore, Ease of Installation (C4, Criterion 4) is the key criterion in this scenario. These systems can require a large area of land, up to 8 m^2, in a central location. However, this criterion is only of moderate importance because these locations are normally open and spacious.

Figure 4a is a star chart (cobweb diagram) that illustrates the criteria contribution for water treatment packages in an emergency situation. It is important to mention that the weights given to the evaluation criteria are not considered in this diagram. In other words, all criteria are assigned similar importance. Figure 4a shows that T29 performs well under many criteria. On the other hand, it is shown that although T32 performs well with respect to many criteria (shown in Figure 4a), its overall score (shown in Figure 4b) is not high; this is due to the fact that the capacity (water production per day) of this package is below those of the other packages.

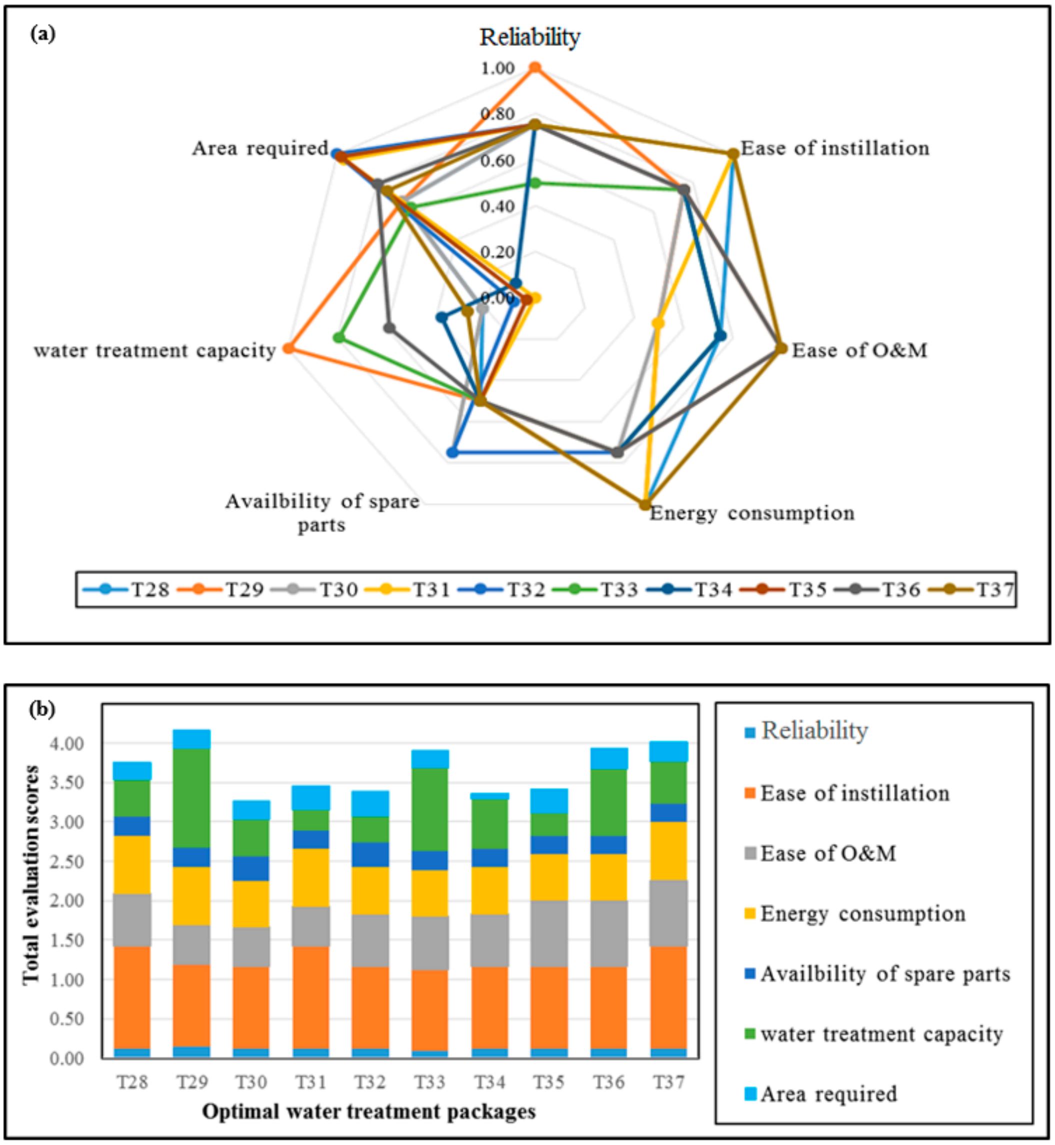


Figure 4. Results of Scenario 3—packaged drinking water treatment systems for an emergency situation: (**a**) Criteria/objective contribution star chart; (**b**) Stacked column on performance of water treatment systems.

It can be seen from the results illustrated in Figure 4a,b that there are four leading systems, of which the differences between these are marginal. Package (T29) is the preferred technology with a score of 4.17, followed by T37 (0.3441) and T36 (0.3353), respectively. T30 is the least preferred technology, with a score of 3.27. T37 is a hybrid system which provides solar power for the operation; this is one of the main reasons that this system has been selected as the second preferred technology. Few studies have analyzed the use of renewable energy technologies, particularly solar systems, for emergency situations [54]; renewable energy based technology devices are usually larger, therefore more difficult to transport. Another disadvantage of these systems is that the setup process is time consuming and should be maintained by an expert. However, these systems can be still considered the best options in many emergency situations where traditional power sources are not available [54].

3.2.2. The Effect of Income in an Urban Household Level Packaged Treatment System Selection (Scenario 4)

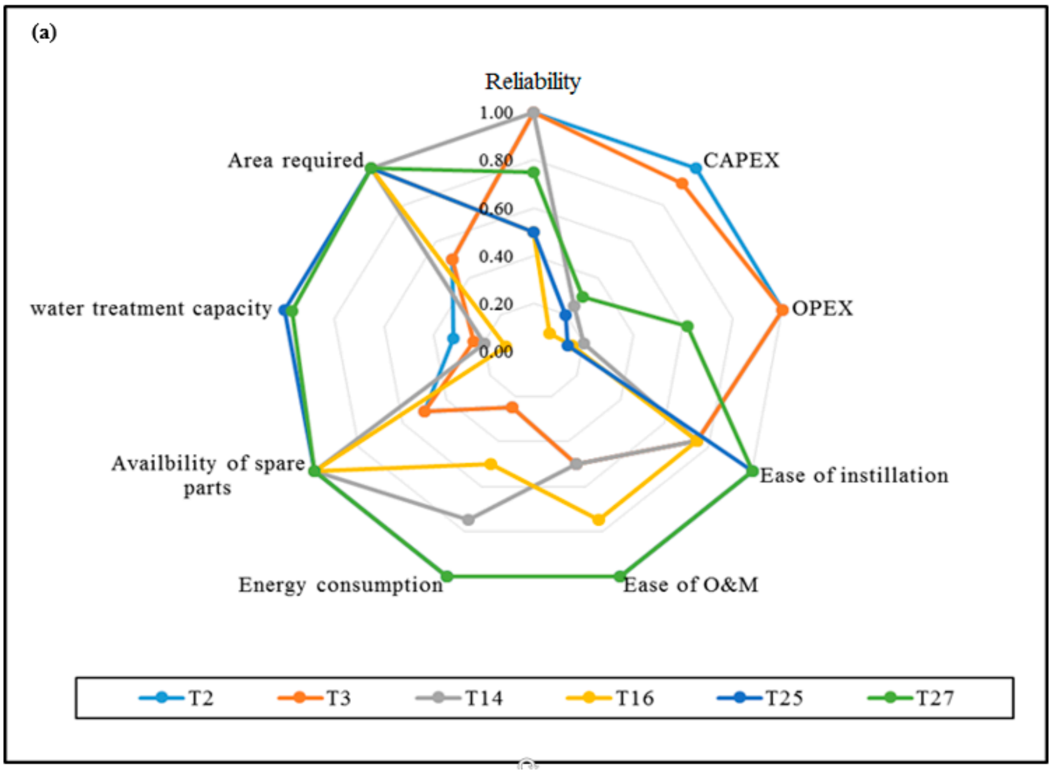
In this decentralized water treatment scenario (Scenario 4), the effect of income on the appropriate water treatment package for an urban Indian household is investigated. Income is an important factor to investigate within India. An Indian census conducted by the Socio Economic and Caste Census (SECC) in 2011 showed " . . . 79.53 per cent of households highest earning member earns less than INR 5000" and 60% have no literate adult above 25 years old [55]. In the modern world, income plays a large part on what resources are available to a household and therefore, has an effect on all criteria. A large income typically comes with a desire to live with more luxuries [56] and thus, a higher water usage [52]. In the families with low income (here, considered as Scenario 4a), cost-related criteria (C2 and C3) will have a considerable impact on technology selection, likewise, with energy consumption (C6) as it is directly related to O&M costs. The ease of installation and use (C4 and C5) are likely to be important due to the low education of occupants. Finally, space is often limited in poorer areas due to the rudimentary design and construction of houses and the number of people living under one roof.

On the other hand, in a family/community with a high income (Scenario 4b), cost-related criteria will have smaller impacts. Due to the expected expense of the system, the ease of operation will be expected to be hassle-free and the installation and maintenance can be performed by hiring personnel and are thus, of lower importance. Furthermore, with more resources and space, less importance is assigned to the criteria of installation space/area (C9) and availability of spare parts (C7). Electricity supply, also, can be expected to be regular within wealthy households [57] and the finance of energy consumption would not be a problem. The more affluent a household, the more luxuries are sought, such as a shower, bath (not bucket bath), garden etc., and therefore, more water is required. Consequently, packages that produce large quantities of water are more desired [44], giving more importance for the criterion water quantity or capacity of treatment (C8). The main assumptions and importance weights of criteria are presented in Tables 3 and 5.

Figure 5a details a range of results for decentralized water treatment packages. It can be seen that T25 (microfiber mess + activated carbon trap + magnet cartridge; with a storage tank of 20 liters; it does not require running water or electricity) and T27 (20 µm Pre-filter + activated carbon + ion-exchange; it requires running water and electricity) perform well under most criteria in this scenario. It is also shown that T2 (5 µm sediment filter + 2 stages of activated carbon + reverse osmosis membrane + activated carbon with coconut shells; with a storage tank of 53 liters; it requires running water or electricity; with a water purification capacity of 900 liters per day) and T3 (5 µm sediment filter + 2 stages of activated carbon + reverse osmosis membrane + activated carbon with coconut shells; with a storage tank of 53 liters; it requires running water or electricity; with a water purification capacity of 680 liters per day) have the lowest scores performances. It is important to mention that the importance weights are not considered in the star diagram. In other words, all criteria are assigned equal important weights. Figure 5a also shows that all these preselected six packages perform well under several criteria. Therefore, it is very difficult to finalize a decision merely based on this figure.

All packages went through two similar scenarios (Scenarios 4a and 4b); when compared alongside each other, they produced different results. The technologies have similar traits and as such, are predisposed to having similar results. Whilst the discrepancies were minor, the results did not follow the same trend, indicating the influence of scenarios.

The effect of income on selection of water treatment packages on WETSUiT can be demonstrated by comparing technologies in the stacked column (Figure 5b). All packages have been evaluated in two sub-scenarios (in low-income families and high-income families). In Figure 5b, the technologies which have been considered for Scenario 4b are marked with '(£)'. Figure 5b outlines the strengths and weaknesses of the packaged systems; treatment capacity (in brown color) is the most significant factor for the high-income household, whereas it is a lesser factor in the low income household, relative to the overall score. It is shown that in Scenario 4a, T25 has the highest overall score, whereas T2 has the lowest overall score. T27, which has the second highest score in Scenario 4a, is shown to be the most preferred solution in Scenario 4b. It can be concluded that the importance weights/factors of criteria are very influential on the final MCDA results.



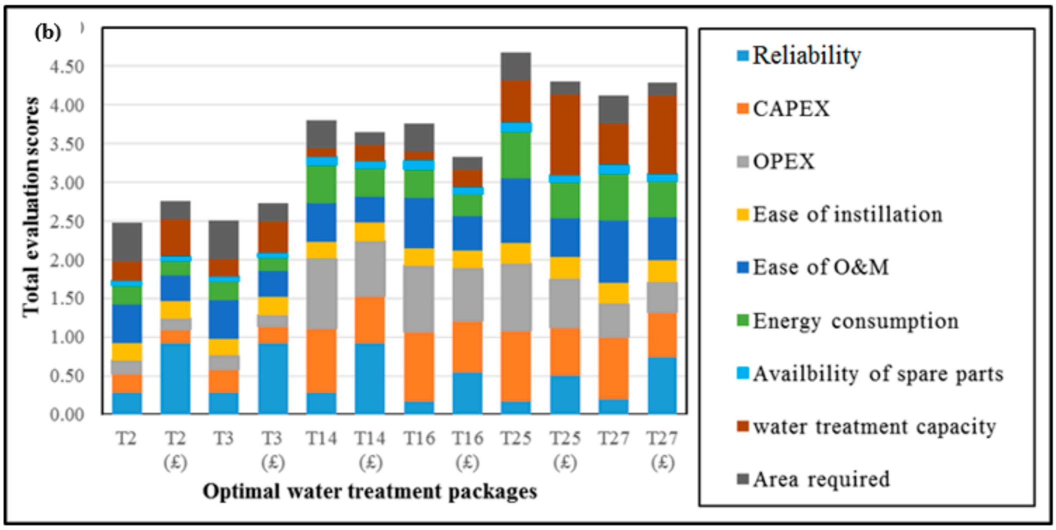


Figure 5. Results on Scenario 4—the effect of income in the selection of packaged drinking water treatment systems: (**a**) Criteria/objective contribution star chart; (**b**) Stacked column on performance of water treatment systems; technologies with '(£)' represent the evaluation results in families with high income (Scenario 4b).

4. Conclusions

In this study, a decision support tool (WETSUiT) for the selection of (drinking) water treatment systems at both community and city scales was proposed. WETSUiT is a user-friendly standalone tool that uses both Many-Objective Optimization (MOO) and Multi-Criteria Analysis (MCA) to identify optimal treatment technologies combinations/configurations. This involved a consideration of a number of criteria under four categories of financial, technical, social, and environmental aspects. The approach implemented in WETSUiT was tested for different contexts, including for different types of raw water sources, income range, living conditions, and system implementation scales. The key messages resulting from this research are:

- The WETSUiT Tool identified optimal drinking water treatment technologies with low costs, low energy consumption, and high contaminant removal efficiencies.
- The number and type of water treatment solutions vary widely based on many factors, including the ones related to user objectives and preferences and context constraints.
- The results revealed that in almost all scenarios, there was a significant trade-off between removing the amount of contaminants and having a high scoring technology.
- If a technology receives high contributions from all or most criteria, it is most likely to perform well in that scenario and vice versa. However, the final result (scores based on MCDA) can be significantly affected based on weights assigned to each criterion.
- The tool is designed in a way that can used by any user with basic knowledge of computer and/or decision making processes.
- WETSUiT offers evidence and evaluation of the effect of the individual unit processes from the treatment trains on the overall performance of each treatment train.
- The quality of the results can be further improved by adding more details on each unit process or water treatment package and/or by adding more technologies to the database. The tool has been designed in a way that its technology library (i.e., database) is expandable at any time by the user.

Supplementary Materials: This document consists of 17 pages, 2 tables and 23 Figures, and presents the templates for the developed drinking water technology library (as part of the database) and shows an overview of the main pages/forms on the decision support tool. The document is available online at http://www.mdpi.com/2073-4441/12/10/2836/s1. Figure S1: Worksheet Section S1: Technology Description, Figure S2: Worksheet Section S2: Technology installation, Figure S3: Worksheet Section S3: Technology Operation and Maintenance, Figure S4: Worksheet Section S4: Maintenance activities, Figure S5: Worksheet Section S5: Chemical Requirement for Operation and Maintenance, Figure S6: Worksheet Section S6: Chemical Requirement for Operation and Maintenance, Figure S7: Worksheet Section S7: Chemical Requirement for Operation and Maintenance, Figure S8: Worksheet Section S8: Technology performance in terms of contaminant removal, Figure S9: Main tabs on WETSUiT: Welcome to WETSUiT, Figure S10: Main tabs on WETSUiT: User Information, Figure S11: Main tabs on WETSUiT: Context Definition, Figure S12: Navigator tool on WETSUiT. Button (**a**): create a new record, (**b**): delete/remove a record and (**c**): save changes, Figure S13: Main tabs on WETSUiT: Raw Water Source, 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), Figure S18: Main tabs on WETSUiT: Results: MCDA Solution, 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, 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, Figure S23: Aspects, criteria and sub-criteria (sustainability indicators) identified in this study and used in the DSS, Table S1: Ranking system of the AHP (adopted from Saaty, (1987)), 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).

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References

1. UN. *Water Scarcity|International Decade for Action "Water for Life" 2005–2015*; United Nation (UN): New York, NY, USA, 2015.
2. Water Project. Facts and Statistics about Water and Its Effects. Water Proj. 2016. Available online: https://thewaterproject.org/water-scarcity/water_stats (accessed on 9 February 2019).
3. Ghupta, A.; Mall, R.K.; Singh, R.; Singh, R.S.; Rathore, L.S. Water resources and climate change: An Indian Perspective. *Curr. Sci.* **2006**, *90*, 1610–1626.
4. Countrymeters. Live India Population—Countrymeters. 2019. Available online: https://countrymeters.info/en/India (accessed on 9 February 2019).
5. Dadax. India Population. Worldometers. 2019. Available online: http://www.worldometers.info/world-population/india-population/ (accessed on 9 February 2019).
6. The World Bank. GDP Growth. GDP Growth Annu. 2019. Available online: https://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=IN (accessed on 10 February 2019).
7. WHO; UNICEF. *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*; World Health Organization (WHO): Geneva, Switzerland; The United Nations Children's Fund (UNICEF): New York, NY, USA, 2017.
8. Water Organisation. Water in India—India's Water Crisis & Sanitation Issues in 2019. Water.org. 2019. Available online: https://water.org/our-impact/india/ (accessed on 10 February 2019).
9. Nelson, V.I. *New Approaches in Decentralized Water Infrastructure*; The Coalition for Alternative Wastewater Treatment: Gloucester, MA, USA, 2008; p. 79.
10. W4I. (Smart, Cost-Effective Solutions for Water Treatment and Monitoring in Small Communities in India. Decision Support System Integration)|Report Summary|WATER4INDIA|FP7-ENVIRONMENT. CORDIS Eur. Comm. 2016. Available online: https://cordis.europa.eu/project/id/308496 (accessed on 19 February 2019).
11. Pain, A. Decentralised Supply. Sustain. Sanit. Water Manag. Toolbox. 2018. Available online: https://sswm.info/water-nutrient-cycle/water-distribution/hardwares/water-network-distribution/decentralised-supply (accessed on 10 February 2019).
12. Alfa, D.; Rathilal, S.; Pillay, V.L.; Pikwa, K.; Chollom, M.N. Development and evaluation of a small scale water disinfection system. *J. Water Sanit. Hyg. Dev.* **2016**, *6*, 389–400. [CrossRef]
13. Cook, S.; Tjandraatmadja, G.; Ho, A. *Definition of Decentralised Systems in the South East Queensland Context*; Technical Report No. 12; Urban Water Security Research Alliance: City East, QLD, Australia, 2009.
14. Peter-Varbanets, M.; Zurbrügg, C.; Swartz, C.; Pronk, W. Decentralized systems for potable water and the potential of membrane technology. *Water Res.* **2009**, *43*, 245–265. [CrossRef] [PubMed]
15. Pavan, M.; Todeschini, R. 1.19—Multicriteria Decision-Making Methods. In *Comprehensive Chemometrics*; Brown, S.D., Tauler, R., Walczak, B., Eds.; Elsevier: Oxford, UK, 2009; pp. 591–629. [CrossRef]
16. Rossman, L.A. Computer-aided synthesis of wastewater treatment and sludge disposal systems. In *Computer-Aided Synthesis of Wastewater Treatment and Sludge Disposal Systems*; EPA: Washington, DC, USA, 1979.
17. Rossman, L.A. Synthesis of Waste Treatment Systems by Implicit Enumeration. *J. Water Pollut. Control. Fed.* **1980**, *52*, 148–160.
18. Tang, S.; Wong, C.L.; Ellis, K.V. An Optimization Model for the Selection of Wastewater and Sludge Treatment Alternatives. *Water Environ. J.* **1997**, *11*, 14–20. [CrossRef]
19. Chen, J.; Beck, M.B. Towards designing sustainable urban wastewater infrastructures: A screening analysis. *Water Sci. Technol.* **1997**, *35*, 99–112. [CrossRef]
20. Balkema, A.J.; A Preisig, H.; Otterpohl, R.; Lambert, F.J. Indicators for the sustainability assessment of wastewater treatment systems. *Urban Water* **2002**, *4*, 153–161. [CrossRef]
21. Economopoulou, M.; Economopoulos, A. Expert system for municipal wastewater management with emphasis in reuse. *Water Sci. Technol. Water Supply* **2003**, *3*, 79–88. [CrossRef]
22. Finney, B.A.; Gerheart, R.A. *A User's Manual for WAWTTAR*; Environmental Resources Engineering, Humboldt State University: Arcata, CA, USA, 2004.
23. Joksimovic, D.; Kubík, J.; Hlavinek, P.; Savic, D.; Walters, G. Development of an integrated simulation model for treatment and distribution of reclaimed water. *Desalination* **2006**, *188*, 9–20. [CrossRef]

24. Bottero, M.; Comino, E.; Riggio, V. Application of the Analytic Hierarchy Process and the Analytic Network Process for the assessment of different wastewater treatment systems. *Environ. Model. Softw.* **2011**, *26*, 1211–1224. [CrossRef]
25. Adewumi, J.R. A Decision Support System for Assessing the Feasibility of Implementing Wastewater Reuse in South Africa. Ph.D. Thesis, The University of Witwatersrand, Johannesburg City, South Africa, 2011.
26. Kalbar, P.P.; Karmakar, S.; Asolekar, S.R. Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. *J. Environ. Manag.* **2012**, *113*, 158–169. [CrossRef] [PubMed]
27. Kalbar, P.P.; Karmakar, S.; Asolekar, S.R. The influence of expert opinions on the selection of wastewater treatment alternatives: A group decision-making approach. *J. Environ. Manag.* **2013**, *128*, 844–851. [CrossRef] [PubMed]
28. Loo, S.-L.; Fane, A.G.; Krantz, W.B.; Lim, T.-T. Emergency water supply: A review of potential technologies and selection criteria. *Water Res.* **2012**, *46*, 3125–3151. [CrossRef] [PubMed]
29. Garrido-Baserba, M.; Reif, R.; Hernandez, F.; Poch, M. Implementation of a knowledge-based methodology in a decision support system for the design of suitable wastewater treatment process flow diagrams. *J. Environ. Manag.* **2012**, *112*, 384–391. [CrossRef]
30. Sadr, S.M.K.; Saroj, D.P.; Kouchaki, S.; Ilemobade, A.A.; Ouki, S.K. A group decision-making tool for the application of membrane technologies in different water reuse scenarios. *J. Environ. Manag.* **2015**, *156*, 97–108. [CrossRef]
31. Sadr, S.M.K.; Saroj, D.P.; Mierzwa, J.C.; McGrane, S.J.; Skouteris, G.; Farmani, R.; Kazos, X.; Aumeier, B.; Kouchaki, S.; Ouki, S.K. A multi expert decision support tool for the evaluation of advanced wastewater treatment trains: A novel approach to improve urban sustainability. *Environ. Sci. Policy* **2018**, *90*, 1–10. [CrossRef]
32. Sadr, S.M.K.; Onder, T.; Saroj, D.; Ouki, S. Appraisal of membrane processes for technology selection in centralized wastewater reuse scenarios. *Sustain. Environ. Res.* **2013**, *23*, 69–78.
33. Oertlé, E.; Hugi, C.; Wintgens, T.; Karavitis, C. Poseidon—Decision Support Tool for Water Reuse. *Water* **2019**, *11*, 153. [CrossRef]
34. Duncan, A.P.; Sadr, S.M.K.; Memon, F.A.; Savic, D.A. Comparison of Many-Objective Optimisation and Multi-Criteria Analysis for Improved Water Energy Efficient Design of Water Treatment Works for India. In Proceedings of the Water Efficiency Conference 2015, WatEfNetwork, Exeter, UK, 5–7 August 2015. [CrossRef]
35. WaterAid. *Drinking Water and Sanitation—Status in India; Covering Financing and Emerging Concerns*; WaterAid India: New Delhi, India, 2005.
36. Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197. [CrossRef]
37. Lu, J.; Zhang, G.; Ruan, D.; Wu, F. *Multi-Objective Group Decision Making: Methods, Software and Applications with Fuzzy Set Techniques (With CD-ROM)*; World Scientific: Singapore, 2007.
38. Dodgson, J.S.; Spackman, M.; Pearman, A.; Philips, L.D. *Multi-Criteria Analysis: A Manual*; Department for Communities and Local Government Wetherby: West Yorkshire, UK, 2009.
39. De FSM Russo, R.; Camanho, R. 2015. Criteria in AHP: A Systematic Review of Literature. *Procedia Comput. Sci.* **2015**, *55*, 1123–1132. [CrossRef]
40. Zyoud, S.H.; Kaufmann, L.G.; Shaheen, H.; Samhan, S.; Fuchs-Hanusch, D. A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS. *Expert Syst. Appl.* **2016**, *61*, 86–105. [CrossRef]
41. Sadr, S.M.K. Application of Membrane Assisted Technologies in Water Reuse Scenarios. Ph.D. Thesis, Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey, UK, 2014.
42. Saaty, R.W. The analytic hierarchy process—What it is and how it is used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
43. Zeleny, M.; Cochrane, J.L. Compromise Programming. In *Multiple Criteria Decision Making*; University of South Carolina Press: Colombia, SC, USA, 1974; pp. 1296–1298.
44. MuthuNesaBeula, T.; Prasad, E.G. Multiple Criteria Decision Making with Compromise Programming. *Int. J. Eng. Sci. Technol.* **2012**, *94*, 4083–4086.

45. Gorantiwar, S.D.; Smout, I.K. Multi-criteria decision making (compromise programming) for integrated water resources management in an irrigation scheme. In Proceedings of the the 3rd International Perspective on Current & Future State of Water Resources & the Environment, Chennai, India, 5–7 January 2010.
46. CFI. *The Effects of Natural Disasters*; Child Fund International (CFI): Henrico County, VA, USA, 2015.
47. CDC. Flood Water After a Disaster or Emergency Floods; Emergency Preparedness and Response. Center for Disease Control and Prevention (CDC). 2016. Available online: http://emergency.cdc.gov/disasters/floods/cleanupwater.asp. (accessed on 13 April 2016).
48. ORGCC. *Census of India: Office of the Registrar General & Census Commissioner, India: Karnataka*; Office of the Registrar General & Census Commissioner (ORGCC): New Delhi, India, 2011.
49. Tratschin, R.; Spuhler, D. Community and Camp Water Supply. *Sustain. Sanit. Water Manag.* 2011. Available online: http://www.sswm.info/content/community-and-camp-water-supply. (accessed on 13 April 2016).
50. BIS. *Indian Standard Drinking Water—Specification (Second Revision), (Standards No. IS:10500:2012)*; Drinking Water Sectional Committee, Bureau of Indian Standards (BIS): New Delhi, India, 2012.
51. IANS. In Bulk of Rural India, Rs 5,000 is Highest Monthly Wage (Newspaper Report). CNN News18, India. 2015. Available online: https://www.news18.com/news/india/in-bulk-of-rural-india-rs-5000-is-highest-monthly-wage-1015585.html. (accessed on 22 February 2019).
52. Gleick, P.H. Water Use. *Ann. Rev. Environ. Resour.* **2003**, *28*, 275–314. [CrossRef]
53. Sadr, S.M.K.; Memon, F.A.; Duncan, A.P.; Johns, M. *Water Treatment Technology Selection Tool Capable of Identifying Optimal Treatment Terrain Configurations*; EU FP7 Water4India Project Deliverable D6.5., (EU FP7 Water4India Project, Deliverable No. D6.5); University of Exeter: Exeter, UK, 2016.
54. Ray, C.; Jain, R. *Low Cost Emergency Water Purification Technologies: Integrated Water Security Series*; Butterworth-Heinemann: Oxford, UK, 2014.
55. IBN Live. In Bulk of Rural India, Rs 5,000 is Highest Monthly Wage—IBNLive [WWW Document]. CNN IBN Live. 2015. Available online: http://www.ibnlive.com/news/india/in-bulk-of-rural-india-rs-5000-is-highest-monthly-wage-1015585.html (accessed on 9 April 2016).
56. EO. Income Elasticity of Demand'. Economics Online (EO). 2016. Available online: http://www.economicsonline.co.uk/Competitive_markets/Income_elasticity_of_demand.html. (accessed on 20 August 2016).
57. Banerjee, S.G.; Barnes, D.; Mayer, K.; Singh, B.; Samad, H. *Power for All: Electricity Access Challenge in India*; World Bank Publications: Washington, DC, USA, 2014.