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Maintenance Prioritisation of Irrigation Infrastructure Using a Multi-Criteria Decision-Making Methodology under a Fuzzy Environment

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Abstract: The aging infrastructure and rising demand in the irrigation industry as a result of population growth have increased maintenance works in recent years. The most efficient asset maintenance practice is proactive. However, while a limited budget and an increase in aging infrastructure has made proactive asset maintenance challenging, customers still expect quality service, and contemporary challenges such as climate change and the competitive market further add to the existing pressure on asset owners. In this context, the present work has the primary objective of developing a novel, accurate, efficient and straightforward methodology for measuring assessment criteria weights and using them to prioritise assets for maintenance. For this aim, fuzzy multi-criteria decision-making (MCDM) methods are developed for the optimisation of asset maintenance prioritisation. Using objective and subjective data, the proposed method will be utilised to prioritise six irrigation channels in Northern Victoria, Australia, for maintenance. To verify the efficiency and accuracy of the developed MCDM method, the prioritised channels are validated by comparing against their existing physical condition. Results prove the ability of the proposed method in distinguishing and taking into account the differences between the channels (in terms of their size, physical condition, financial impacts, etc.) in prioritisation for maintenance. This study will also provide suggestions to improve the existing asset maintenance prioritisation methods in practice

Keywords: asset maintenance prioritisation; irrigation infrastructure; multi-criteria decision-making (MCDM) methods; fuzzy logic

1. Introduction

Many organisations, including public service providers (such as local governments, road authorities, rail authorities and water supply authorities) as well as others from the private sector (such as utility providers, including telecommunications, electricity and gas etc.), own a considerable network of assets that needs to be maintained to continue providing services to their customers. To put the concept of “considerable network of assets” into context, Table 1 lists the number of assets owned by some major asset owners in Australia.

Rising demand for services as a consequence of population growth and limited asset maintenance budgets necessitates that owner organisations practise an efficient maintenance prioritisation method to provide sustainable, affordable and quality service to their customers. In cases where the number of assets is limited, an organisation may cope with an informal technique for asset maintenance prioritisation. For asset owners with a vast network of infrastructure and limited maintenance budget, a scientific and well-structured prioritisation methodology is required.

The focus of this study is irrigation infrastructure. Since irrigation infrastructure maintenance prioritisation (like any other infrastructure asset) requires taking different cost and benefit criteria into account, it is considered a multi-criteria decision-making problem.
Table 2 lists some of the decision-making methods, their core processes and limitations in considering benefit and cost criteria.

**Table 1.** Assets of some major asset owners in Australia.

| Asset Owner          | Asset Type                              | Asset Length (km) | Number of Assets |
|----------------------|-----------------------------------------|-------------------|------------------|
| VicRoads [1]         | bridge and major culvert                | 6353              |                  |
|                      | freeway and arterial road               | 23,000            |                  |
|                      | electrical asset                        | 8235              |                  |
|                      | sign structure                          | 1082              |                  |
| Sydney Water [2]     | reservoir                                | 249               |                  |
|                      | water main                              | 22,342            |                  |
|                      | wastewater main                         | 26,169            |                  |
|                      | wastewater pumping station               | 689               |                  |
| V/Line [3]           | rail track                              | 3520              | 94               |
|                      | stations                                |                   |                  |
| Melbourne Water [4]  | water main                              | 1067              |                  |
|                      | drainage line                           | 1491              |                  |
|                      | aqueduct                                | 221               |                  |
|                      | storage and service reservoir           | 47                |                  |
|                      | earthen channel bank                    | 6000              |                  |
|                      | surface drain                           | 3162              |                  |
|                      | pipeline                                | 1479              |                  |
| GMW [5]              | bridge                                  | 2874              |                  |
|                      | culvert                                 | 10,553            |                  |
|                      | footbridge                              | 383               |                  |
|                      | regulator                               | 5007              |                  |
|                      | weir                                    | 208               |                  |
|                      | flume and fish ladder                   | 39                |                  |
|                      | subways and syphons                     | 2857              |                  |
| Water New South Wales [6] | storage dam                        | 42                |                  |
| South Australia Water [7] | water main                           | 27,066            |                  |
|                      | sewerage main                           | 8977              |                  |
| City of Melbourne [8] | open spaces including parks and gardens | 114               |                  |

**Table 2.** Different decision-making methods and their limitations.

| Decision-Making Method                  | Core Process                                         | Accommodating Cost and Benefit Criteria | Limitation                                      |
|----------------------------------------|------------------------------------------------------|-----------------------------------------|-------------------------------------------------|
| Risk score-based prioritisation (RSBP) | Calculating failure risk of each alternative         | Only cost criteria                      | Cannot accommodate multi-criteria and multi-dimensional attributes. |
| Cost–benefit analysis (CBA)            | Monetising the impact of criteria in terms of alternatives | Cost and benefit criteria               | Uncertainty attached to the estimations and approximations. |
Table 2. Cont.

| Decision-Making Method | Core Process | Accommodating Cost and Benefit Criteria | Limitation |
|------------------------|--------------|-----------------------------------------|------------|
| Asset renewal strategy | Identifying and choosing optimum asset via a comprehensive optimisation of both the technical, operational and financial options | Cost and benefit criteria | Difficult to agree with an objective assessment of multi-criteria from an asset renewal perspective. Estimating gains or losses resulting from asset renewals includes assumptions. |
| Life-cycle cost methods | Quantifies the risk losses and gains attached to an alternative | Cost and benefit | Do not allow for consideration of an operator’s level of experience (which can result in uncertainty) in the assessment. |
| Pros and cons method | Identifies, lists and compares the pros and cons of each alternative | Cost and benefit | Cannot computationally consider uncertainty in assessment. |
| Maximin and maximax | Maximising the minimal performing criterion | Cost and benefit | Suitable for problems with single-dimensional criteria. |
| Conjunctive and disjunctive method | Defines minimum and maximum performance thresholds | Cost and benefit | More advanced methods such as ESM provide more structure to the problem. |
| Lexicographic | Prioritises the decision criteria and ranks the alternatives based on their importance | Cost and benefit | More advanced methods such as MCDM can be more comprehensive in analysis as they consider all criteria, not just the important ones. |
| Hierarchical decision modelling | Uses pairwise comparison for calculating the relative importance of criteria | Cost and benefit | More advanced methods such as AHP can consider inconsistencies in assessment and address subjectivity. |
| Multi-criteria decision-making (MCDM) method | Calculating performance values of alternatives | Cost and benefit | Subjectivity in qualitative assessment, though subjectivity can be addressed by using fuzzy logic. |

Furthermore, assigning numerical values for trade-off in qualitative decision-making is not always possible. Existing decision-making methodologies for prioritising irrigation infrastructure for maintenance utilise the concept of risk-to-rank alternatives. Even though these methods are scientifically based on a logical concept, the computational procedure does not necessarily utilise the latest mathematical methods to improve the accuracy of final rankings. To elaborate, since the irrigation infrastructure maintenance prioritisation is based on expert opinions, existing methods in subjective decision-making environments are not able to address the uncertainty attached to human thinking. Moreover, the nature of criteria has become more diverse in current irrigation infrastructure maintenance prioritisation systems due to emerging challenges such as climate change or more emphasis on safety and wellbeing in new organisational policies. Furthermore, not all criteria present the same impact on an organisation; that is, criteria could be benefits or costs. All these challenges are too complex to be addressed by the computational capability of existing methods for irrigation infrastructure maintenance prioritisation. On the other hand, methodologies that have a difficult computational procedure are unlikely to be utilised in real-world scenarios. Complicating the calculation procedure in a subjective decision-making environment, such as prioritising assets for maintenance, is likely a result of the requirement for digitising
linguistic terms. Since enhancing the digitisation accuracy necessitates more complicated mathematical processes, their applications tend to become more and more unlikely due to the computational hardship. At the same time, a limited maintenance budget almost warrants the need for utilisation of an efficient and accurate methodology for prioritising assets for maintenance. This fact has led many authors to apply the fuzzy set theory, Zadeh 1965 [9], to model the uncertainty and vagueness in decision processes [10]. Some of the applications are listed in Table 3.

Table 3. MCDM methods applications in decision-making.

| Researcher            | Application                                                                 |
|-----------------------|-----------------------------------------------------------------------------|
| Ozcan et al. [11]     | Used compensatory and non-compensatory MCDM methods for warehouse location selection. |
| Paksoy et al. [12]    | Organisational strategy development in distribution channel management for an edible vegetable oils manufacturer firm operating in Turkey. |
| Uçal Sarý et al. [13] | Warehouse location selection application.                                   |
| Kilic and Kaya [10]   | Evaluation of investment projects.                                          |
| Kilic and Kaya [14]   | Grant allocation system of regional development agencies in Turkey.         |
| Vasiliki et al. [15]  | Spillway selection for a dam in the district of Kilkis in Northern Greece.   |

Table notes: Compensatory MCDM methods allow explicit trade-offs among criteria and exhibit high dependency on the weights of dominant criteria. Non-compensatory MCDM methods, on the other hand, are principally based on the comparison of alternatives with respect to individual criteria.

MCDM methods are well-placed to address the challenge of taking into account cost and benefit criteria as well as subjectivity and uncertainty in qualitative decision-making environments. The purpose of MCDM is to choose the best candidate from a set of alternatives by evaluating multiple attributes of the alternatives [16]. There are three stages that all MCDM methods follow [17]:

- Determining relevant criteria;
- Attaching numerical measures to the criteria’s relative importance and the alternative’s impacts;
- Processing the numerical values to determine the ranking of alternatives.

The general flowchart of the MCDM method is shown in Figure 1.

![Figure 1. General flowchart of MCDM methods [18].](image-url)
The literature does not prescribe any particular MCDM methodology for a specific MCDM problem [19].

The literature lacks MCDM methods application in irrigation infrastructure maintenance management. Moreover, there are no applications that use fuzzy logic to tackle subjectivity in qualitative assessments of irrigation infrastructure for maintenance. Dun and Wicks [20] tried to improve asset management in irrigation by considering the risks to assets, but their assessment did not consider subjectivity in evaluations. Ika [21] broadly presented a cost-effective asset management planning for the sustainable future of rural irrigation systems. His thesis studied the tertiary level irrigation system in rural Indonesia, which included offtakes from main channels. His goal was to provide an asset management method for new owners to effectively manage their small channels. However, he only considered limited impacting criteria, as his assessment did not include broader users or bigger channels, which obviously have more economic impact.

In this paper, an MCDM method in a fuzzy environment is developed, which takes multi-criteria and sub-criteria into account. The method will be applied to evaluate seven criteria and their sub-criteria and rank six irrigation channels for maintenance in Northern Victoria, Australia.

2. Fuzzy Sets

Fuzzy theory was introduced in 1965 [9]. The fuzzy theory has been successfully utilised in many different areas of research including decision-making. Figure 2 illustrates an example of a type-1 fuzzy set. The $x$ values in this figure are alternatives in a universal set $X$, and $\mu(x)$ values are their performance values. Hypothetically, the alternatives in Figure 2 are supposed to be six different channels, for which their likelihood of failure is evaluated in terms of a decision criterion (such as service delivery/channel size).

![Figure 2. A type-1 trapezoidal fuzzy set.](image)

In the above fuzzy set $\tilde{A}$, the evaluation of the likelihood of failure of assets is certain in the sense that its membership values are crisp numbers. However, in real-world scenarios, asset management experts cannot be certain to this extent about the likelihood of failure of an asset in terms of any given criteria. For this reason, where criteria do not carry a transparent and clear meaning (consequences are not certain) and/or the asset management experts do not hold the same opinions, the type-1 fuzzy set will not be able to offer effective decision support to model various points of views from different decision-makers [10].

In comparison to the type-1 fuzzy set, the type-2 fuzzy set is represented by membership values that are themselves fuzzy. Figure 3 illustrates the discretisation of membership values in modelling a real-world scenario [22].
A trapezoidal interval type-2 fuzzy number.

In the above figure, \( a_{11}^{\text{LU}}, a_{12}^{\text{LU}}, a_{13}^{\text{LU}} \) and \( a_{14}^{\text{LU}} \) have the maximum membership values of the upper and lower membership functions at \( H_1\left(\tilde{A}_1^{\text{LU}}\right) \), \( H_2\left(\tilde{A}_1^{\text{LU}}\right) \), \( H_1\left(\tilde{A}_1^{\text{LI}}\right) \) and \( H_2\left(\tilde{A}_1^{\text{LI}}\right) \), respectively. \( a_{11}^{\text{LU}}, a_{13}^{\text{LU}} \) and \( a_{14}^{\text{LU}}, a_{12}^{\text{LU}} \) are the smallest and largest elements of the upper and lower membership functions with \( \mu(x) \) values of 0. The shaded region bounded by the upper membership function and lower membership function in Figure 4 is called the footprint of uncertainty, which means interval type-2 fuzzy sets are useful when is difficult to determine a crisp membership function or in modelling the various point of views of different decision-makers. In Figure 4, a value equal to zero means no membership, a value equal to one means full membership and intermediate numbers reflect intermediate membership degrees [24].

2.1. Operations on Trapezoidal Interval Type-2 Fuzzy Sets

If \( \tilde{A}_1 \) and \( \tilde{A}_2 \) are two trapezoidal interval type-2 fuzzy sets:

\[
\tilde{A}_1 = \left(\tilde{A}_1^{\text{LU}}, \tilde{A}_1^{\text{LI}}\right) = \left(a_{11}^{\text{LU}}, a_{12}^{\text{LU}}, a_{13}^{\text{LU}}, a_{14}^{\text{LU}}; H_1\left(\tilde{A}_1^{\text{LU}}\right), H_2\left(\tilde{A}_1^{\text{LU}}\right), a_{11}^{\text{LI}}, a_{12}^{\text{LI}}, a_{13}^{\text{LI}}, a_{14}^{\text{LI}}; H_1\left(\tilde{A}_1^{\text{LI}}\right), H_2\left(\tilde{A}_1^{\text{LI}}\right)\right)
\]

and

\[
\tilde{A}_2 = \left(\tilde{A}_2^{\text{LU}}, \tilde{A}_2^{\text{LI}}\right) = \left(a_{21}^{\text{LU}}, a_{22}^{\text{LU}}, a_{23}^{\text{LU}}, a_{24}^{\text{LU}}; H_1\left(\tilde{A}_2^{\text{LU}}\right), H_2\left(\tilde{A}_2^{\text{LU}}\right), a_{21}^{\text{LI}}, a_{22}^{\text{LI}}, a_{23}^{\text{LI}}, a_{24}^{\text{LI}}; H_1\left(\tilde{A}_2^{\text{LI}}\right), H_2\left(\tilde{A}_2^{\text{LI}}\right)\right)
\]
\[
\tilde{A}_2 = (\tilde{A}^U_2, \tilde{A}^L_2) = \left(\tilde{a}^{U}_{21}, \tilde{a}^{L}_{21}, \tilde{a}^{U}_{22}, \tilde{a}^{L}_{22}, \tilde{a}^{U}_{23}, \tilde{a}^{L}_{23}, \tilde{a}^{U}_{24}, \tilde{a}^{L}_{24}; H_1(\tilde{A}^U_2), H_2(\tilde{A}^L_2)\right)
\]

Their addition, \(\oplus\) is defined in (4):
\[
\tilde{A}_1 \oplus \tilde{A}_2 = \left(\left((\tilde{a}^{U}_{11} + \tilde{a}^{U}_{21}, \tilde{a}^{L}_{11} + \tilde{a}^{L}_{21}, \tilde{a}^{U}_{12} + \tilde{a}^{L}_{12}, \tilde{a}^{U}_{13} + \tilde{a}^{L}_{13}, \tilde{a}^{U}_{14} + \tilde{a}^{L}_{14}, \min(H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)), H_1(\tilde{A}^U_1)), \min(H_2(\tilde{A}^U_1), H_2(\tilde{A}^L_1))\right)\right),
\]
\[
(\tilde{a}^{U}_{11} + \tilde{a}^{U}_{21}, \tilde{a}^{L}_{11} + \tilde{a}^{L}_{21}, \tilde{a}^{U}_{12} + \tilde{a}^{L}_{12}, \tilde{a}^{U}_{13} + \tilde{a}^{L}_{13}, \tilde{a}^{U}_{14} + \tilde{a}^{L}_{14}, \min(H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)), H_1(\tilde{A}^U_1)), \min(H_2(\tilde{A}^U_1), H_2(\tilde{A}^L_1))\right)
\]

Moreover, their multiplication, \(\otimes\), is defined in (5):
\[
\tilde{A}_1 \otimes \tilde{A}_2 = \left(\left(\left(\tilde{a}^{U}_{11} \times \tilde{a}^{U}_{21}, \tilde{a}^{L}_{11} \times \tilde{a}^{L}_{21}, \tilde{a}^{U}_{12} \times \tilde{a}^{L}_{12}, \tilde{a}^{U}_{13} \times \tilde{a}^{L}_{13}, \tilde{a}^{U}_{14} \times \tilde{a}^{L}_{14}, \min\left(H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)\right), H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)), \min(H_2(\tilde{A}^U_1), H_2(\tilde{A}^L_1))\right)\right),
\]
\[
(\tilde{a}^{U}_{11} \times \tilde{a}^{U}_{21}, \tilde{a}^{L}_{11} \times \tilde{a}^{L}_{21}, \tilde{a}^{U}_{12} \times \tilde{a}^{L}_{12}, \tilde{a}^{U}_{13} \times \tilde{a}^{L}_{13}, \tilde{a}^{U}_{14} \times \tilde{a}^{L}_{14}, \min\left(H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)\right), H_1(\tilde{A}^U_1), H_1(\tilde{A}^L_1)), \min(H_2(\tilde{A}^U_1), H_2(\tilde{A}^L_1))\right)
\]

2.2. Linguistic Variables

A linguistic variable has its value expressed in linguistic terms instead of numbers. This concept allows the linguistic variable to be used in a situation that is complex and cannot easily be described using conventional quantitative terms. The first step in any MCDM problem is to form a decision matrix. In the irrigation infrastructure maintenance prioritisation, the decision matrix expresses the evaluations of failure impacts of the maintenance alternatives in terms of agreed criteria, which are judged by irrigation infrastructure management experts. Table 4 shows the linguistic variables and their equivalent trapezoidal interval type-2 fuzzy numbers [16]. These values will be used to express the failure impact of irrigation infrastructure assets in terms of the evaluation criteria.

| Linguistic Variable | Trapezoidal Interval Type-2 Fuzzy Scales |
|---------------------|----------------------------------------|
| Very low—VL         | ((0, 0, 0, 0.1; 1, 1), (0, 0, 0, 0.05; 1, 1)) |
| Low—L               | ((0, 0.1, 0.1, 0.3; 1, 1), (0.05, 0.1, 0.1, 0.2; 0.9, 0.9)) |
| Medium low—ML       | ((0.1, 0.3, 0.3, 0.5; 1, 1), (0.2, 0.3, 0.3, 0.4; 0.9, 0.9)) |
| Medium—M            | ((0.3, 0.5, 0.5, 0.7; 1, 1)), (0.4, 0.5, 0.5, 0.6; 0.9, 0.9)) |
| Medium high—MH      | ((0.5, 0.7, 0.7, 0.9; 1, 1)), (0.6, 0.7, 0.7, 0.8; 0.9, 0.9)) |
| High—H              | ((0.7, 0.9, 0.9, 1; 1, 1), (0.8, 0.9, 0.9, 0.95; 0.9, 0.9)) |
| Very high—VH        | ((0.9, 1, 1, 1; 1, 1), (0.95, 1, 1, 1; 0.9, 0.9)) |

Table 5 lists the linguistic variables and their equivalent trapezoidal interval type-2 fuzzy numbers that will be utilised to evaluate criteria and obtain their weights [13].

| Linguistic Variables   | Trapezoidal Interval Type-2 Fuzzy Scales |
|------------------------|----------------------------------------|
| Absolutely strong—AS   | ((7, 8, 9, 9; 1, 1), (7.2, 8.2, 8.8, 9; 0.8, 0.8)) |
| Very strong—VS         | ((5, 6, 8, 9; 1, 1), (5.2, 6.2, 7.8, 8.8; 0.8, 0.8)) |
| Fairly strong—FS       | ((3, 4, 6, 7; 1, 1), (3.2, 4.2, 5.8, 6.8; 0.8, 0.8)) |
| Slightly strong—SS     | ((1, 2, 4, 5; 1, 1), (1.2, 2.2, 3.8, 4.8; 0.8, 0.8)) |
| Exactly equal—EE       | ((1, 1, 1, 1; 1, 1), (1, 1, 1, 1; 1, 1)) |
3. Determining Factors in Selecting an MCDM Methodology

MCDM methods are a good tool for real-world multi-criteria decision-making cases. They are efficient and accurate, and their procedural and methodological elements determine how much attention and popularity they receive in practical applications. Further, their calculation procedures and level of complexity play a massive role in their popularity and applications in real-world cases. Generally, if an MCDM method is complex, its application in real-world practical cases is less likely as, according to previous comparative analysis studies, evaluation techniques that have simpler procedures are often superior [19]. As such, by utilising MCDM methods, this study attempts to develop a prioritisation method that is user-friendly, efficient and accurate for use in real-world cases.

3.1. Problem Structure

Selecting the appropriate decision method to address the structural requirements of a decision problem is paramount in reaching an accurate final outcome. For example, the Analytical Hierarchy Process (AHP) is an MCDM method that is suitable for decision scenarios where the problem structure can be arranged in a hierarchy of criteria and sub-criteria, and the alternatives and prioritisation require the impact of every element of the decision to be incorporated in the assessment. However, the size of a decision problem plays a key role in the AHP method’s ability to address the decision situation. This is because of the necessity of making pairwise comparisons in the decision hierarchy, which could become complex as the number of alternatives and criteria increases. On the other hand, AHP can easily accommodate quantitative or qualitative information when evaluating alternatives in terms of decision criteria. Analytical Network Process (ANP) is another MCDM method that is useful for situations when there are interdependencies between criteria and alternatives, which, as can be expected, make the calculation procedure more complicated than the AHP method.

3.2. The Core Process of Methods

The core process of an MCDM method includes the step(s) that is (are) unique for each decision-making method and plays an important role in the solution algorithm. Establishing the hierarchy of the decision levels and pairwise comparisons of alternatives and criteria across different levels of the hierarchy forms the core process of the AHP method [25]. Measuring the distance of each alternative to the identified positive and negative ideal solutions is the core process of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), which is another MCDM method. Attaining the global and net ranking of the decision alternatives is the result of the calculation procedure of the AHP and TOPSIS methodologies. In the ELimination and Choice Translating REality method (ELECTRE) method, preference and indifference thresholds are defined while the method determines concordance and discordance indexes. The ELECTRE III method acquires partial ranking among alternatives parallel with reliability matrix formation as a result of the comparison of concordance and discordance indexes with thresholds [11]. The VIšekriterijumsko Kompromisno Rangiranje method (VIKOR) introduces multi-criteria ranking indexes according to particular closeness measures to the decision problem’s ideal solution. The core process of the VIKOR method lies in prioritising the series of alternatives in the decision problem, which contain contradicting criteria [26]. The Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE) method allows the building of an outranking relationship between alternatives and, using the preference function, it determines the degree of preference of one alternative over another. It also calculates the positive and negative outranking flows, which, respectively, express the extent to which each decision option outranks or is outranked by all other available options.

3.3. Determining the Weight of Criteria

Determining criteria weights in MCDM methods is an important step. Criteria weights are used in measuring the performance values of alternatives and, consequently, determin-
ing their final ranking. In almost all MCDM methods—including AHP, TOPSIS, ELECTRE, Weighted Product Model (WPM), Weighted Sum Model (WSM) and COmplex PRoportional ASsessment (COPRAS)—criteria weights need to be measured for solving the decision-making problem and prioritising the alternatives. AHP uses pairwise comparison matrices to determine the criteria weights [25]. However, while AHP is capable of determining criteria weights using pairwise comparison matrices, the uncertainty in subjective judgments, which can in turn result in inaccurate criteria weights, is one of its disadvantages. However, using fuzzy sets instead of crisp values can help address the uncertainty attached to decision-makers’ subjective thinking. That said, as previously stated, fuzzy sets have different types, some of which can add to the complexity of the computational procedure of MCDM methods.

3.4. Cost and Benefit Criteria

As discussed earlier, asset management currently faces new and challenging criteria. The difficulty with considering several criteria in an MCDM problem originates from the nature of the criteria; that is, cost versus benefit or qualitative versus quantitative. Different MCDM methods handle cost–benefit criteria assessments in different ways. For example, a drawback of WSM and WPM is that the methods’ utility assumptions limit their capability to incorporate both benefit and cost criteria simultaneously within the same analysis [27]. Therefore, in the case of asset maintenance prioritisation, benefit criteria should be transferred into cost criteria before normalising the performance values. One option, which is justified mathematically, is to represent cost criteria as negative values in the calculations. However, such an approach to managing the cost criteria has not been adapted in real-world decision-making problems, and therefore it is preferable to handle cost criteria in a more acceptable manner.

4. The Proposed Methodology

MCDM methods have become very popular in decision-making problems. In all decision-making scenarios in MCDM applications, a series of criteria (and in some cases sub-criteria) are established based on the problem owner’s policies, plans or challenges. The available options or alternatives are then assessed using these criteria. Generally, there are two different schools of thought for the multi-attribute/criteria decision-making problems (MADM/MCDM): multi-attribute utility theory (MAUT, representing the American school) and outranking methods (representing the French school). The MAUT-based methods (such as TOPSIS, WSM, COPRAS, WPM and AHP) have a compensatory nature and involve combining the decision attributes into a maximising function [28]. The outranking methods, on the contrary, have a non-compensatory nature and allow incomparability among the decision options [29]. The most comprehensively utilised outranking methods are ELECTRE and PROMETHEE.

This study aims to develop a practical and straightforward methodology to assess and prioritise different alternatives for maintenance based on a set of established assessment criteria. Therefore, the decision-making situation is a ranking problem where available options must be prioritised from the most preferred to the least preferred. There has not been any application of the MCDM methods in a fuzzy environment in prioritising irrigation assets for maintenance. Almost all MCDM methods are well advanced compared to the prioritisation methods in practice. However, the literature review concludes that non-compensatory methods are not suggested for maintenance prioritisation problems as they might not be able to yield a full ranking of alternatives [19]. Since the maintenance prioritisation requires a fully ranked list of decision options, outranking methods might not be suitable for the asset maintenance prioritisation problem. Therefore, outranking methods will not be further considered in this study, and the study focuses on compensatory methods. Fuzzy logic will also be used to address the uncertainty in subjective judgments in decision-making. The proposed model for prioritising irrigation asset maintenance is composed of fuzzy AHP and fuzzy TOPSIS methods, as illustrated in Figure 5.
4.1. Determining Decision Criteria and Computing Criteria Weights

The structure of the AHP decision problem hierarchy that Saaty [30] developed consists of a group of criteria and sub-criteria that link decision alternatives to an overall goal [13].

As an example, Figure 6 illustrates the hierarchical structure of decision criteria, sub-criteria and alternatives with the final goal of prioritising the alternatives for maintenance.

AHP is a weighted factor-scoring technique that can detect inconsistencies in the decision-making procedure [13]. The AHP method uses the pairwise comparison matrices...
for the criteria to compute a final set of weights $w_j \ (w_j \geq 0, \ w_1 + w_2 + \cdots + w_n = 1)$ [31].

Equation (6) illustrates a typical pairwise comparison matrix:

$$\tilde{A}_k = \left( \tilde{a}_{ij}^k \right)_{n \times n} = \begin{bmatrix}
1 & \tilde{a}_{12}^k & \cdots & \tilde{a}_{1n}^k \\
\tilde{a}_{21}^k & 1 & \cdots & \tilde{a}_{2n}^k \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{n1}^k & \tilde{a}_{n2}^k & \cdots & 1
\end{bmatrix}$$

In (6), $\tilde{a}_k$ is the decision matrix constructed by the $k$th decision-maker and $\tilde{a}_{ij}^k$ represents the pairwise comparison of the $i$th versus the $j$th criterion. As can be seen in (6), the values below the main diagonal or leading diagonal (all values on the leading diagonal are 1 as they represent the importance of a criterion compared to itself) are reciprocal of the values located above the main diagonal. To put this in context, if a criterion is evaluated to be twice more important than another criterion, then the importance of criterion $b$ will be evaluated as $1/2$ compared to criterion $a$.

In a typical AHP method, a defined scale varying from 1 to 9 is utilised to form a pairwise comparison matrix, which becomes the basis for determining the decision criteria importance index. Criteria comparisons are often subject to some level of uncertainty and subjectivity; for example, an asset management expert may know one criterion is more important than another, but the uncertainty on the intensity scale of importance between each criterion can lead the expert to not being able to assign a definite scale to the comparison. In some cases, comparison cannot be performed by experts because of inadequate information [32]. AHP was integrated with type-1 fuzzy sets by Buckley [31] for capturing uncertainty in judgments. Kahraman et al. [33] extended AHP based on interval type-2 fuzzy sets. The interval type-2 fuzzy sets (Table 5) are a good tool to address the uncertainties attached to the thinking of decision-making experts in such situations [10].

After the pairwise comparison matrix is constructed, geometric mean in (7) is used to aggregate multiple judgments from different experts:

$$\tilde{a}_{ij} = \sqrt[k]{\tilde{a}_{ij}^1 \tilde{a}_{ij}^2 \cdots \tilde{a}_{ij}^q}$$

The result of this aggregation is an interval type-2 fuzzy number. In the above equation, $\tilde{a}_{ij}$ represents the relative importance of $i$th criterion in regard to $j$th criterion and $0 \leq k \leq q$ is the number of experts. The resulted matrix from aggregation should be checked for consistency.

4.2. Consistency Check

Some inconsistency in the pairwise comparison matrices is expected, as the numeric values are derived from the qualitative preferences of individual experts [34]. As stated earlier, AHP can identify and incorporate inconsistencies in a qualitative decision-making process. For this reason, a consistency ratio (CR) is calculated, which compares the consistency index (CI) of the present decision matrix versus the consistency index of a randomly filled matrix (RI). Judgments in a random matrix are entered arbitrarily and are thus expected to be highly inconsistent [34]. The ratio index (RI) is the average consistency index of 500 matrices that have been randomly filled. It is been shown by Saaty and Vargas [35] that a 10% or less inconsistency ratio in the AHP analysis is acceptable for continuing the assessment. If the inconsistency ratio is more than 10%, the judgments must be revised to identify the cause of high inconsistency and correct the evaluations to then continue the calculations. The consistency index is calculated using (8):

$$\text{Consistency Index (CI)} = \frac{\lambda_{\text{max}} - n}{n - 1}$$
In (8), \( \lambda_{\text{max}} \) represents the maximum eigenvalue of the pairwise comparison matrix and \( n \) is the number of criteria [36]. The consistency ratio (CR) is calculated using (9):

\[
CR = \frac{CI}{RI}
\]

(9)

In the (9), CI is the consistency index. The measured ratio index (RI) values for different sizes of pairwise comparison matrices are provided by Saaty and Vargas [35] and shown in Table 6.

Table 6. Consistency indices for randomly generated matrices of different sizes.

| \( n \) | 3   | 4   | 5   | 6   | 7   |
|-------|-----|-----|-----|-----|-----|
| RI    | 0.58| 0.90| 1.12| 1.24| 1.32|

After confirming the consistency of the pairwise comparison matrix, (10) is used to calculate the fuzzy priority vector \( \hat{r}_i \) of the criterion located on the \( i \)th row of fuzzy pairwise comparison matrix \( \hat{A} = \begin{bmatrix} \hat{a}_{ij} \end{bmatrix} \):

\[
\hat{r}_i = \sqrt[n]{\hat{a}_{i1} \otimes \hat{a}_{i2} \otimes \ldots \otimes \hat{a}_{in}}
\]

(10)

where \( n \) is the number of criteria. The values obtained for \( \hat{r}_i \) will be used to compute fuzzy weights, \( \hat{w}_j \), of criteria through (11):

\[
\hat{w}_j = \left( \frac{\hat{r}_i}{\hat{r}_1 \oplus \hat{r}_2 \oplus \ldots \oplus \hat{r}_n} \right)
\]

(11)

The fuzzy weights need to be turned into crisp values or "defuzzified".

4.3. Defuzzification

The literature presents various defuzzification methods that have been utilised in previous studies, including the simple centroid method of Chang and Wang [37] to obtain the best non-fuzzy performance value; Chen and Lee [16] with a likelihood-based approach, ranking values of interval type-2 fuzzy sets; and Niewiadomski et al. [38] with a type reduction indices method and defuzzified trapezoidal and triangular type-2 fuzzy set approach, which were developed by Kahraman et al. [33]. The defuzzified trapezoidal type-2 fuzzy set method was developed through adjusting the best non-fuzzy performance value for defuzzifying and ranking interval type-2 fuzzy sets. This defuzzification method yields the most consistent result for trapezoidal fuzzy numbers. Therefore, this defuzzification method is used in this study. In the following equations, the defuzzified upper and lower membership function elements are calculated by \( Def_{UMF} \) and \( Def_{LMF} \) in (12) and (13) to be fed into (14), which represents the defuzzified weight of \( j \)th criterion:

\[
Def_{UMF} = \left[ \frac{(u_u - 1_u) + (\beta_u \cdot m_{1u} - l_u) + (a_u \cdot m_{2u} - l_u)}{4} \right] + l_u
\]

(12)

\[
Def_{LMF} = \left[ \frac{(u_L - 1_L) + (\beta_L \cdot m_{1L} - l_L) + (a_L \cdot m_{2L} - l_L)}{4} \right] + l_L
\]

(13)

\[
Def \left( W_j \right) = \frac{Def_{UMF} + Def_{LMF}}{2}
\]

(14)

In (12) and (13), \( \alpha \) and \( \beta \) are the elements of the upper and lower membership functions on the X axis with maximum membership values of \( m_{1u}, m_{2u} \) and \( u_u, l_u \) are the largest and \( u_l, l_l \) the smallest elements of the upper and lower membership functions on the X axis.
The defuzzified weights \( \text{Def} (W_j) \) are then normalised using (15) [39]:

\[
W_j = \frac{\text{Def} (W_j)}{\sum_{j=1}^{n} \text{Def} (W_j)}
\tag{15}
\]

In (15), \( W_j \) is the weight of the \( j \)th criterion and \( n \) denotes the number of decision criteria.

### 4.4. Ranking the Alternatives Using Fuzzy TOPSIS

The TOPSIS method is based on the concept of selecting the decision alternative that is closest to the positive ideal solution (the positive ideal solution maximises criteria of the type “the more, the better” and minimises criteria of the type “the less, the better”) and has the farthest straight-line distance in a two-dimensional space to the negative ideal solution (the negative ideal solution maximises “the less, the better” and minimises “the more, the better” criteria.) [15]. In asset management, positive ideal solutions are considered as the alternatives that have the highest failure impact represented by their performance value in terms of a cost criterion. Such alternatives are called positive ideal solutions because prioritising them, in the example case of asset maintenance prioritisation, prevents shutdowns and helps an asset owner provide a sustainable service with less likelihood of an imminent breakdown. Figure 7 illustrates the concept of TOPSIS method [40].

![Figure 7. Straight-line distances to positive and negative ideal solutions in two-dimensional space.](image)

Jun et al. [41] outline the following advantages of the TOPSIS method:

- The logic behind the method’s concept is considered rational and reasonable to decision-makers.
- The method is capable of representing quantitative values accounting for the best and worst performers among the decision alternatives.
- The method’s calculation procedure is straightforward and easily programmable.
- The alternatives’ performance measures can be visually presented in a two-dimensional space on a polyhedron (Figure 7).

Revising the method proposed by Chen and Lee [16], the following sections outline the fuzzy AHP-TOPSIS method as a new decision-making technique for handling irrigation asset maintenance prioritisation problems by using crisp numbers and qualitative linguistic variables. The first step is to construct the evaluation matrix using linguistic variables in Table 4. Then, (16) is used to aggregate the expert’s judgments:

\[
\tilde{a}_{ij} \approx \frac{a_{ij}^{1} \oplus a_{ij}^{2} \oplus \ldots \oplus a_{ij}^{k}}{q}
\tag{16}
\]

where \( \tilde{a}_{ij} \) is an interval type-2 fuzzy or a crisp number representing performance value of \( i \)th alternative in regard to \( j \)th criterion, \( \oplus \) is addition, and \( q \) is the number of asset experts.

Equation (14) is used to defuzzify the evaluation matrix. The defuzzified decision matrix then needs to be normalised. Normalisation is to transform performance ratings with different data measurement units into a compatible unit. According to Tzeng and
Huang [42], linear normalisation (maximum performance value) method can be used with different MCDM methods including Simple Additive Weighting (SAW), fuzzy TOPSIS, Weighted Sum Model (WSM) and Weighted Aggregated Sum–Product Assessment (WASPAS) methods. Linear normalisation (maximum) for benefit and cost criteria are represented by (17) and (18), respectively:

\[ r_{ij} = \frac{x_{ij}}{x_{j}^{\text{max}}} \] (17)

\[ r_{ij} = 1 - \frac{x_{ij}}{x_{j}^{\text{max}}} \] (18)

where \( x_{ij} \) is the performance value of the \( i \)th alternative in regard to the \( j \)th criterion and \( x_{j}^{\text{max}} \) is the maximum performance value of the \( j \)th criterion in terms of all evaluated alternatives.

Next, normalised values are multiplied by the criteria weights obtained from the AHP method to construct weighted normalised matrix. Therefore, weighted normalised values, \( v_{ij} \), are calculated using (19):

\[ v_{ij} = w_{j} \times r_{ij} \] (19)

In (19), \( 1 \leq i \leq m \) is the number of alternatives, \( 1 \leq j \leq n \) is the number of criteria and \( w_{j} \) is the weight of the \( j \)th criterion obtained by the fuzzy AHP method.

Positive ideal solutions \( v^{+} \) and the negative ideal solutions \( v^{-} \) are determined using (20) and (21):

\[ v_{i}^{+} = \begin{cases} 
\max v_{i} & \text{if criteria } \in C \\
\min v_{i} & \text{if criteria } \in B
\end{cases} \quad 1 \leq j \leq n \] (20)

\[ v_{i}^{-} = \begin{cases} 
\max v_{i} & \text{if criteria } \in B \\
\min v_{i} & \text{if criteria } \in C
\end{cases} \quad 1 \leq j \leq n \] (21)

In (20) and (21), \( B \) represents the set of benefit criteria, \( C \) is the set of cost criteria, and \( 1 \leq i \leq m \) and \( 1 \leq j \leq n \) refer to the number of alternatives and criteria respectively. Next, the distance of each alternative to \( v^{+} \) and \( v^{-} \) is calculated by using (22) and (23) respectively. This step is the core of the TOPSIS method. As TOPSIS calculates a final score for each alternative in terms of all evaluation criteria including cost and benefit, this step distinguishes the performance of each alternative in terms of benefit and cost criteria. This shows the power of the TOPSIS method in decision-making scenarios where both cost and benefit criteria are present. (22) and (23) define each alternative’s distance to the positive \( d^{+}(A_{i}) \) and negative \( d^{-}(A_{i}) \) ideal solutions identified for each criterion in the previous step.

\[ d^{+}(A_{i}) = \sqrt{\sum_{i=1}^{m} (v_{ij} - v_{i}^{+})^2} \] (22)

\[ d^{-}(A_{i}) = \sqrt{\sum_{i=1}^{m} (v_{ij} - v_{i}^{-})^2} \] (23)

In (22) and (23), \( 1 \leq j \leq n \) represents the number of criteria and \( 1 \leq i \leq m \) denotes the number of alternatives, \( v^{+} \) represents the positive ideal solution and the \( v^{-} \) denotes the negative ideal solutions, and \( v_{ij} \) is the weighted normalised performance value of the \( j \)th alternative in regard to the \( j \)th criterion.

The closeness coefficient measures the similarity of each alternative to the positive and negative ideal solutions in terms of all the criteria. In other words, the closeness coefficient determines the relative distance of each alternative in a two-dimensional space to the alternatives that are identified as positive or negative ideal solutions depending on
the application. In the asset maintenance prioritisation case, for example, the closeness coefficient measures the overall performance value of each alternative compared to the safest and riskiest assets. The closeness coefficient of each alternative $C_c(A_i)$ is calculated using (24):

$$C_c(A_i) = \frac{d^-(A_i)}{d^+(A_i) + d^-(A_i)}$$  (24)

In (24), $(d^+(A_i))$ represents the distance to the positive ideal solution and $(d^-(A_i))$ denotes the distance to the negative ideal solution. Since the distance to the negative ideal solution has a direct relationship with $C_c(A_i)$, the larger the $C_c(A_i)$, the more its geometric distance to negative ideal solution and the higher its preference. In the case study for this paper, negative ideal solutions are defined as the alternatives with least failure impact to an asset owner and, therefore, if an alternative has higher $C_c(A_i)$, it implies a higher failure impact to the asset owner and is thus suggested to be prioritised for maintenance first.

5. Application of the Method to Maintenance Prioritisation of Irrigation Infrastructure

GMW administers the storage, delivery and drainage systems for 70% of Victoria’s stored water resources, 50% of Victoria’s underground water supplies and Australia’s largest irrigation delivery network. GMW operates and maintains 23 storages and thousands of kilometres of channel infrastructure, which provide water storage, delivery and drainage services to gravity irrigators, river diverters, groundwater users, urban water providers and the environment. Figure 8 shows the waterways and storages in Northern Victoria, Australia [43].

We have previously provided a snapshot of the number of assets owned by G-MW in Table 1. Furthermore, Table 7 lists the length of channels owned by G-MW constructed from 1896 to 1935.
Table 7. G-MW constructed channel lengths from 1896 to 1935.

| Period Constructed/Rehabilitated | Average Age Years | Bank Length | % of the Total Length |
|---------------------------------|-------------------|-------------|-----------------------|
| 1896–1905                       | 104               | 3912        | 0.6%                  |
| 1906–1915                       | 94                | 694         | 0.0%                  |
| 1916–1925                       | 84                | 322,383     | 5.3%                  |
| 1926–1935                       | 74                | 2,849,011   | 46.6%                 |

As can be seen in Table 7, at least 3000 km of the channels owned by G-MW have an average age of 74 years and more. Maintenance of such old infrastructure with a limited available budget warrants an accurate and reliable prioritisation method.

5.1. Evaluation Criteria and Channel Remodeling Candidates

Service delivery (C1), financial loss (C2), safety (C3), credibility (C4), environment (C5), compliance (C6) and asset condition rating (C7) are determined as the evaluation criteria (these evaluation criteria are derived from G-MW’s corporate risk framework). Moreover, Figure 9 shows the six irrigation channels to be prioritised for maintenance using the proposed methodology.

Figure 9. Case study channels.

5.2. Conducting Fuzzy AHP Computations

Table 8 presents the pairwise comparison matrix of the evaluation criteria. Three asset experts participated in filling this matrix using linguistic variables in Table 5.
Table 8. Pairwise comparison matrix for the case study.

|    | C1    | C2    | C3    | C4    | C5    | C6    | C7    |
|----|-------|-------|-------|-------|-------|-------|-------|
| C1 | EE, EE, EE | EE, SS, SS | 1/FS, AS, 1/AS | 1/SS, VS, FS | 1/SS, FS, AS | EE, FS, FS | EE, VS, VS |
| C2 | EE, 1/SS, 1/SS, EE | EE, EE, EE | 1/FS, VS, 1/AS | 1/FS, FS, SS | 1/FS, SS, VS | 1/FS, SS, SS | 1/FS, FS, FS |
| C3 | FS, 1/AS, AS | FS, 1/VS, AS | EE, EE, EE | FS, 1/SS, AS | FS, 1/SS, AS | FS, 1/FS, AS | FS, 1/SS, AS |
| C4 | SS, 1/VS, 1/FS | FS, 1/FS, 1/SS | 1/FS, SS, 1/AS | EE, EE, EE | EE, 1/SS, FS | EE, 1/SS, EE | EE, EE, SS |
| C5 | SS, 1/FS, 1/AS | FS, 1/SS, 1/VS | 1/FS, SS, 1/AS | EE, SS, 1/FS | EE, EE, EE | EE, 1/FS | EE, SS, 1/SS |
| C6 | EE, 1/FS, 1/FS | FS, 1/SS, 1/FS | EE, SS, EE | EE, EE, FS | EE, EE | EE, EE | EE, SS, SS |
| C7 | EE, 1/VS, 1/VS | FS, 1/FS, 1/FS | 1/FS, SS, 1/AS | EE, 1/EE, 1/SS | EE, 1/SS, 1/SS | EE, 1/SS, 1/SS | EE, EE, EE |

The judgements are then aggregated as presented in Table 9.

The consistency ratio is calculated at 0.04, which makes the matrix in Table 9 consistent.

Next, the fuzzy geometric mean is calculated.

\[ \approx r_1 = ((1.315, 1.587, 2.114, 2.465; 1, 1), (1.373, 1.641, 2.053, 2.382; 0.8, 0.8)) \]
\[ \approx r_2 = ((0.663, 0.85, 1.25, 1.552; 1, 1), (0.703, 0.886, 1.202, 1.48; 0.8, 0.8)) \]
\[ \approx r_3 = ((1.402, 1.654, 2.204, 2.617; 1, 1), (1.452, 1.708, 2.129, 2.513; 0.8, 0.8)) \]
\[ \approx r_4 = ((0.542, 0.653, 0.894, 1.093; 1, 1), (0.566, 0.675, 0.864, 1.043; 0.8, 0.8)) \]
\[ \approx r_5 = ((0.456, 0.558, 0.768, 0.931; 1, 1), (0.479, 0.578, 0.743, 0.891; 0.8, 0.8)) \]
\[ \approx r_6 = ((0.684, 0.822, 1.095, 1.294; 1, 1), (0.715, 0.848, 1.063, 1.247; 0.8, 0.8)) \]
\[ \approx r_7 = ((0.429, 0.501, 0.682, 0.855; 1, 1), (0.444, 0.516, 0.658, 0.81; 0.8, 0.8)) \]

Then, the fuzzy weight of each criterion:

\[ \approx w_1 = ((0.239, 0.24, 0.235, 0.228; 1, 1), (0.24, 0.239, 0.236, 0.23; 0.8, 0.8)) \]
\[ \approx w_2 = ((0.121, 0.128, 0.139, 0.144; 1, 1), (0.123, 0.129, 0.138, 0.143; 0.8, 0.8)) \]
\[ \approx w_3 = ((0.255, 0.25, 0.245, 0.242; 1, 1), (0.253, 0.249, 0.244, 0.242; 0.8, 0.8)) \]
\[ \approx w_4 = ((0.09870, 0.09856, 0.09925, 0.10114; 1, 1), (0.09874, 0.09875, 0.09917, 0.1006; 0.8, 0.8)) \]
\[ \approx w_5 = ((0.083, 0.084, 0.085, 0.086; 1, 1), (0.084, 0.084, 0.085, 0.086; 0.8, 0.8)) \]
\[ \approx w_6 = ((0.125, 0.124, 0.122, 0.12; 1, 1), (0.125, 0.124, 0.122, 0.12; 0.8, 0.8)) \]
\[ \approx w_7 = ((0.078127, 0.07571, 0.07553, 0.07511; 1, 1), (0.07746, 0.07556, 0.07555, 0.07514; 0.8, 0.8)) \]
Table 9. Aggregated pairwise comparison matrix for the case study.

| C1                             | C2                             | C3                             | C4                             | C5                             | C6                             | C7                             |
|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| (1.0, 1.0, 1.0, 1.0; 1, 1)     | (1.0, 1.587, 2.52, 2.924; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) | (1.442, 1.817, 2.884, 3.979; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (0.928, 1.261, 2.0, 2.465; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) |
| (0.481, 0.529, 0.655, 0.754; 0.49, 0.544, 0.635, 0.732; 0.8, 0.8) | (0.342, 0.397, 0.63, 0.754; 0.439, 0.495, 0.61, 0.726; 0.8, 0.8) | (0.754, 1.101, 1.817, 2.627; 1, 1) | (0.972, 1.329, 1.818, 2.365; 1, 1) | (0.894, 1.261, 2.0, 2.465; 1, 1) | (0.523, 0.874, 1.587, 2.027; 1, 1) | (1.443, 1.748, 2.381, 2.758; 1, 1) |
| (1.0, 1.0, 1.0, 1.0; 1, 1)     | (1.0, 1.0, 1.0, 1.0; 1, 1)     | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.443, 1.748, 2.381, 2.758; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) |
| (0.411, 0.441, 0.471, 0.491; 0.856, 1.21, 0.8, 0.8) | (0.426, 0.452, 0.48, 0.509; 0.856, 1.21, 0.8, 0.8) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) | (1.443, 1.748, 2.381, 2.758; 1, 1) | (1.613, 2.0, 3.0, 3.979; 1, 1) |
| (0.491, 0.529, 0.56, 0.62; 1, 1) | (0.27, 0.351, 0.48, 0.593; 0.8, 0.8) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) |
| (0.405, 0.452, 0.48, 0.509; 0.426, 0.452, 0.48, 0.509; 0.8, 0.8) | (0.27, 0.351, 0.48, 0.593; 0.8, 0.8) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 1.0, 1.0, 1.0; 1, 1) | (1.0, 0.63, 0.833, 1.2; 1, 1) |
| (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) |
| (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) |
| (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) |
| (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) |
| (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (0.493, 0.529, 0.56, 0.62; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.26, 1.587, 1.71; 1, 1) | (1.0, 1.587, 2.52, 2.924; 1, 1) |
The above fuzzy weights are shown in Figure 10.

Fuzzy weights are then defuzzified.

\[ W_1 = 0.224, \quad W_2 = 0.126, \quad W_3 = 0.235, \quad W_4 = 0.095, \quad W_5 = 0.08, \quad W_6 = 0.117, \quad W_7 = 0.073 \]

Then, they are normalised.

\[ W_1 = 23.6\%, \quad W_2 = 13.31\%, \quad W_3 = 24.75\%, \quad W_4 = 9.95\%, \quad W_5 = 8.46\%, \quad W_6 = 12.27\%, \quad W_7 = 7.69\% \]

Obtained normalised weights will then be used in fuzzy TOPSIS to prioritise the six irrigation channels.

5.3. Evaluating the Channels with Type-2 Fuzzy TOPSIS and Determining the Maintenance Ranking

The first step in the TOPSIS method is constructing the evaluation matrix. In this matrix, asset experts evaluate the performance values of different alternatives in terms of evaluation criteria and sub-criteria by using linguistic variables in Table 4. Evaluation criteria and their sub-criteria can be seen in Table 10.

The decision evaluation matrix can be found in Table 11. This evaluation matrix is filled by three asset experts using the linguistic variables in Table 4.
Table 10. Evaluation criteria and their sub-criteria.

| 1. Service delivery interruption resulting in: |  
| C11, Catastrophic outcomes for many customers. | C14, Moderate impact on a small group of customers.  
| C12, Impacting service to many customers. | C15, Impacting a small number of customers.  
| C13, Major impact on significant number of customers. |  
| 2. Business financial loss is: |  
| C21, Greater than $12 million loss. | C24, Between 1 and $4 million loss.  
| C22, Between 8 and $12 million loss. | C25, Smaller than $1 million.  
| C23, Between 4 and $8 million loss. |  
| 3. Safety incident results in: |  
| C31, Multiple fatalities. | C34, Medical treatment.  
| C32, A permanent injury or a single fatality. | C35, Minor first aid injuries.  
| C33, Recoverable injuries. |  
| 4. Credibility: |  
| C41, Local and national public outage resulting in loss of key stakeholder support. External intervention required. | C44, Criticism from the local community segment, resulting in negative local press coverage.  
| C42, Substantial active criticism from key stakeholders, resulting in national media coverage. | C45, Internal dissent/isolated external criticism. No external impact on reputation.  
| C43, Criticism from stakeholders, involving local community public reactions. |  
| 5. Environment: Impacts that |  
| C51, Cause indigenous species extinction and/or cause irretrievable loss of habitat and or cultural heritage. | C54, Single indigenous species damage or result in damage or loss of species, habitat and/or cultural heritage.  
| C52, Multiple indigenous species damage across a regional area. | C55, No indigenous species damage and/or cause damage to species, habitat and/or cultural heritage.  
| C53, Multiple indigenous species damage within a local area. |  
| 6. Compliance: |  
| C61, Multiple breaches of requirements/prolonged breaches of multiple legal and regulatory obligations. The potential loss of operating license. | C63, Single breach of legal or regulatory obligations.  
| C62, Single breach of requirements or multiple breaches of legal and regulatory obligations. | C64, Partial breach of legal or regulatory obligations.  
| C65, No breach of legal or regulatory obligations |  
| 7. Asset Condition Rating (ACR): Channel has |  
| C71, 89 % average remaining life and 80 % minimum remaining life. | C74, 20 % average remaining life and 15 % minimum remaining life.  
| C72, 58 % average remaining life and 39 % minimum remaining life. | C75, 8 % average remaining life and 3 % minimum remaining life.  
| C73, 32 % average remaining life and 27 % minimum remaining life. | C76, 1 % average remaining life and 0 % minimum remaining life.  

Table notes: C15, C25, C55, C65, C71, C72 are benefit criteria and the rest are considered cost criteria.
| Channel No.1 | Channel No.2 | Channel No.3 | Channel No.4 | Channel No.5 | Channel No.6 |
|-------------|-------------|-------------|-------------|-------------|-------------|
| C11         | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
| C12         | H, L, VL    | VH, L, VL   | MH, L, VL   | VL, VL, VL  | VL, L, VL   |
| C13         | VH, ML, MH  | VH, ML, M   | H, ML, M    | L, VL, VL   | L, ML, M    |
| C14         | VH, H, VH   | VH, H, MH   | VH, MH, MH  | H, M, ML    | M, M, L     |
| C15         | VH, VH, VH  | VH, VH, MH  | VH, MH, MH  | VH, MH, M   | VH, VH, MH  |
| C21         | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
| C22         | VL, VL, MH  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
| C23         | VL, VL, MH  | H, VL, L    | MH, VL, ML  | L, VL, L    | L, VL, ML   |
| C24         | H, ML, H    | H, ML, ML   | VH, L, ML   | MH, L, ML   | MH, VL, ML  |
| C25         | VH, H, VH   | VH, H, MH   | VH, ML, MH  | VH, L, H    | VH, H, MH   |
| C31         | H, VL, L    | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | ML, VL, ML  |
| C32         | VH, VL, MH  | VL, VL, VL  | VL, VL, VL  | H, VL, L    | VL, VL, VL  |
| C33         | VH, VL, MH  | VL, VL, L   | VL, VL, L   | VH, VL, M   | L, VL, L    |
| C34         | VH, VL, MH  | L, VL, ML   | L, VL, ML   | VH, VL, MH  | L, VL, ML   |
| C35         | VH, VL, H   | L, VL, M    | L, VL, M    | VH, VL, H   | L, VL, M    |
| C41         | M, VL, VL   | VL, VL, VL  | VL, VL, VL  | VH, VL, M   | VH, VL, VL  |
| C42         | H, VL, ML   | L, VL, VL   | VL, VL, VL  | H, VL, L    | M, VL, VL   |
| C43         | VH, ML, MH  | M, L, ML    | MH, M, M    | VH, VL, M   | M, L, ML    |
| C44         | VH, H, VH   | H, ML, ML   | H, ML, MH   | VH, VL, MH  | H, ML, M    |
| C45         | VH, MH, VH  | VH, MH, MH  | VH, MH, VH  | VH, ML, H   | VH, H, MH   |
| C51         | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
| C52         | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
| C53         | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  | VL, VL, VL  |
### Table 11. Cont.

| Channel No.1 | Channel No.2 | Channel No.3 | Channel No.4 | Channel No.5 | Channel No.6 |
|--------------|--------------|--------------|--------------|--------------|--------------|
| C54          | L, VL, ML    | VL, VL, VL   | VL, VL, L    | VL, VL, L    | VL, VL, L    |
| C55          | H, VL, H     | H, VL, H     | H, VL, ML    | H, VL, M     | H, VL, H     |
| C61          | VL, VL, VL   | VL, VL, VL   | VL, VL, VL   | VL, VL, VL   | VL, VL, VL   |
| C62          | L, VL, L     | L, VL, L     | L, VL, L     | L, VL, L     | VL, VL, L    |
| C63          | M, VL, ML    | VL, VL, L    | L, VL, L     | M, VL, ML    | L, VL, ML    |
| C64          | M, VL, MH    | L, VL, ML    | MH, VL, M    | M, VL, M     | ML, VL, MH   |
| C65          | H, VL, H     | H, VL, MH    | H, VL, MH    | H, VL, M     | H, VL, H     |
| C71, ACR1    | 0.0001       | 0.0001       | 0.0001       | 0.0001       | 0.0001       |
| C72, ACR2    | 0.1          | 0.0001       | 0.0001       | 0.55         | 0.0001       |
| C73, ACR3    | 0.35         | 0.25         | 0.75         | 0.45         | 0.0001       |
| C74, ACR4    | 0.1          | 0.375        | 0.0001       | 0.35         | 0.7          |
| C75, ACR5    | 0.45         | 0.375        | 0.25         | 0.65         | 0.175        |
| C76, ACR6    | 0.0001       | 0.0001       | 0.0001       | 0.0001       | 0.0001       |
Then, different judgments by three experts are aggregated. Aggregated evaluations are presented in Appendix A. The decision matrix then is defuzzified, as presented in Table 12.

**Table 12.** The defuzzified evaluation matrix.

| Channel No.1 | Channel No.2 | Channel No.3 | Channel No.4 | Channel No.5 | Channel No.6 |
|--------------|--------------|--------------|--------------|--------------|--------------|
| C11          | 0.01875      | 0.05118      | 0.01875      | 0.01875      | 0.01875      |
| C12          | 0.33105      | 0.36395      | 0.27270      | 0.01875      | 0.01875      |
| C13          | 0.48750      | 0.57875      | 0.54645      | 0.14230      | 0.01875      |
| C14          | 0.92383      | 0.83270      | 0.77375      | 0.54645      | 0.36395      |
| C15          | 0.95625      | 0.86500      | 0.86500      | 0.77375      | 0.70868      |
| C21          | 0.01875      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C22          | 0.23993      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C23          | 0.23993      | 0.33105      | 0.33118      | 0.08383      | 0.14230      |
| C24          | 0.67000      | 0.48125      | 0.45508      | 0.36395      | 0.33118      |
| C25          | 0.92383      | 0.83270      | 0.64383      | 0.64383      | 0.64395      |
| C31          | 0.33105      | 0.01875      | 0.01875      | 0.01875      | 0.23993      |
| C32          | 0.55283      | 0.01875      | 0.01875      | 0.01875      | 0.33105      |
| C33          | 0.55283      | 0.05118      | 0.11000      | 0.08383      | 0.48750      |
| C34          | 0.55283      | 0.14230      | 0.14230      | 0.14230      | 0.55283      |
| C35          | 0.61105      | 0.20750      | 0.20750      | 0.20750      | 0.61105      |
| C41          | 0.17508      | 0.01875      | 0.01875      | 0.01875      | 0.23993      |
| C42          | 0.39000      | 0.05118      | 0.01875      | 0.01875      | 0.29875      |
| C43          | 0.64383      | 0.29875      | 0.55283      | 0.14230      | 0.48750      |
| C44          | 0.92383      | 0.48125      | 0.61105      | 0.26633      | 0.55283      |
| C45          | 0.86500      | 0.77375      | 0.86500      | 0.57875      | 0.70230      |
| C51          | 0.01875      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C52          | 0.01875      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C53          | 0.01875      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C54          | 0.14230      | 0.01875      | 0.05118      | 0.05118      | 0.05118      |
| C55          | 0.57875      | 0.57875      | 0.57875      | 0.39000      | 0.45508      |
| C61          | 0.01875      | 0.01875      | 0.01875      | 0.01875      | 0.01875      |
| C62          | 0.08383      | 0.08383      | 0.08383      | 0.08383      | 0.08383      |
| C63          | 0.26633      | 0.05118      | 0.08383      | 0.08383      | 0.26633      |
| C64          | 0.39625      | 0.14230      | 0.39625      | 0.20125      | 0.33118      |
| C65          | 0.57875      | 0.51993      | 0.51993      | 0.45508      | 0.45508      |
| C71          | 0.00010      | 0.00010      | 0.00010      | 0.00010      | 0.00010      |
| C72          | 0.10000      | 0.00010      | 0.00010      | 0.55000      | 0.00010      |
| C73          | 0.35000      | 0.25000      | 0.75000      | 0.45000      | 0.00010      |
| C74          | 0.10000      | 0.37500      | 0.00010      | 0.35000      | 0.07500      |
| C75          | 0.45000      | 0.37500      | 0.25000      | 0.00010      | 0.65000      |
| C76          | 0.00010      | 0.00010      | 0.00010      | 0.00010      | 0.00010      |
Next, the values in Table 12 need to be normalised. Using the determined weights (fuzzy AHP), weighted normalised values are calculated, as presented in Table 13.

Table 13. Case study weighted normalised evaluation matrix and negative and positive ideal solutions.

| Criteria | Channel No.1 | Channel No.2 | Channel No.3 | Channel No.4 | Channel No.5 | Channel No.6 | \( v^- \) | \( v^+ \) |
|----------|--------------|--------------|--------------|--------------|--------------|--------------|---------|---------|
| C11      | 0.145        | 0.000        | 0.145        | 0.145        | 0.145        | 0.145        | 0.000   |
| C12      | 0.023        | 0.000        | 0.058        | 0.219        | 0.219        | 0.199        | 0.219   |
| C13      | 0.000        | 0.023        | 0.035        | 0.180        | 0.224        | 0.124        | 0.224   |
| C14      | 0.000        | 0.023        | 0.038        | 0.095        | 0.133        | 0.031        | 0.133   |
| C15      | 0.231        | 0.209        | 0.187        | 0.171        | 0.209        | 0.171        | 0.231   |
| C21      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C22      | 0.000        | 0.121        | 0.121        | 0.121        | 0.121        | 0.121        | 0.000   |
| C23      | 0.036        | 0.000        | 0.000        | 0.099        | 0.075        | 0.118        | 0.118   |
| C24      | 0.000        | 0.037        | 0.042        | 0.060        | 0.066        | 0.031        | 0.066   |
| C25      | 0.131        | 0.118        | 0.091        | 0.091        | 0.118        | 0.091        | 0.131   |
| C31      | 0.000        | 0.226        | 0.226        | 0.226        | 0.066        | 0.226        | 0.226   |
| C32      | 0.096        | 0.235        | 0.235        | 0.235        | 0.000        | 0.235        | 0.235   |
| C33      | 0.000        | 0.226        | 0.192        | 0.204        | 0.028        | 0.204        | 0.226   |
| C34      | 0.000        | 0.178        | 0.178        | 0.178        | 0.000        | 0.178        | 0.178   |
| C35      | 0.000        | 0.158        | 0.158        | 0.158        | 0.000        | 0.158        | 0.158   |
| C41      | 0.033        | 0.111        | 0.111        | 0.111        | 0.000        | 0.111        | 0.111   |
| C42      | 0.000        | 0.110        | 0.114        | 0.114        | 0.028        | 0.066        | 0.114   |
| C43      | 0.000        | 0.064        | 0.017        | 0.094        | 0.029        | 0.064        | 0.094   |
| C44      | 0.000        | 0.058        | 0.041        | 0.085        | 0.048        | 0.049        | 0.085   |
| C45      | 0.000        | 0.013        | 0.041        | 0.040        | 0.027        | 0.004        | 0.040   |
| C51      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C52      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C53      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C54      | 0.000        | 0.069        | 0.062        | 0.062        | 0.062        | 0.062        | 0.069   |
| C55      | 0.080        | 0.080        | 0.080        | 0.054        | 0.063        | 0.080        | 0.054   |
| C61      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C62      | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
| C63      | 0.000        | 0.106        | 0.083        | 0.083        | 0.000        | 0.056        | 0.106   |
| C64      | 0.000        | 0.077        | 0.000        | 0.059        | 0.020        | 0.020        | 0.077   |
| C65      | 0.120        | 0.108        | 0.108        | 0.094        | 0.094        | 0.120        | 0.094   |
| C71, ACR1| 0.070        | 0.070        | 0.070        | 0.070        | 0.070        | 0.070        | 0.070   |
| C72, ACR2| 0.013        | 0.000        | 0.000        | 0.000        | 0.006        | 0.000        | 0.070   |
| C73, ACR3| 0.037        | 0.046        | 0.000        | 0.028        | 0.069        | 0.063        | 0.070   |
| C74, ACR4| 0.060        | 0.032        | 0.069        | 0.069        | 0.035        | 0.000        | 0.070   |
| C75, ACR5| 0.021        | 0.029        | 0.043        | 0.069        | 0.000        | 0.051        | 0.070   |
| C76, ACR6| 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000        | 0.000   |
As can be seen in Table 14, the results of the application of the developed methodology suggest prioritising channel no. 1 for maintenance followed by channel nos. 5, 2, 3, 6 and 4.

Table 14. Case study alternatives evaluation and ranking results.

| Channel No.1 | Channel No.2 | Channel No.3 | Channel No.4 | Channel No.5 | Channel No.6 |
|--------------|--------------|--------------|--------------|--------------|--------------|
| $d^+$        | 0.204        | 0.543        | 0.543        | 0.644        | 0.437        | 0.598        |
| $d^-$        | 0.619        | 0.386        | 0.339        | 0.132        | 0.480        | 0.207        |
| $C_c(i)$     | 0.751        | 0.422        | 0.388        | 0.176        | 0.518        | 0.257        |
| Preference for maintenance | 1st | 3rd | 4th | 6th | 2nd | 5th |

6. Discussion

The evaluation criteria for the management of irrigation infrastructure are derived from the case study corporate risk framework. Table 15 shows the different criteria, their underlying values and their description.

Table 15. Consequence categories [44].

| Consequence Category | Underlying Values | Description |
|----------------------|-------------------|-------------|
| Service delivery     | Resource stewardship, core service delivery and customer prosperity | (What impact interruption to service delivery will have on how many customers.) |
| Business financial loss | Business viability and sustainability | (What is the range of business financial loss as a result.) |
| Safety               | Individual health and wellbeing | (What impact an incident due to failure has on how many individuals.) |
| Credibility          | Relationships and credibility | (What level of criticism a failure causes and what impacts it has on GMW’s reputation.) |
| Environment          | Cultural heritage, native vegetation, water quality and fauna | (What the impacts and causes to the environment and cultural heritage are and what the extent area-wise is.) |
| Compliance           | Legal and regulatory compliance obligations | (What level of breaches of requirements and legal and regulatory obligations and their level of consequences.) |

The existing method used in G-MW does not calculate weights for criteria, and instead the irrigation infrastructure consequence scores in terms of these criteria are calculated at an asset category level to apply a common rating to logical asset groupings and reduce the need to manually allocate a rating to each of the irrigation and drainage assets (see Appendix B). Although assessing by the asset category enables differentiation of consequence; for example, the failure of a >500 megalitres a day (ML/D) channel has a higher consequence rating compared to the failure of a <100 ML/D channel, but it overlooks differences between assets in the same category. However, the proposed method in this study requires determining weights of each criterion to then use in evaluating irrigation assets for maintenance prioritisation.

To verify the results of the proposed method, three asset management experts were asked for technical judgment and ranking the subject channels for maintenance. The results of the developed methodology and the asset experts’ preferences, based on their visual inspection and assessment of physical condition of the channels, are presented in Table 16. This Table presents the channels’ condition ratings and design capacity data. The preferences of the three experts for the final rank are also presented, which can be compared to the ranking result from the proposed method.
Table 16. Ranking preferences by the developed method and asset experts.

| Channel | Asset Condition Rating (ACR) | Design Capacity (ML/day) | 1st Asset Expert Preferred Ranking | 2nd Asset Expert Preferred Ranking | 3rd Asset Expert Preferred Ranking | Results of the Developed Method |
|---------|-------------------------------|--------------------------|-----------------------------------|-----------------------------------|-----------------------------------|---------------------------------|
|         | 1  2  3  4  5  6             |                          |                                   |                                   |                                   |                                 |
| No.1    |                              |                          |                                   |                                   |                                   |                                 |
| LB *    | 0.2  0.5  0.6  0.2  0.3  0.2 | 200                      | 1st                               | 2nd                               | 1st                               | 1st                             |
| RB *    |                              |                          |                                   |                                   |                                   |                                 |
| No.2    |                              |                          |                                   |                                   |                                   |                                 |
| LB      | 0.3  0.2  0.45  0.25  0.5  0.3 | 180                      | 2nd                               | 3rd                               | 4th                               | 3rd                             |
| RB      |                              |                          |                                   |                                   |                                   |                                 |
| No.3    |                              |                          |                                   |                                   |                                   |                                 |
| LB      | 0.7  0.3  0.3  0.7  0.3  0.7  | 135                      | 3rd                               | 4th                               | 3rd                               | 4th                             |
| RB      |                              |                          |                                   |                                   |                                   |                                 |
| No.4    |                              |                          |                                   |                                   |                                   |                                 |
| LB      | 0.55 0.45  0.55 0.45  0.2   | 70                       | 6th                               | 6th                               | 6th                               | 6th                             |
| RB      |                              |                          |                                   |                                   |                                   |                                 |
| No.5    |                              |                          |                                   |                                   |                                   |                                 |
| LB      | 0.6  0.4  0.6  0.4  0.1  0.9 | 35                       | 5th                               | 1st                               | 5th                               | 2nd                             |
| RB      |                              |                          |                                   |                                   |                                   |                                 |
| No.6    |                              |                          |                                   |                                   |                                   |                                 |
| LB      | 0.05 0.15 0.8 0.05 0.6 0.35 | 190                      | 4th                               | 5th                               | 2nd                               | 5th                             |
| RB      |                              |                          |                                   |                                   |                                   |                                 |

* LB and RB stand for left bank and right bank, respectively.
The proposed fuzzy MCDM method prioritised channels 1 and 4 to be the first and last asset alternatives for maintenance. This is already an improvement compared to the current method in practice, which evaluates all the assets with the same risk score. Taking a closer look to investigate the reason why channel no. 1 has been prioritised (by the proposed method and the asset management experts) as the first priority shows the ability of the MCDM methods to identify the differences between alternatives. This channel is the biggest amongst all with a 200 megalitre per day capacity. Its asset condition ratings under tier 5, represented by ACR5 (which means almost close to failure bank) for the left-hand bank, is the highest compared to all others. The ACR5 percentage of the right-hand bank is the third compared to all the rest of the evaluated channels. However, it should be noted that the channel with worst right-hand bank in tier 5 of ACR is a relatively small channel (design capacity of 35 megalitre per day). Furthermore, the channel which possesses the second position in the ACR5 percentage of its right-hand bank is just 5% worse off compared to channel no. 1. Obviously, channel number 1 will have a higher financial impact in the case of failure due to its size; thus, the basic figure comparisons prioritise this channel for maintenance ahead of the others. The same principle can be applied for the consequence of the channel failure in terms of safety (if it fails, the consequence would be more severe due to the size of channel), service delivery, compliance and credibility.

If the same observation be applied for channel no. 4, the results of the MCDM method make sense. This channel is the second from the last in terms of its design capacity. The smallest is 35 ML/D, and channel no. 4 is 70 ML/D. Its banks are the healthiest according to their percentages of different tiers of ACR. It does not have any percentage of its length in ACR5, 6 or even 4; therefore, at least 30–40% of this channel’s effective life of each of the banks is remaining (just 45% of both banks are ACR3). This is actually a good example of the MCDM methods’ ability to take multiple criteria into account and release very accurate rankings, which provide an opportunity for the asset owners to spend their budget on worst assets, especially in the current challenging situation that asset owners are facing.

Based on the results from the MCDM methods, despite having a scientific basis, the current methodology in practice is not able to distinguish the different channels’ conditions, as all these channels had been evaluated with the same risk score and therefore the same ranking. Below are some suggestions for improving the effectiveness and accuracy of the existing maintenance prioritisation methods:

- Since irrigation channels could run along bends or paddocks (which can expedite deterioration due to livestock movement, especially if banks are not protected by fences), their physical condition can vary along their length. The existing prioritisation method utilises the highest-evaluated ACR as the likelihood of failure of an irrigation channel. This makes the assessment inaccurate, as a channel might have 20% of its length in ACR5 but most of its length in good condition yet still be prioritised for maintenance over another channel (with the same capacity but with, for example, 50% of its length with ACR5 and the rest in much worse condition compared to the first channel). Despite having the same risk score, if not investigated in more detail, the second channel could be easily overlooked by the current practice. Given the length of channel infrastructure, mistakes such as this can result in inefficient operation and cause reputational damage to the irrigation infrastructure owner. The research methodology suggests considering different percentages of different asset condition ratings when assessing an irrigation channel for maintenance, which would yield more accurate maintenance prioritisation rankings compared to the existing method.

- The current irrigation asset maintenance prioritisation method utilises a category-based approach to determine the consequence score and subsequent maintenance ranking for assets; that is, channels with <500 ML/D capacity have a consequence score of 14, and channels with 500–2000 ML/D capacity have a consequence score of 16. Considering existing budget restrictions, this approach is too generalised and could overlook the subtle differences between irrigation channels with similar characteristics. Thus, changing this approach could make a significant difference in (more accurately)
identifying the riskiest assets to maintain, which in turn improves asset maintenance efficiency in the long term.

- The existing method for measuring the criteria weights and alternative performance values is subjective. Therefore, uncertainty attached to asset management experts’ thinking (in measuring the criteria weight and deciding on asset condition ratings, which ultimately result in the evaluation of maintenance prioritisation) can add to the inaccuracy of the maintenance prioritisation assessment. The literature suggests employing the fuzzy theory to capture the uncertainty associated with the subjective decision-making and thus result in more accurate rankings. This is the core and most important suggestion of this study, as no existing irrigation asset maintenance prioritisation methods consider the issue of subjectivity in assessment.

- Another shortcoming of the existing prioritisation method is the lack of a procedure to check consistency when measuring criteria weights. As the number of criteria is considerable and the evaluation scale is subjective (with linguistic variables such as more important, less important, equally important), irrigation infrastructure management experts could easily lose track while evaluating. In other words, the process of measuring the criteria importance index does not have any controlling stage to make sure that judgments are not random and reflect realistic and accurate assessments by irrigation infrastructure management experts. To put this in an easier context, when an asset decision-maker decides service delivery is twice as important as safety, which is in turn three times more important than financial loss, currently, there is no procedure to assure service delivery is assessed as six times more important compared to financial loss. Inconsistent judgments while undertaking trade-offs create inaccuracy in the criteria weight determination and consequently asset maintenance prioritisation. The methodologies, such as AHP, enable detecting such inconsistencies in the decision-making process.

Considering the number of irrigation infrastructure assets, it might be more efficient to use the existing prioritisation method to refine the (long) list of alternatives. The final list from the existing method can then be prioritised using the fuzzy MCDM method for a more accurate final prioritisation, which ultimately results in better asset management practice.

The agreement between the prioritisation results from the fuzzy MCDM method and the experts’ ranking preferences proved the accuracy of the newly developed fuzzy MCDM method in distinguishing the differences between the alternatives. Therefore, it is concluded that the fuzzy MCDM method improved the prioritisation results and is thus an appropriate methodology to apply to the problem of irrigation infrastructure prioritisation for maintenance.

7. Conclusions

In this study, a fuzzy multi-criteria decision-making methodology was developed. The developed method is suggested for the maintenance prioritisation of irrigation assets. Using type-2 fuzzy sets for digitising linguistic variables is a reliable tool to capture uncertainty associated with the human cognitive process and to model diverse opinions from different experts.

Type-2 fuzzy AHP that is based on pairwise comparison was used to measure criteria weights. Seven criteria were considered and pairwisely compared to determine their weights to use in assessing irrigation infrastructure and prioritise them for maintenance. AHP proposes a mechanism (i.e., applying a 10% tolerance for inconsistent judgements) to assure consistency in evaluation while assessing criteria weights using the pairwise comparison matrix. Fuzzy TOPSIS was utilised to evaluate and rank alternatives (maintenance candidates) by establishing ideal solutions and ranking the irrigation infrastructure based on their performance relative to the ideal solutions.

The developed method was applied to six different channels in Goulburn Murray Water irrigation areas. Results from the proposed method provided a reasonable prioritisation
ranking in a multi-criteria problem, which was in line with the physical conditions of the studied channels.

The proposed method can be utilised to prioritise assets for maintenance in other multi-criteria scenarios, with the ability to save millions of dollars for asset owners.

To further improve the practice of asset maintenance prioritisation, one area to investigate in more detail is the list of established criteria used to prioritise assets for maintenance. Sometimes, organisational risk framework criteria should be updated more often than what currently occurs in practice. Therefore, a closer look into the list of assessment criteria could be a starting point to further optimise maintenance prioritisation methods. This point is also important from the organisation’s strategic point of view, as the criteria to base decisions on can evolve depending on the customer’s expectations, a change in the market and a change in regulations.

Trying to only use criteria without any sub-criteria for evaluating the alternatives is another area to investigate. If this exercise proves to have similar results (as when utilising both criteria and sub-criteria), it would simplify the process, which, in turn, increases the likelihood of utilisation of more advanced methods in real-world cases.

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**Appendix A**

### Table A1. Aggregated evaluation matrix by three asset management experts.

|       | Channel No.1                      | Channel No.2                      | Channel No.3                      | Channel No.4                      | Channel No.5                      | Channel No.6                      |
|-------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| **C11** | 
|       | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.1; 0.9, 0.9)) | ((0.033, 0.033, 0.1; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) |
| **C12** | 
|       | ((0.233, 0.333, 0.333, 0.467; 1, 1), (0.283, 0.333, 0.333, 0.400; 0.9, 0.9)) | ((0.300, 0.367, 0.367, 0.467; 1, 1), (0.333, 0.367, 0.367, 0.417; 0.9, 0.9)) | ((0.167, 0.267, 0.267, 0.433; 1, 1), (0.217, 0.267, 0.267, 0.350; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0.033, 0.033, 0.167; 1, 1), (0.017, 0.033, 0.033, 0.100; 0.9, 0.9)) |
| **C13** | 
|       | ((0.300, 0.500, 0.300, 0.500; 0.9, 0.9)) | ((0.433, 0.600, 0.600, 0.733; 1, 1), (0.517, 0.600, 0.600, 0.867; 0.9, 0.9)) | ((0.367, 0.567, 0.567, 0.733; 1, 1), (0.467, 0.567, 0.567, 0.650; 0.9, 0.9)) | ((0.033, 0.133, 0.133, 0.300; 1, 1), (0.083, 0.133, 0.133, 0.217; 0.9, 0.9)) | ((0, 0, 0, 0.100; 1, 1), (0, 0, 0, 0.050; 0.9, 0.9)) | ((0.133, 0.300, 0.300, 0.500; 1, 1), (0.217, 0.300, 0.300, 0.400; 0.9, 0.9)) |
| **C14** | 
|       | ((0.833, 0.967, 0.967, 1.1), (0.900, 0.967, 0.967, 0.983; 0.9, 0.9)) | ((0.700, 0.867, 0.867, 0.967; 1, 1), (0.785, 0.867, 0.800, 0.933; 1, 1)) | ((0.633, 0.800, 0.800, 0.933; 1, 1), (0.717, 0.800, 0.567, 0.650; 0.9, 0.9)) | ((0.367, 0.567, 0.567, 0.733; 1, 1), (0.467, 0.567, 0.567, 0.650; 0.9, 0.9)) | ((0.200, 0.367, 0.367, 0.567; 1, 1), (0.283, 0.367, 0.367, 0.467; 0.9, 0.9)) | ((0.633, 0.833, 0.833, 0.967; 1, 1), (0.733, 0.833, 0.833, 0.9; 0.9, 0.9)) |
| Channel No.1          | Channel No.2          | Channel No.3          | Channel No.4          | Channel No.5          | Channel No.6          |
|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| C31                  | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) |
| C32                  | (0.150, 0.200, 0.067, 0.067, 0.150; 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) |
| C33                  | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) |
| C34                  | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) |
| C35                  | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) | (0.0, 0.0, 0.100; 1, 1, 0.9, 0.9) |

Table A1. Cont.
| Channel No.1                              | Channel No.2                              | Channel No.3                              | Channel No.4                              | Channel No.5                              | Channel No.6                              |
|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| \((0.100, 0.167, 0.167, 0.500; 1, 1), \((0.133, 0.167, 0.167, 0.233; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.167, 0.233, 0.233, 0.533; 1, 1), (0.200, 0.233, 0.233, 0.300; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) |
| C41                                      | C42                                      | C43                                      | C44                                      | C45                                      | C46                                      |
| \((0.267, 0.400, 0.400, 0.533; 1, 1), \((0.333, 0.400, 0.400, 0.467; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.233, 0.300, 0.300, 0.400; 1, 1), (0.267, 0.300, 0.300, 0.350; 0.9, 0.9))\) | \((0.100, 0.167, 0.167, 0.300; 1, 1), (0.133, 0.167, 0.167, 0.233; 0.9, 0.9))\) |
| C46                                      | C47                                      | C48                                      | C49                                      | C50                                      | C51                                      |
| \((0.500, 0.667, 0.667, 0.800; 1, 1), \((0.583, 0.667, 0.667, 0.733; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.033, 0.033, 0.167; 1, 1), (0.033, 0.033, 0.100; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) |
| C51                                      | C52                                      | C53                                      | C54                                      | C55                                      | C56                                      |
| \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) |
| C56                                      | C57                                      | C58                                      | C59                                      | C60                                      | C61                                      |
| \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) |
| C61                                      | C62                                      | C63                                      | C64                                      | C65                                      | C66                                      |
| \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) | \((0.0, 0.0, 0.100; 1, 1), (0.0, 0.0, 0.050; 0.9, 0.9))\) |
### Table A1. Cont.

| Channel No. 1 | Channel No. 2 | Channel No. 3 | Channel No. 4 | Channel No. 5 | Channel No. 6 |
|---------------|---------------|---------------|---------------|---------------|---------------|
| C63 ((0.133, 0.267, 0.267, 0.433; 1, 1), (0.200, 0.267, 0.267, 0.350; 0.9, 0.9)) | ((0.033, 0.133, 0.033, 0.100; 1, 1), (0.017, 0.033, 0.033, 0.100; 0.9, 0.9)) | ((0.067, 0.067, 0.233; 1, 1), (0.033, 0.067, 0.067, 0.150; 0.9, 0.9)) | ((0.067, 0.067, 0.233; 1, 1), (0.033, 0.067, 0.067, 0.150; 0.9, 0.9)) | ((0.133, 0.267, 0.267, 0.433; 1, 1), (0.200, 0.267, 0.267, 0.350; 0.9, 0.9)) | ((0.033, 0.133, 0.033, 0.100; 1, 1), (0.017, 0.033, 0.033, 0.100; 0.9, 0.9)) |
| C64 ((0.267, 0.400, 0.400, 0.567; 1, 1), (0.333, 0.400, 0.400, 0.483; 0.9, 0.9)) | ((0.033, 0.133, 0.033, 0.100; 1, 1), (0.017, 0.033, 0.033, 0.100; 0.9, 0.9)) | ((0.067, 0.067, 0.233; 1, 1), (0.033, 0.067, 0.067, 0.150; 0.9, 0.9)) | ((0.067, 0.067, 0.233; 1, 1), (0.033, 0.067, 0.067, 0.150; 0.9, 0.9)) | ((0.200, 0.333, 0.333, 0.500; 1, 1), (0.267, 0.333, 0.333, 0.417; 0.9, 0.9)) | ((0.033, 0.133, 0.033, 0.100; 1, 1), (0.017, 0.033, 0.033, 0.100; 0.9, 0.9)) |
| C65 * ((0.467, 0.600, 0.600, 0.700; 1, 1), (0.533, 0.600, 0.600, 0.650; 0.9, 0.9)) | ((0.400, 0.533, 0.533, 0.533; 1, 1), (0.467, 0.533, 0.533, 0.533; 0.9, 0.9)) | ((0.400, 0.533, 0.533, 0.533; 1, 1), (0.467, 0.533, 0.533, 0.533; 0.9, 0.9)) | ((0.333, 0.467, 0.467, 0.600; 1, 1), (0.400, 0.467, 0.467, 0.533; 0.9, 0.9)) | ((0.333, 0.467, 0.467, 0.600; 1, 1), (0.400, 0.467, 0.467, 0.533; 0.9, 0.9)) | ((0.467, 0.600, 0.600, 0.700; 1, 1), (0.533, 0.600, 0.600, 0.650; 0.9, 0.9)) |
| C71 * 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| C72 * 0.1000 | 0.0001 | 0.0001 | 0.5500 | 0.0001 | 0.0500 |
| C73 0.3500 | 0.2500 | 0.7500 | 0.4500 | 0.0001 | 0.0750 |
| C74 0.1000 | 0.3750 | 0.0001 | 0.0001 | 0.3500 | 0.7000 |
| C75 0.4500 | 0.3750 | 0.2500 | 0.0001 | 0.6500 | 0.1750 |
| C76 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |

* entries represent benefit criteria.

### Appendix B

Table A2. * An example of asset consequence scoring assessment [44].

| Rating | General Risk Categorisation as per Corporate Risk Framework | Major Channels | Non-Major Channels |
|--------|----------------------------------------------------------|----------------|-------------------|
| 5      | C11, catastrophic outcomes for many customers.            |                |                   |
| 4      | C12, service impacts to many customers.                   |                |                   |
| 3      | C13, major impact to a significant number of customers.   |                |                   |
| 2      | C14, moderate impact to a small group of customers.       |                |                   |
| 1      | C15, impacts a small number of customers and has minimal impact on their operations. |                |                   |
| 5      | C21, greater than $12 million loss.                       |                |                   |
| 4      | C22, between $8 and $12 million loss.                     |                |                   |
| 5      | C23, between $4 and $8 million loss.                      |                |                   |
| 2      | C24, between $3 and $4 million loss.                      |                |                   |
| 1      | C25, smaller than $1 million.                             |                |                   |
| 5      | C31, multiple fatalities.                                 |                |                   |
| 4      | C32, a permanent injury or a single fatality.             |                |                   |
| 3      | C33, recoverable injuries.                                |                |                   |
| 2      | C34, medical treatment.                                   |                |                   |
| 1      | C35, minor first aid injuries.                            |                |                   |
| Rating | General Risk Categorisation as per Corporate Risk Framework | Major Channels | Non-Major Channels |
|--------|-------------------------------------------------------------|----------------|-------------------|
| 5      | C41, local and national public outage resulting in loss of key stakeholder support. External intervention required. |                |                   |
| 4      | C42, substantial active criticism from key stakeholders, resulting in national media coverage. | 4              |                   |
| 3      | C43, criticism from stakeholders, involving local community public reactions. |                |                   |
| 2      | C44, criticism from local community segment, resulting in negative local press coverage. | 2              |                   |
| 1      | C45, internal dissent/isolated external criticism. No external impact to reputation. |                |                   |
| 5      | C51, impacts to the biological or physical environment that cause indigenous species extinction and/or irretrievable loss of habitat and/or cultural heritage. |                |                   |
| 4      | C52, impacts to the environment that cause multiple indigenous species damage. | 4              |                   |
| 3      | C53, impacts to the environment that cause multiple indigenous species damage within a local area. |              |                   |
| 2      | C54, impacts to the environment that cause single indigenous species damage or result in damage or loss of species, habitat and/or cultural heritage. |              |                   |
| 1      | C55, impacts on the environment that cause no indigenous species damage and/or cause damage to species, habitat and/or cultural heritage. | 1              |                   |
| 5      | C61, multiple breaches of requirements. Prolonged breaches of multiple legal and regulatory obligations. Potential loss of operating license. |                |                   |
| 4      | C62, single breach of requirements or multiple breaches of legal and regulatory obligations. Regulator issues a corrective notice. |              |                   |
| 3      | C63, single breach of legal or regulatory obligations. Cooperate risk issues corrective actions notice. | 3              |                   |
| 2      | C64, partial breach of legal or regulatory obligations. | 2              |                   |
| 1      | C65, no breach of legal or regulatory obligations detected; however, improvements to the manner in which compliance is attained can be made. |          |                   |

Total 22 11
Table A2. Cont.

| Rating                | General Risk Categorisation as per Corporate Risk Framework | Major Channels | Non-Major Channels |
|-----------------------|-----------------------------------------------------------|----------------|--------------------|
| Rare—low (1)          |                                                            |                |                    |
| Unlikely—low (2)      |                                                            |                |                    |
| Possible—medium (3)   |                                                            |                |                    |
| Likely—significant (4)|                                                            |                |                    |
| Almost certain—extreme (5) |                                                        |                |                    |

* assessment in this table are just examples and do not represent the assessment scores by the case study.

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