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Strategic Evaluation Tool for Surface Water Quality Management Remedies in Drinking Water Catchments

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Received: 6 July 2017; Accepted: 22 September 2017; Published: 27 September 2017

Abstract: Drinking water catchments (DWC) are under pressure from point and nonpoint source pollution due to the growing human activities. This worldwide challenge is causing number of adverse effects, such as degradation in water quality, ecosystem health, and other economic and social pressures. Different evaluation tools have been developed to achieve sustainable and healthy drinking water catchments. However, a holistic and strategic framework is still required to adequately consider the uncertainty associated with feasible management remedies of surface water quality in drinking water catchments. A strategic framework was developed to adequately consider the uncertainty associated with management remedies for surface water quality in drinking water catchments. A Fuzzy Multiple Criteria Decision Analysis (FMCDA) approach was embedded into a strategic decision support framework to evaluate and rank water quality remediation options within a typical fixed budget constraint faced by bulk water providers. The evaluation framework consists of four core aspects; namely, water quality, environmental, economic and social, and number of associated quantitative and qualitative criteria and sub-criteria. Final remediation strategy ranking was achieved through the application of the Euclidean Distance by the In-center of Centroids (EDIC).

Keywords: drinking water catchments; evaluation framework; Fuzzy Multiple Criteria Decision Analysis (FMCDA); Fuzzy Decision Tree Analysis (FDTA)

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1. Introduction

Drinking water catchments (DWC) are sites where fresh water is collected and used for drinking water supply purposes. These resources are under pressure from point and nonpoint source pollution due to the growing human activities. Enhanced water quality for these resources will lead to a wide range of benefits including: healthy ecosystems, decreased sediment and nutrient load, quality drinking water, amenity, and other recreation benefits [1–3]. Moreover, it will lead to catchment sustainability [4–6]. In general, the quality of water in DWC has been greatly affected by point and nonpoint source of pollution due to growing human activities. Point and Non-Point Source (PNPS) of pollutants can be one or more of the following types: sediment, from wind and water soil erosion, nutrients from fertilizer, animal waste, and sewage-treatment plants, pathogens from livestock husbandry and septic systems, herbicides and pesticides such as insecticides, fungicides, etc., salt from winter road application, and toxic minerals, from manufactured and refined products [7–9]. Consequently, these impacts will affect the biodiversity, geochemical, and hydrological cycles of DWC [10].

Healthy DRCs are important resources for secure drinking water supplies [11,12]. They can also be desirable sources for recreation activities [13,14], habitat for plants and animals [15,16], healthy vegetation and waterways [17,18], and reliable and clean water for stock and irrigation [16,19]. However, these dynamics can directly influence the environmental, social, and economic aspects of any city. Furthermore, any decision regarding water quality in any DWC will directly impact on the above dynamic status. Therefore, evaluating management strategies for water quality improvement in DWC is crucial.

Different frameworks have been developed to evaluate water resources management strategies. Recent studies focused on the evaluation of surface water quality management options are summarized in Table S1 (supplementary files section A). Most of the researchers have completed evaluations for the purpose of assessing management strategies to meet specific water quality standards and/or to meet sustainability standards for a river or catchment. None of these studies have comprehensively considered the assessment of different quantitative and qualitative criteria and management remediation strategies in DWC. Moreover, few have iteratively considered the direct and indirect impacts of criteria variable on environmental and socio-economic factors, along with the well-established water quality factors. Other researchers have evaluated different management strategies to improve water quality in catchments, such as soil conservation measures [20], risk assessment for effective restoration management [21], and watershed conservation management [22,23]. The challenge is to determine a solution to obtain sustainable DWC and enhance its water quality, environmental, societal, and economic values [24]. A holistic and flexible framework is needed to quantify the extent to which each potential management options addresses the water quality, environmental, social, and economic objectives of a particular water authority.

Uncertainty always exists in management decisions. Some of the studies shown in Table S1 address various aspects of uncertainty, either through considering mathematical, statistical and computational aspects of formulations, or for other environmental and socio-economic aspects of management implementation. Sensitivity analysis has often been applied to handle uncertainty. While, uncertainty is acknowledged as being critical for an adequate evaluation, few reported studies have sufficiently addressed uncertainty. To enhance the sustainability of DWC, it is necessary to deal with uncertainties and their associated barriers. Miljkovic [25] studied the decision-making process in a nonpoint source of pollutants control system. He found that uncertainties have a direct impact on the correspondence between emission and ambient levels of a pollutant. A multi-level mathematical programming methodology was developed associated with an economic model for Non-Point Source (NPS) pollution prevention based on a microeconomic method. However, uncertainty should be iteratively addressed across a range of diverse quantitative and qualitative criteria, and be able to assess multiple remediation options that are being considered. Moreover, any developed evaluation framework should be able to involve decision makers in the evaluation and assessment process, particularly for the more qualitative economic and social criteria.

Different approaches and methodologies have become prominent for evaluating water quality remediation strategies, including Multiple Criteria Decision Analysis (MCDA) [26–29], hydrologic modeling [30–32], cost-effective analysis [33–35] and statistical analysis [36–38]. MDCA has been widely used as an approach to evaluate water quality strategies in catchments through different study approaches, such as catchment water planning and management, catchment assessment and prioritization, water quality management, mining water management, and urban water management. Haider et al. [4] have developed a framework to evaluate different water quality management options (using four wetland types) to meet the water quality objectives of natural rivers. Most of the framework examples show the effectiveness of the conservation and restoration management measures. Badar et al. [22] have shown the assessment of the conservation and management strategies for the Dal Lake ecosystem in Kashmir. The MCDA approach was considered to be the most accepted, time efficient, data tolerant, and reliable approach to be adopted for this study [4,17,39–41]. MCDA complemented by fuzzy-set theory to handle uncertainty, led to the adoption of the FMCDA framework in this study.

Accordingly, water resources decision makers and planners in need of an integrated framework which is flexible and reliable for identifying problems and applying solutions [4]. To set an integrated framework, a goal will be identified with a set of objectives that will interact with and influence the goal accordingly. The evaluation process will begin by establishing the criteria and sub-criteria variables. Evaluation of sub-criteria is the key to quantifying the extent to which an objective has been achieved [42]. Criteria should be quantifiable and limited in number [43,44]. The difficulties in water resource management center around uncertainty and especially in quantifying certain elements that contribute to the criteria performances of the management options [45]. To take into account this uncertainty, a method such as fuzzy set theory is required [46].

To the best of our knowledge, there is presently no flexible and comprehensive DWC mediation option evaluation framework that includes the following key elements: (i) evaluating NPS of pollution controls to manage surface water quality in DWC considering multi-criteria and uncertainty; (ii) development of a system to score qualitative and quantitative sub-criteria variables using a Fuzzy Scoring System (FSS) and expert elicitation technique; and (iii) the ranking of multiple potential management options using the Euclidean Distance by the In-center of Centroids (EDIC) method. Therefore, the holistic framework presented in this paper was developed using FMCDA to incorporate these essential elements. An illustrative application of the developed framework has been provided to demonstrate its functionality.

The sections of the paper are organized as follows. Section 2 describes the development process and components of the overall framework along with the evaluation steps, criteria and, sub-criteria, and finally the management options assessment and ranking. Section 3 summarizes the main conclusions of the study and directions for future research. Readers should note that this current work is part of an ongoing study to strategically evaluate remediation options for drinking water resources.

2. Framework Development

In this research, a Fuzzy Multiple Criteria Decision Analysis (FMCDA) approach was embedded into a strategic decision support framework to evaluate and rank proposed water quality remediation strategies within a typical fixed budget constraint faced by bulk water providers. The proposed evaluation framework consists of four core aspects, namely, water quality, environmental, economic, and social. Each aspect includes a number of associated criteria and sub-criteria encompassing both quantitative and qualitative fuzzy sets for each performance category. The evaluation of considered drinking water catchment management strategies was completed using a Fuzzy Decision Tree Analysis (FDTA) process, following by strategy ranking as achieved through the application of the EDIC method. The framework has been designed for senior water authority managers seeking to efficiently identify the best strategy for improving drinking water reservoir catchment water quality, in a holistic multi-criteria manner and within a constrained budget. Such a framework reduces the amount of redundant feasibility and design activities undertaken for exploring remediation strategies that will not optimally address the water authorities' objectives and budget constraints.

The proposed framework includes the following six main steps (Figure 1):

- Step 1—Identification and selection of available management options
- Step 2—Identification and selection of criteria and sub-criteria
- Step 3—Baseline evaluation of sub-criteria and weighting
- Step 4—Evaluation of management remediation options using FDTA
- Step 5—Aggregation of sub-criteria score
- Step 6—Ranking of management remediation strategies using EDIC

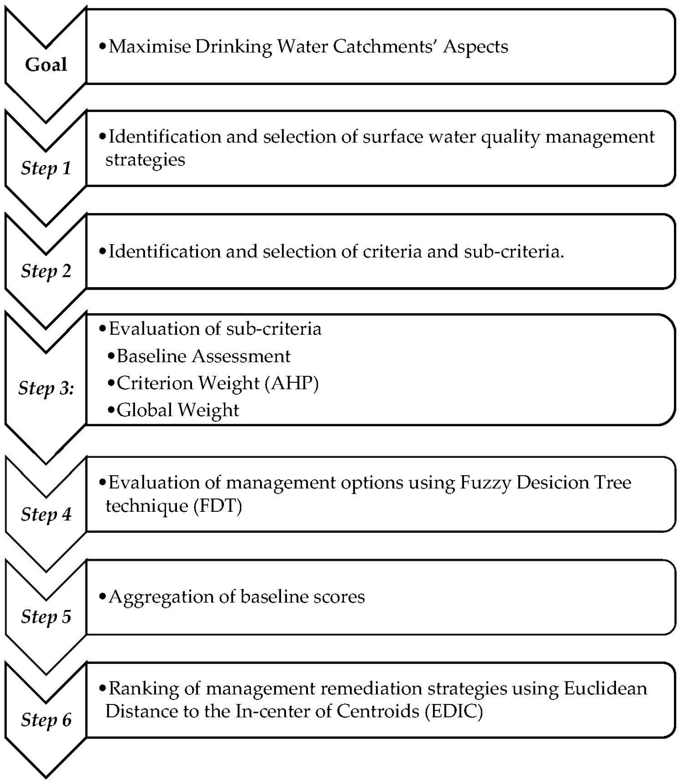


Figure 1. Proposed framework structure flow chart.

2.1. Step 1: Identification and Selection of Surface Water Quality Management Remedies

Catchments can be classified based on geographical conditions, climate, and land use and management. In this study, the selection of "catchment" refers to the land usage as a drinking water supply catchment. Many countries have developed a water management plan in which a set of management options has been studied or implemented through some projects to solve water problems. These management options are various in terms of their budget and outcome quality. Logically, the most expensive option would be expected to result in the best quality outcome. However, that outcome may not always be true when the problem is complicated and related to a set of qualitative and quantitative criteria [47]. For instance, delaying the implementation of an expensive management options through implementing simple nutrient or sediment control options at appropriate locations in the catchment can save time and money. In South East Queensland, drinking water catchments are managed by state-owned agencies with strictly allocated budgets, and so are typically constrained by these funding allocations when deciding on potential water quality remediation strategies.

There are different management remediation options that apply in drinking water catchments to treat point and non-point source of pollutants. Decision makers are required to select the most appropriate management remediation options to address water quality and other issues within their unique catchments. The recommended strategies advocated by reservoir custodians include: erosion and sediment control, nutrient control, animal contamination prevention, pest management plan, fire management plan, sediment stability, and other training and educational sessions. Figure 2 shows some examples of different surface water quality management remediation techniques. In this paper, an evaluation of grass riparian filter strips techniques has been used as an example. Strategy 1 refers to grass filter strips (GFS).

The National Management Measures to Protect and Restore Wetlands and Riparian Areas for the Abatement of Nonpoint Source Pollution guideline [48] explained the factors influencing the increase/decrease of NPS pollutants, such as: frequency and duration of extreme events, types of soil, slope of landscape, type of vegetation, balance of nitrogen and carbon, and the ratio of edge to water area or riparian area. Table 1 presents some evidence describing the effectiveness of deferent remediation options for reducing NPS of pollutants.

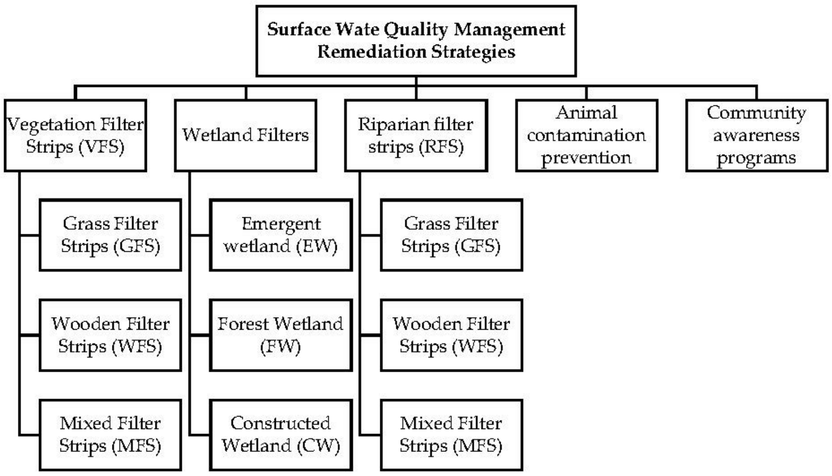


Figure 2. Example of surface water quality management remediation strategies.

Table 1. Example of evidence of management option effectiveness of reduction of NPS pollutants.

Variables	Nutrient Control	Erosion & Sediment Control	Riparian Filter Strips	Wetland Filters	Reference
Turbidity/ Total Suspended Solids	86–90%	50%	84–90%	76–97%	[48]
Nitrates (NO_3^-)	61–92%	67%	79–93%	86%	[48]
Nitrites (NO_2^-)	61–92%	79%	>80%	47%	[48]
Phosphorus (P)	65–78%	25%	80%	48%	[48]
Water-quality Treatment Cost (WTC)	10%	40%	15%	20%	[48]
Project/ Investment Cost (IC)		$500–$10,000/acre	$26,000 per acre	$18,793/acre	[48,49]
Boating, Fishing, Camping (BFC)	$371,350/year		$3714/year/acre	$3714/year/acre	[50]
Maintenance Cost (MC)			$1.5 m–$2.1 m/year	$1.6 m/year	[48]

Palone et al. [49] examined how riparian forest buffers were used to treat stormwater in the Chesapeake Bay catchment. They found that the cost of engineered stormwater Best Management Practices (BMPs) that incorporate natural systems, such as grassed swales and bio-retention areas, is less expensive than the construction of storm drain systems, and cost between $500 and $10,000 per acre. Moreover, they showed that these types of BMPs can reduce nutrient levels between 40–90%. 70% of riparian zone restoration can contribute to savings of more than US $1 million annually, through reducing river dredging and water treatment costs [48]. The cost of restoring 19.7 miles of Gale Creek and 26.1 miles of Dairy Creek, two tributaries of the Tulatin River, were estimated at US $660,000, or US $2 per person in Washington County. According to The National Management Measures to Protect and Restore Wetlands and Riparian Areas for the Abatement of Nonpoint Source Pollution guideline [48], four wetlands were constructed in the Des Plaines River Catchment to improve water quality. The four wetlands were found to reduce TSS by 86–90%, nitrogen by 61–92% and phosphorus by 65–78%. Sperl et al. [50] showed in their study that the total recreational benefits of the constructed wetland amounts to US $371,350 per year.

2.2. Step 2: Identification and Selection of Criteria and Sub-Criteria

The identification of the different criteria and sub-criteria to evaluate alternatives should consider the DWC custodians objectives and key water related policies. Each country has a set of external and internal conditions to ensure integrated planning and management, starting with the objectives, such as legal, institutional, technical, economic, and social. In water management projects, water-related policies may include government decisions on environmental protection and social issues, such as enhancing the quality of water in reservoirs [4,18,21,51]. Four broad evaluation aspects were adopted in this study, namely: water quality, environmental, economic, and social aspects. Each aspect consists of a set of main criteria and associated sub-criteria variables. Relevant criteria and sub-criteria can be selected by decision makers from a broader suite of options.

Each DWC has its own unique characteristics with a particular climate, hydro-morphology, soil type, etc. The formulated framework is flexible enough to include appropriate criteria and sub-criteria that will cater for the unique DWC characteristics, as well as objectives of the custodian water authority. The identified suite of useable criteria and sub-criteria was assembled by completing a comprehensive review of surface water quality planning and management projects, covering the four the broad evaluation aspects mentioned above. A review list of criteria and sub-criteria is shown in Table S2, supplementary files section B. The final list of criteria and sub-criteria was refined using a series of in-depth interviews with 11 selected experts covering both the practitioner (i.e., planning scientists, water authority managers) and the science field (i.e., university professors and researchers). The interviewees were asked to rate each criterion and associated sub-criteria according to their importance level using a five-point Likert scale (where 1 = least important/or not relevant; 2 = less important; 3 = neutral; 4 = important; and 5 = most important) with an explanation of the reason why they selected that particular rating. Janhunen [52] identified the advantages of using Likert-type rating among visually-aided rating. Some experts believed that including all types of dissolved nitrogen was not necessary and that Total Nitrogen value was the most important type of dissolved nitrogen to include. Other experts critiqued the presence of criterion that were difficult to measure, such as the social and cultural aspect such as the willingness to pay, or change conservation activities. The final list of criteria and sub-criteria were selected using only those that were considered 'important' and 'most important' according to the rating scale. The final list of criteria and sub-criteria is shown in Table 2.

Table 2. Final list of evaluation criteria and sub-criteria.

Aspects	Criteria	Sub-Criteria	
		Code	**Variables**
Water Quality	Physical (P)	P 1	Turbidity/ Total Suspended Solids (TSS)
		P 2	pH
		P 3	Temperature (T)
		P 4	Salinity/Conductivity
		P 5	Taste and Odour
		P 6	Colour
	Chemical (C)	C 1	Total Dissolved Solids (TDS)
		C 2	Dissolved Oxygen (DO)
		C 3	Chlorophyll a (Chl *a*)
	Dissolved Nutrients (DN)	DN 1	Total Nitrogen (TN)
		DN 2	Total Phosphorus (TP)
	Primary and Secondary Production (PSP)	PSP 1	Aquatic plants (AP)
		PSP 2	Aquatic Macroinvertebrate (AMI)
		PSP 3	Fish
		PSP 4	Terrestrial Wildlife (Biodiversity) (TW)
Environmental	Water-Based Toxins (WT)	WBT 1	Cyanobacteria
		WBT 2	Herbicide (HR)
		WBT 3	Pesticides (PS)
		WBT 4	Heavy metals (HM)
	Health-Based Pathogens (HBP)	HBP 1	Bacteria
		HBP 2	Viruses
		HBP 3	Protozoa
	Flow and Morphology (FM)	FM 1	Environmental flow (EF)
		FM 2	Bank stability (BS)
		FM 3	Soil erosion (SE)

Table 2. *Cont.*

Aspects	Criteria	Sub-Criteria	
		Code	Variables
Economical	Reduction benefits (RB)	RB 1 RB 2	Water quality treatment (WQT) Water quality monitoring (WQM)
		RB 4 RB 5	Project/Investment (PI) Operation & Maintenance (MN)
	Indirect benefits (IB)	IB 1 IB 2	Capability development (CD) Job creation opportunity (JO)
Social and Cultural	Recreational Values (RV)	RV 1 RV 2 RV 3	Amenity & visual use (VU) Primary contact (PC) Secondary contact (SC)
	Cultural Values (CV)	SCV 1 SCV 2	Aboriginal heritage values (AHV) Culture & Spiritual (CAS)

2.3. Step 3: Baseline Evaluation of Sub-Criteria and Weighting

The evaluation step of each sub-criteria consisted of three parts, namely: Step (3a) baseline assessment; Step (3b) create global weights; and Step (3c) baseline score. The details of each step are as follows:

2.3.1. Step 3a: Baseline Assessment Using Fuzzy Set Analysis (FSA)

One of the difficulties encountered when attempting to quantify criteria and sub-criteria in the field of water resources management is uncertainty [47]. These uncertainties contributed to the selection of the most suitable scoring system as well as weighting preferences [53]. It is essential that the proposed systems have the capability to represent and process uncertain information in a logic way. There are two types of models that have been proposed for processing uncertain knowledge. One is based on the probabilistic theory [54], while the other is based on the possibility or fuzzy sets theory which we have adopted in our methodology [55,56]. The application of probabilistic models to the herein water resources problem is challenging, since variable probabilities are not often available and their dependencies are not precisely known [47]. In contrast, fuzzy sets theory is more suitable for problems such as this one where extensive data is was not available. Any uncertainty can be represented by a fuzzy set that deals with the membership or non-membership of objects in a set with imprecise boundaries [57].

In this study, we applied the fuzzy set theory approach to evaluate the sub-criteria variables. The fuzzy membership functions used in this study were the triangular Equation (1) and trapezoidal Equation (2) fuzzifiers. The triangular fuzzy membership represents a crisp value to solve critical variable, for example, if cyanobacteria toxins more than 20,000 cells/mL then the score is poor. If below 20,000 cells/mL then the score is good.

$$Triangular: \ fi(x;a,b,c) = \begin{Bmatrix} 0 & x \leq a \\ \frac{x-a}{b-a} & a \leq x \leq b \\ \frac{c-x}{c-b} & b \leq x \leq c \\ 0 & c \leq x \end{Bmatrix} \quad (1)$$

$$Trapezoidal: \ fi(x;a,b,c,d) = \begin{Bmatrix} 0 & x < a \, or \, d < x \\ \frac{a-x}{a-b} & a \leq x \leq b \\ 1 & b \leq x \leq c \\ \frac{d-x}{d-c} & c \leq x \leq d \end{Bmatrix} \quad (2)$$

Accordingly, the quantitative and qualitative criterion will be assessed based on If-Then rules and the fuzzy inference method with the support of evidence from literature and/or through an expert's elicitation process (Figure 2). Basili et al. [58] provided a comparative analysis with Fuzzy set advantages as: (i) the form of conditional rules is the easiest and best understood way for decision makers (DM); (ii) it is straightforward to establish the rule based on a unit of measure so that the addition, retrieval and deletion of rules can be carried out independently; and (iii) conditional rules can deal with uncertainty effectively by the introduction of certainty factors. For example:

- If odor concentration is more than 0.009 ppb, then score is poor
- If water treatment cost is increased by 15%, then water quality treatment cost (WTC)score is poor

Alternatively, if the rule is still uncertain (especially when assessing a qualitative criterion) then the problem can be described in fuzzy inference. In fuzzy inference, imprecise information concerning the logic structure or the conclusions of rules is represented. Yan et al. [59] described the classification of the uncertainty knowledge in fuzzy inference. Fuzzy inference allows determination of the output of the system from fuzzy inputs and fuzzy rules. The principle of fuzzy inference is based on the Mamdani method [56,57]. For example:

- If odor score is poor, then amenity score is poor
- If dissolved oxygen (DO) score is good, then restoration score is good
- If water treatment cost is poor, then water bill is poor

Finally, the qualitative and quantitative criterion value was normalized and their real value transformed into a Fuzzy Value (FV) using a cardinal scale of 1–10. The validation process of the baseline scoring assessment is shown in Figure 3. Table 3 shows that the rating levels for the Fuzzy Linguistic Variable used were: very poor, poor, average, good, and very good. These represented the variable condition value. In this way, one can express imprecise and subjective premises or conclusions in a quantitative form. The interpretation of the linguistic variable and the Fuzzy Score is also shown in Table 3.

Table 3. Interpretation of the linguistic variable and fuzzy score for sub-criteria assessment.

Linguistic Term	Fuzzy Score	Effectiveness	Riskiness
Very Poor	1, 1, 2, 3	Have a very poor effect	Causing a huge negative impact to the system
Poor	2, 3, 4, 5	Have a poor effect	Causing a negative impact to the system
Average	4, 5, 6, 7	Have an average effect	Causing a slightly improved to the system
Good	6, 7, 8, 9	Have a good effect	Causing a positive impact to the system
Very Good	8, 9, 10, 10	Have a very good effect	Causing a high positive impact to the system

An example of assessing quantitative sub-criteria is shown in Table 4. The threshold values refer to references in Table 4. An example of the qualitative sub-criteria assessment is shown in Table 5. The Australian Guidelines for Recreational Water Quality and Aesthetics [60] was used to assess the suitability of water for recreational use.

Table 4. Example of quantitative criterion assessment.

Aspects	Criteria	Sub-Criteria		Unit Measures	Threshold	Scoring Evaluation					References
		Code#	Variables			Very Good	Good	Average	Poor	Very Poor	
Water Quality	Physical (P)	P 1	Total Suspended Solids	mg/L	<100	<100	100–200	201–500	501–1000	>1000	[61]
		P 2	pH	Unit	6.5–8.5	6.5–8.5	6.4–5.5 8.6–9	5.4–5 9–9.5	5–4.5 9.6–10.5	<4.4 >10.6	[62]
		P 3	Taste & Odour	mg/L	<0.005	<0.005	0.005–0.01	0.01–0.02	0.02–0.03	>0.03	[63,64]
		P 4	Salinity/Conductivity.	$\mu S/cm^{-1}$	<300	<300	310–400	410–700	700–1000	>1000	[62]
	Chemical (C)	C 1	Total Phosphorous.	mg/L	<0.01	<0.01	0.01–0.06	0.06–0.1	0.1–0.5	>0.5	[65,66]
		C 2	Total Nitrogen	mg/L	<0.35	<0.35	0.35–0.5	0.5–1.5	1.5–2.5	>2.5	[65,66]

Table 5. Visual use sub-criteria assessment.

Linguistic Score	Description
Very Good	Desirable aquatic life, no substances that produce undesirable colour, odor, taste or foaming, no floating substance, desirable wildlife, no attached plants or insects, pedestrian's pathway, shaded BBQ and picnicking area.
Good	Desirable aquatic life, no substances that produce undesirable colour, odor, taste or foaming, some floating substance, desirable wildlife, no insects, pedestrian's pathway, shaded BBQ and picnicking area.
Average	Desirable aquatic life, no substances that produce undesirable colour, odor, taste or foaming, presents of floating substance, desirable wildlife, presents of insects, pedestrian's pathway, shaded BBQ and picnicking area.
Poor	Desirable aquatic life, presents of substances that produce undesirable colour, odor, taste or foaming, presents of floating substance, desirable wildlife, presents of attached plants or insects, no pedestrian's pathway, no shaded BBQ and picnicking area.
Very Poor	No desirable aquatic life, presents of substances that produce undesirable colour, odor, taste or foaming, presents of floating substance, no present of wildlife, presents of attached plants or insects, no pedestrian's pathway, no shaded BBQ and picnicking area.

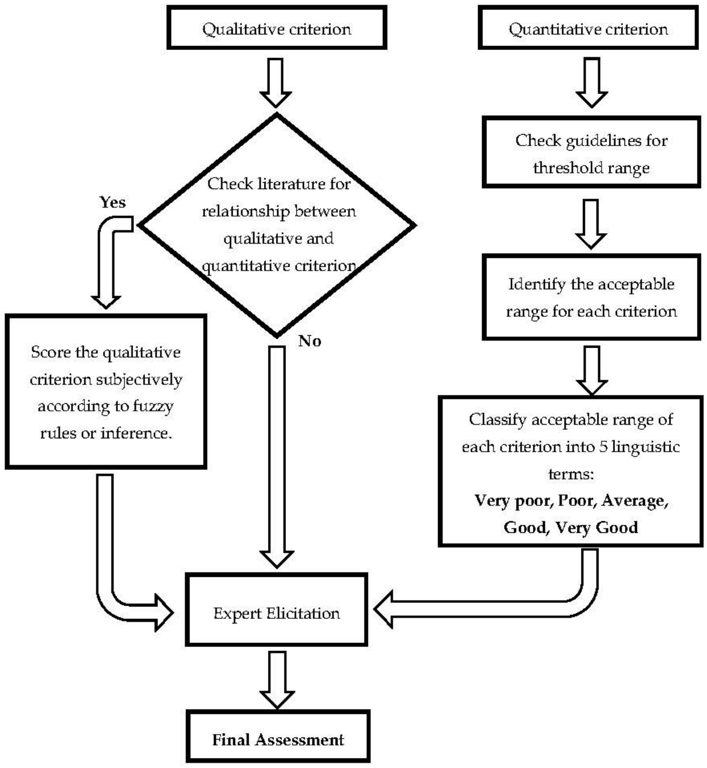


Figure 3. Validation of baseline scoring assessment.

2.3.2. Step 3b: Global Weights Using AHP Pairwise Comparison

The analytic hierarchy process (AHP) is a simple and easy psycho-mathematical process to structure and analyse complex decisions. Saaty developed a scaling method for priorities in hierarchical structures in the 1970s. The AHP method can help with representing and quantifying problem elements, relating those elements to overall goals, and for evaluating alternative solutions [67]. In this study, the weight of each aspect and their associated criterion and sub-criteria was determined using AHP pairwise comparison.

The Global Weight (*GWgt*) of each criterion was obtained by multiplying the aspect weight (*AWgt*), criteria weight (*CWgt*), and sub-criteria weight (*SCWgt*) of the hierarchy (Equation 3).

$$GWgt(\mathrm{x}) = (AWgt_{\mathrm{x}} \times CWgt_{\mathrm{x}} \times SCWgt_{\mathrm{x}}) \quad (3)$$

2.3.3. Step 3c: Create Baseline Score

The overall baseline score for the present DWC condition was calculated by multiplying each criterion's baseline fuzzy number with the corresponding global weight using a simple additive weighting method. The final baseline score is obtain from Equation 4 below:

$$BS_{\mathrm{x}} = (FV_{\mathrm{x}} \times GWgt_{\mathrm{x}}) \quad (4)$$

where *BS* is the baseline score for each criterion, *FV* is the fuzzy value, and *GW* is global weight of each criterion. An illustrative example showing calculations for the global weights and the overall baseline score details will be shown in Section 2.5.

2.4. Step 4: Evaluation of Management Remediation Options Using FDTA

A decision tree facilitates the process of making the most appropriate selection from multiple outcomes. The advantage of this technique is that it is visual and easy to follow, thereby helping the decision maker to understand the consequences associated with each choice. The first node usually represents the alternative or the option to be applied, while the branches represent the set of different portfolios or scenarios from each remediation strategy. Branches can also represent the uncertainty as to what outcomes might happen.

In this study, selected surface water quality management remediation strategies represented the first node. For quantitative sub-criteria, management options were quantified for each set of the portfolio using mathematical functions created from the relationship between the management options and the changes in quantitative criterion value, which were supported from the literature and/or expert elicitation. For the qualitative criterion, management remediation options were quantified using a fuzzy logic approach supported by evidence from the literature. The fuzzy ranges used for the evaluation of the qualitative sub-criteria are shown in Table 6. The validation process of the evaluation of management options.is shown in Figure 4.

Table 6. Interpretation of linguistic variable for the evaluation of qualitative management options.

Linguistic Term	Fuzzy Range	Effectiveness
Very Poor	<10%	Causing a little change to the system
Poor	10–30%	Causing a low change to the system
Average	30–50%	Causing an average change to the system
Good	50–80%	Causing a high change to the system
Very Good	>80%	Causing a very high change to the system

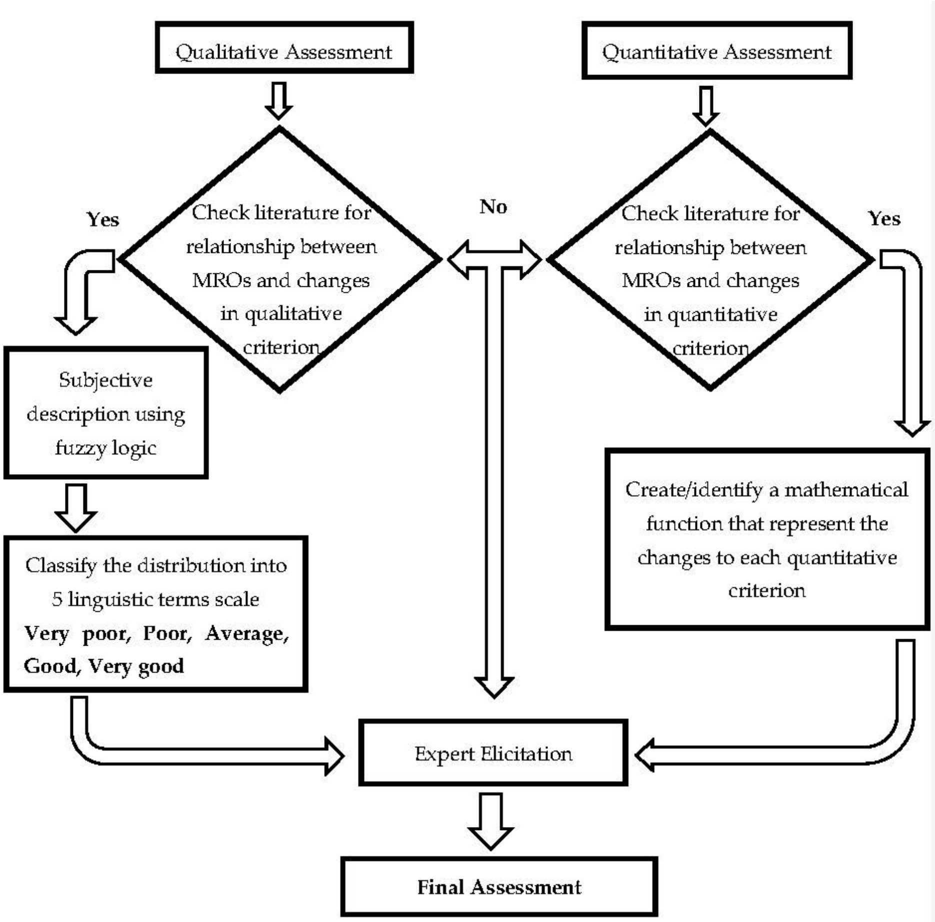


Figure 4. Validation of the evaluation of management options. MROs refer to Management Remediation Options (MRO)

Example of Quantitative Management Option Assessment

Vegetation filter strips (VFS) are an engineered design treatment system which are used as the NPS pollution abatement/reduction strategy. Construction of a particular vegetation filter strip arrangement depends on several factors, including: quantity and quality of the inflowing runoff, the characteristics of the existing hydrology, and physical limitations of the area surrounding the riparian area. VFS requires the following:

1. A device such as a level spreader (ex. berms) that insures that runoff reaches the VFS as sheet flow.
2. A dense vegetative cover of erosion-resistant plant species.
3. A gentle slope less than five percent.
4. A length at least as long as the adjacent contributing area.

The scenarios for VFS can be classified as: Grass Filter Strips (GFS), Shrub Filter Strips (SFS), and Wood Filter Strips (WFS). Several studies have shown the effectiveness of GFS in removing Total Suspended Solids (TSS), Total Nitrogen (TN), and Total Phosphorus (TP) pollutants as illustrated in Table 7.

Readers are referred to the evidence detailed in Table 7 and the relevant quantitative criterion assessment from Table 4. Assuming the current situation score for TSS is poor, TN is poor, TP is very poor and by implementing the GFS strategies, consequently, the score of TSS can be improved from poor to good; TN from poor to good; and TP from very poor to good. The mechanism has been shown in Tables 8 and 9.

Table 7. Evidence of the effectiveness of GFS management options on water quality parameters.

Grass Filter Strips (GFS)			
TSS	**TN**	**TP**	**References**
73%	83%	78%	[68]
78%	90%	85%	[69]
-	54%	61%	[70]
77%	27%	70%	[71]
73%	-	80%	[72]
86%	23%	34%	[73]
66%	69%	27%	[49]
86%	84%	83%	[74]
>70%	>50%	>50%	[48]
77%	61%	65%	Average
66–86%	23–90%	27–85%	Fuzzy range

Table 8. Example of quantitative criterion function for Grass Filter Strips (GFS).

Sub-Criteria Variable	GFS Management Strategy	
	Average	**Strategy Function**
Total suspended solids (mg/L)	77%	$f_{TSS} = (1 - 0.77) \times 500 = 115$
Total nitrites (mg/L)	61%	$f_{TN} = (1 - 0.61) \times 0.066 = 0.0257$
Total phosphorus (mg/L)	65%	$f_{TP} = (1 - 0.65) \times 0.11 = 0.0385$

Table 9. Changing in criterion score using Grass Filter Strips (GFS) strategy.

Sub-Criteria Variable	Target Threshold	Assuming Current Situation	Very Poor	Poor	Average	Good	Very Good
TSS (mg/L)	<100	500	>1000	501–1000	201–500	100–200	<100
TN (mg/L)	<0.01	0.066	>0.1	0.06–0.08	0.04–0.06	0.02–0.04	<0.01
TP (mg/L)	<0.01	0.11	>0.1	0.08–0.1	0.05–0.08	0.03–0.05	<0.03

2.5. Step 5: Aggregation of Baseline Scores

The overall baseline score for each considered remediation option is aggregated using a simple additive weighting method as provided in Equation (5) below:

$$A_i = \sum\nolimits^{n}{}_{(i=1)}(A_{SCi1}) + \ldots + (A_{SCix}) \quad (5)$$

where A_i is the overall score for a particular remediation option that incorporates the aggregation of the global weighted sub-criteria score (Table 10).

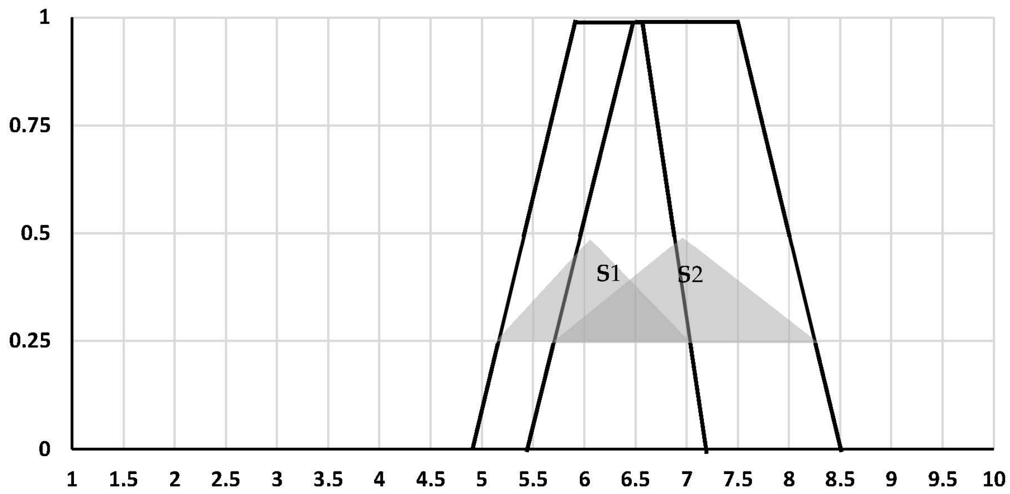
2.6. Step 6: Ranking of Management Remediation Options Using EDIC

In this study, the Euclidean Distance by the In-center of Centroids (EDIC) method was used to rank the proposed management remediation options. The method of ranking fuzzy numbers started in 1976 [75]. Many ranking methods have been proposed, however, there is still no agreement on the method that can provide a satisfactory solution for every situation. One of the most commonly used is the centroid of trapezoid, which was first proposed by Yager [76] based on the fuzzy scoring class with weighting function. Many methods have been developed, such as the centroid index ranking method, the area between the centroid point and original point, and the gravity center point. These centroid methods have been successfully tested using triangular fuzzy numbers. In the case of trapezoidal fuzzy numbers, it is necessary to have a generalization process in its ranking. In this study, the recently developed centroids method for ranking of trapezoidal fuzzy numbers by [77] was included in the framework. This method is based on the EDIC. The basic operation in this method involves splitting the area of a trapezoid into three parts. The first, second, and third parts consist of a triangle, a rectangle, and a triangle respectively. The details of the mathematical operation of this method and the definitions of fuzzy number operations are discussed in supplementary files, section C.

The results from the illustrative example in Table 10 showed that applying Strategy 1 and 2 will expectedly enhance DWC objectives. Using the EDIC technique helped to identify the most beneficial strategy for the DWC. According to Table 10, by computing and then comparing the aggregated score for each strategy following the procedure outlined in Supplementary Files, section C, the R^2 value for Strategy 1 was (4.42), while the R^2 value for Strategy 2 was (5.31). Therefore, following the EDIC procedure findings allowed the determination that Strategy 2 was ranked ahead of Strategy 1 (Figure 5).

Table 10. An illustrative example of the proposed framework evaluation process.

Goal	Aspects	Aspect Weight	Criteria Code	Criteria Weight	CRITERIA EVALUATION					S1	S2
					Sub-Cri Code	Sub-Cri Weight	Fuzzy Value	Global Weight	Baseline Score		
Maximise DWC Aspects (1.000)	Water quality	0.30	P	0.40	P 1	0.60	(0, 1.2, 3)	0.072	(0.00, 0.07, 0.14, 0.22)	(0.00, 0.05, 0.11, 0.17)	(0.22, 0.25, 0.29, 0.32)
					P 2	0.40	(2, 3, 4, 5)	0.048	(0.10, 0.14, 0.19, 0.24)	(0.19, 0.22, 0.24, 0.24)	(0.14, 0.17, 0.19, 0.22)
			DN	0.60	DN 1	0.50	(2, 3, 4, 5)	0.09	(0.18, 0.27, 0.36, 0.45)	(0.11, 0.16, 0.22, 0.27)	(0.29, 0.34, 0.38, 0.43)
					DN 2	0.50	(0, 1, 2, 3)	0.09	(0.00, 0.09, 0.18, 0.27)	(0.00, 0.06, 0.12, 0.16)	(0.43, 0.50, 0.58, 0.65)
	Environmental	0.30	WBT	0.60	WBT 1	0.70	(6, 7, 8, 9)	0.126	(0.76, 0.88, 1.09, 1.13)	(1.01, 1.13, 1.26, 1.26)	(0.76, 0.88, 1.01, 1.13)
					WBT 2	0.30	(2, 3, 4, 5)	0.054	(0.19, 0.16, 0.25, 0.27)	(0.43, 0.49, 0.54, 0.54)	(0.32, 0.38, 0.43, 0.49)
			FM	0.40	FM 1	0.60	(6, 7, 8, 9)	0.072	(0.43, 0.50, 0.58, 0.65)	(0.43, 0.50, 0.58, 0.65)	(0.14, 0.22, 0.29, 0.36)
					FM 2	0.40	(2, 3, 4, 5)	0.048	(0.10, 0.14, 0.19, 0.24)	(0.29, 0.34, 0.38, 0.43)	(0.10, 0.14, 0.19, 0.24)
	Economical	0.20	RB	0.50	RB 1	0.50	(2, 3, 4, 5)	0.050	(0.10, 0.15, 0.20, 0.25)	(0.30, 0.35, 0.40, 0.45)	(0.30, 0.35, 0.40, 0.45)
					RB 2	0.50	(4, 5, 6, 7)	0.050	(0.20, 0.25, 0.30, 0.35)	(0.30, 0.35, 0.40, 0.45)	(0.30, 0.35, 0.40, 0.45)
			IB	0.50	IB 1	0.40	(6, 7, 8, 9)	0.040	(0.24, 0.28, 0.32, 0.36)	(0.24, 0.28, 0.32, 0.36)	(0.24, 0.28, 0.32, 0.36)
					IB 2	0.60	(4, 5, 6, 7)	0.060	(0.20, 0.25, 0.30, 0.35)	(0.36, 0.42, 0.48, 0.54)	(0.36, 0.42, 0.48, 0.54)
	Social and Cultural	0.20	RV	0.50	RV 1	0.70	(2, 3, 4, 5)	0.070	(0.14, 0.21, 0.28, 0.35)	(0.42, 0.49, 0.56, 0.63)	(0.42, 0.49, 0.56, 0.63)
					RV 2	0.30	(4, 5, 6, 7)	0.030	(0.24, 0.27, 0.30, 0.30)	(0.18, 0.21, 0.24, 0.27)	(0.18, 0.21, 0.24, 0.27)
			SCV	0.50	SCV 1	0.50	(4, 5, 6, 7	0.050	(0.10, 0.15, 0.20, 0.25)	(0.30, 0.35, 0.40, 0.45)	(0.30, 0.35, 0.40, 0.45)
					SCV 2	0.50	(4, 5, 6, 7)	0.050	(0.20, 0.25, 0.30, 0.35)	(0.30, 0.35, 0.40, 0.45)	(0.30, 0.35, 0.40, 0.45)
Aggregation								1.000	(3.18, 4.06, 5.18, 6.03)	(4.97, 5.75, 6.65, 7.32)	(5.52, 6.52, 7.52, 8.52)



Alternatives	(x_0^-, y_0^-)	R	Rank
S1	(4.40,0.42)	4.42	1
S2	(5.30,0.42)	5.31	2

Figure 5. Ranking management options using EDIC.

3. Conclusions and Future Research

This study provides DWC managers with a strategic evaluation framework consisting of a Fuzzy Multiple Criteria Decision Analysis (FMCDA) to evaluate and rank proposed water quality remediation strategies within a typical fixed budget constraints and considering a range of diverse environmental, social, and economic values in an integrative manner. The proposed framework is intended to be adopted by water quality managers in the early needs analysis and feasibility stages of decision making process related to DWC remediation options selection. The adoption of the proposed framework will narrow down remediation options to those few which best meet DWC custodian objectives, thereby reducing the requirement for costly science and engineering feasibility studies. This research examined the uncertainty associated with the assessment of sub-criteria, as well as the assessment of management remediation strategies. Some of the studies in Table S1 address various aspects of uncertainty, such as the computational aspects of the MCDA formulations, and some of the implementation for environmental and socio-economic aspects, but not for the assessment of the management remediation strategies. Also shown in Table S1, the reviewed studies were conducted to support decision makers to choose the best evaluated outcome, which related mainly for conservation and rehabilitation rather than sustaining the quality of the drinking water catchment. Moreover, some of these studies evaluated either qualitative or quantitative aspects, whereas this study combined both quantitative and qualitative aspects accordingly.

The authors contend that the developed framework:

- Is flexible, logical, systematic, and transparent to accommodate a wide variety of qualitative and quantitative surface water quality-related measures.
- Is practical and can be applied by custodians of DWC for optimal remediation strategy decision making.
- Promotes a consensus to reach a preferred option amongst stakeholders and decision makers (e.g., an expert opinion).
- Goes beyond assessing only quantitative water quality measures, by considering a holistic multi-aspects assessment of the effect of remediation strategies on DWC.

- Assists decision makers to deal with uncertainty associated with criteria and management remediation assessment evaluation.

Framework development was the first phase of the ongoing project. Future research will focus on completing the following activities:

1. Develop assessment guidelines for the baseline as well as for the management remediation options to assist decision makers to select the best management practice (BMP) in order to improve surface water quality in drinking water catchments; and
2. Apply the research framework to an actual case study from South East Queensland, Australia.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/9/10/738/s1.

Acknowledgments: We are grateful to experts that provided advice on the design of the evaluation procedure, as well as reviewers of earlier versions of the manuscript. We acknowledge the living allowance and tuition fee scholarships received from Griffith University.

Author Contributions: All three authors contributed equally in terms of paper design and methodology. Huda Almaarofi was the primary author of the manuscript and drafted the first version of the paper, which was subsequently edited and refined by Rodney A. Stewart and Amir Etemad-Shahidi.

Conflicts of Interest: The authors declare no conflict of interest.

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