Multi-Criteria Decision Based Evaluation of Water Management Scenarios for Minna Metropolis, Nigeria

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Abstract

Considering the relative importance of accommodating temporal expansion through the development of alternative strategies regarding water supply problems and probable augmentation in Minna and its metropolis, this study was designed to appraise water supply scarcity and proffer water loss reduction strategy. Against the backdrop of this fact, for this study, a Multi-Criteria based decision method (MCDM) was employed to evaluate management scenarios. It is imperative to note that the sensitivity analysis of the conditional notions in the MCDM as implemented was divided into two levels: first level (input data), second level (elements of the MCDM proper) and also an enhanced module was incorporated in the application of the MCDM for the generation of robust alternatives. Results obtained showed that: (a) the adoption of MCDM with a robust knowledge expert base is effective for water supply analysis, (b) two plausible water management scenarios in terms of supply and allocation were identified to be effective, i.e., Individual and Group Decision Making Scenarios, (c) combination of Improved Speed and Quality of Repairs (S3) and Selective Mains and Service Line Replacements (S4) decision making options can enhance substantial water supply loss reduction. This accounted for 82.23% and 78.74% reduction respectively in water loss on transit. Results obtained also indicate that the employment of the Geometrical Analysis for Interactive Assistance (GAIA) is a viable complement in the implementation of the MCDM, especially for the preference ranking and organization method for enrichment evaluation (PROMETHEE) approach.

Keywords: Decision support, GAIA, Multi-criteria, PROMETHEE, Water resources

1. Introduction

Lack of proper planning and management of water resources is often accompanied with significant consequences ranging from insufficient water quantity, compromised water quality and high cost of the available one. How well our water resources are managed today determines how well these resources will serve us and our descendants in the long-term. Hence, much attention should be focused on the management of these resources (Daniel, 2005). Water resources planning and management is associated with decision supports for managing water crisis (water scarcity, water pollution, water disasters such as floods and draughts as well as soil erosion problems) which emanate from concentrated utilization of lands and aquifers (Loucks et al., 2005).

In recent time, water resources planning and management has grown to be an increasing challenge due to many considerable changes and uncertainties linked to the water utility industry. One significant challenge arises from compelling rivalry between water use for drinking purpose and for other domestic and industrial functions, and from enormous leakage along the treated water distribution channel. Complexity of water resource planning circumstance due to extensive planning interval, decision variables as well as organization limitations, has rendered unfit some of the earlier methods such as multi-objective optimization (MO) (Haimes et al., 2005; Loucks et al., 2005). More so, deficiency of accurate data and inherent hydrological variability cause a number of uncertainties which complicate decision making in water resource management (Simonovic, 2000).

There is therefore, the need to develop a competent approach in order to facilitate effective planning and management of this resource as it has become a topical issue in most national and international discourse. More so, water engineering projects cannot be better planned or undertaken to harness or address water related issue without identifying various alternatives for maximizing water saving, water supply consistency and incomes while the expenditure is minimized. Thus, the various impacts of each proposed alternative need to be evaluated and assessed.

In dealing with these water resources management problems, various Multi-Criteria based decision method (MCDM) techniques have broadly been applied. Zimmermann (2007) employed fuzzy set theory in addressing vagueness, imprecision and uncertainty and Silva et al. (2010) used preference ranking and organization method for enrichment evaluation (PROMETHEE) for group decision model to support watershed committees in Brazil. In recognition of all this, this study evaluates the workability of a multi- criteria decision support framework to prioritize water loss reduction approaches in managing existing water supply systems for water resources planning and management.

Materials and Methods

Study Area and Data Collection

The study area is Minna, Niger State Capital. It lies on latitudes 9°37□N- 9°79□N and longitude6°16□E - 6°65□E. The city has an estimated population of 350,287 as at 2006 and a land area of about 6,789 km^2 (Ishiaku et al., 2014).

The data used for this study were derived through a qualitative research strategy. The primary data were sourced from a structured interviewer-assisted questionnaire and open-ended interviews to derive preference functions (PFs) and weights for the evaluation criteria (EC) and objectives. Respondent were selected following a purposive sampling frame of senior officials of the Niger State Water Board Minna (NSWB).

Methods

In this study PROMETHEE–GAIA Decision Lab software was employed in multi-criteria decision analysis (MCDM) of the study area data. MCDM is a set of techniques for resolving research problems with a fixed number of decision options amongst which decision-makers (DMs) have to evaluate and rank based on the weights of a finite set of evaluation criteria (EC) (Malczewski, 1999; Mutikanga et al., 2011). While PROMETHEE method belongs to the outranking multi criteria methods, GAIA is a visual modelling method connected to the PROMETHEE methods (Ánagnostopoulos, 2005). .

The methodology used in this study for generating options, determining evaluation criteria, model formulation, preference elicitation were adopted from Mutikanga, et al. (2011) for its advantages over previous methods like WDSs by Morais and Almeida (2007) which could not tackle water loss in totality which is a significant problem in developing country (Nigeria inclusive) (Mutikanga et al. 2011)

Problem Formulation for the NSWB

Based on the case study information, a problem statement was documented as "Scarcity and non-uniform distribution of water vis-à-vis the absence of effective and strategic water supply scheduling system for Minna metropolis", "Absence of quantifiable water loss reduction frame work in the water supply chain management system" and Government policy-implementation conflict vis-à-vis stakeholders' response to water resource management issues".

Problem Definition and Structuring:

Based on the problem definition, the following key requirements were proposed for the decision problem:

Strategy options should address both real and apparent losses.

Strategies should lead to a water loss reduction of at least 12 million m^3 per year.

Cost of implementing the selected strategies should not exceed N350 million per year.

Implementation period to achieve water loss reduction target should not exceed 10 years.

Actors: The actors (i.e. DMs in this study) were proposed by the analyst and approved by the General Manger of NSWB. They were all selected from within and outside the utility. Three actor groups were identified to represent utility DMs, water users and environmentalists. In this study, a total of eight DMs (DM1 to DM8) were selected for the preference elicitation process. Four persons which include manager and heads of departments in the utility represented utility interests (DM1, DM2, DM3, and DM4). Two experts in the field of water resources who are also users of the water represented Water Users/customer's interests (DM5, DM6). Two experts from geography department represented the environmental interests (DM7 and Dm8).

Generating Options: In order to generate appropriate water loss reduction strategy options, a water balance (Table 1) was established using the International Water Association /American Water Works Association (IWA/AWWA water balance methodology as the proposed methodology for assessing the apparent loss component (Mutikanga, et al., 2010).

Table 1: NSWB water balance for year 2012

Parameter	Water Loss Component	Unit	Quantity
System Input Volume		m^3	19,749,199
Revenue water		m^3	9,182,424
Non-revenue water		m^3	4,611,775
Water losses		m^3	6,143,584
	Real losses	m^3	5,247,352
	Apparent losses	m^3	4,164,802
	Unauthorised consumption	m^3	592,212

Source: NSWB (2014)

Based on the NSWB water balance, the following seven strategy options were adopted: Meter replacement (S1), Illegal use control (S2), Improved speed and quality of repairs (S3), Selective mains and service line replacements (S4), Establishing District Meter Areas (DMAs) and Network zoning (S5), Pressure management (S6) and Active leakage control (S7).

Determining Evaluation Criteria (EC):

For the realization of the set objectives, the following seven EC were used for performance evaluation of the strategy options: Revenue generation (EC1), Investment cost (EC2), Operation & maintenance costs (EC3), Water saved (EC4), Water quality (EC5), Supply reliability (EC6) and Affordability (Ec7).

Preference Functions (PF) and weights for the Evaluation Criteria (EC) and Objectives, were elicited from Decision Makers (DM), Water Users (WUs) and Environmentalists (ENs) using an interviewer-assisted questionnaire. Weights were then obtained and the PF was also applied using "usual criterion" type. This is one of the six generalized criteria described by Brans and Mareschal (2005). Sensitivity Analysis and Robustness Analysis for Water Loss Reduction Strategy Options were evaluated and analyzed using the capabilities of the Decision Lab/PROMETHEE in-built algorithm.

Predicting Performance: The Evaluation Matrix (EM) (Table 2) represents the evaluation of an option according to its performance based on a criterion. Scoring of options was based on experience and literature research as real outcomes of the decision options will be realized in future. In addition there was lack of reliable quantitative data for some options that are currently in use due to institutional challenges coupled with database limitations. To ensure accurate and objective evaluations, the evaluation matrix was completed by a team of the utility personnel in the water loss control unit who are experts on this subject matter. Since the criteria were qualitative in nature, the strategy options were evaluated using criteria measured on a Li-kert Scale ranging from 1 (very poor performance) to 5 (very good performance) (Table 3).

Sensitivity Analysis: In MCDA it is common to examine the sensitivity of output results for variations in PM weights or PM evaluations. Delgado and Sendra (2004) claimed that the sensitivity analysis in most MCDA models are based on the variation of the weights of the PMs applied in the process to check if it significantly affects the results obtained. However, attempts to study the sensitivity due to preference threshold values, such as in PROMETHEE type outranking methods, were rarely sighted in literature. The sensitivity of the results was analyzed using the Decision Lab Software routine.

Table 2: Evaluation matrix

Objective	Criteria	Direction	Strategy options						
			S1	S2	S3	S4	S5	S6	S7
Financial-economic	EC1 Revenue	Maximise	4	2	2	2	1	1	1
	EC2 Investment Cost	Minimise	1	1	1	5	2	2	2
	EC3 O & M Cost	Minimise	1	5	4	1	1	2	5
Environmental	EC4 Water Saved	Maximise	1	1	5	4	2	5	2
Public Health	EC5 Water Quality	Maximise	1	1	1	4	2	5	2
Technical	EC6 Supply Reliability	Maximise	1	?	2	4	1	5	2
Socio-economic	EC. Affordability	Maximise	4	5	1	2	1	2	1

Results and Discussion

Ranking Result for Individual Decision Making Scenario

Rankings obtained for DM5 (Water Users Preference) are given in Figures 1 and 2 respectively. These rankings sort the best water loss reduction strategies from the worst, taking all the actors' preferences into account. The partial ranking is based on strongly established (no compensations, but with incomparability's) preferences only whereas complete ranking is based on a numerical rating of the alternatives from the best alternative to the worst alternative leaving no incomparable pair of alternatives. PROMETHEE ranks the strategies in the order of their decreasing net flows, therefore the higher the net flow (Φ) value, the better the strategy.

As indicated in Figures 1 and 2, improved speed and quality of repairs (S3) emerged the optimum water management option for the partial and complete rankings obtained for DM5 for water loss reduction in the NSWB by having the highest net flow (Φ) value.

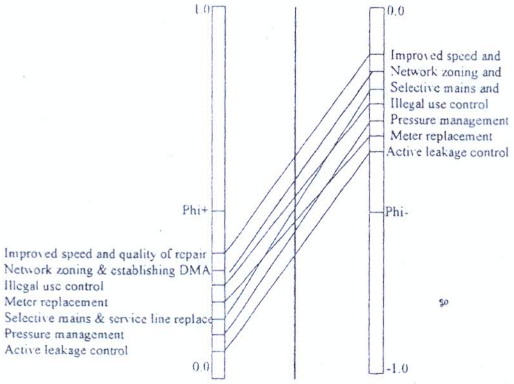


Figure 1: Partial rankings obtained for Dm5

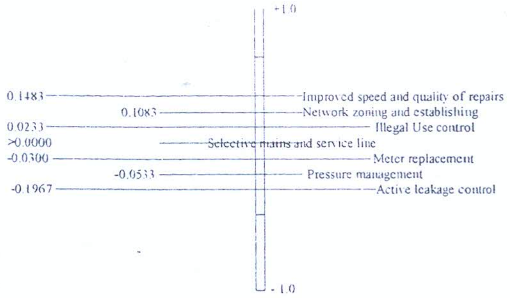


Figure2: Complete rankings obtained for Dm5

GAIA-criteria plane Result for Individual Decision Making Scenario

GAIA-criteria plane for DM5 case as illustrated in Figure 3 yields a sufficiently high decision quality value of 90.09%. Therefore, if DM5 is considered to be the only DM group, the information shown in Figure 3 could be used to arrive at a decision with reasonable accuracy.

Here, the Preferences Measures/evaluations are denoted by solid shapes and the circular ones present the seven ECs with their identification names. Of all the six individual decision making scenarios considered in this study, weights assigned by DM 5 emerged the most preferred water loss reduction strategy for the NSWB having a decision quality of 90%. Others are DM1-87.1%, DM2-79.5%, DM3-84.2%, DM4-80.7% and DM7-87.7%.

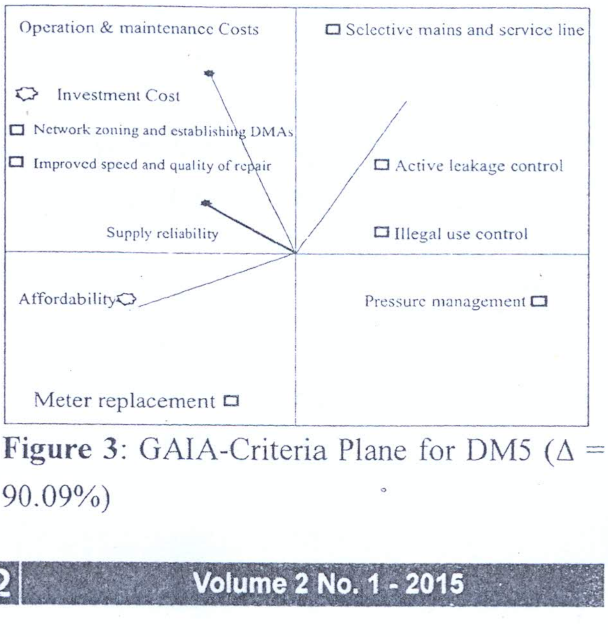
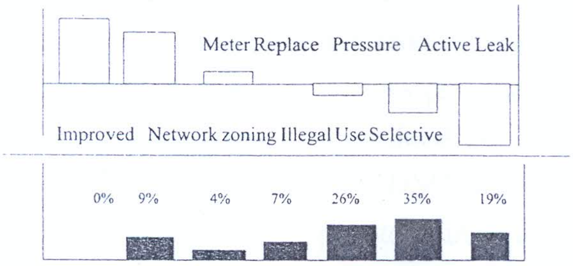


Figure 3: GAIA-Criteria Plane for DM5 (Δ = 90.09%)

Walking Weights Results for Individual Decision Making Scenario

A screen display for DM5 is given in Figure 4. The top chart is the graphical display of the net preference flows of water loss reduction strategies (y-axis) according to DM5's preferences. The bottom chart shows the PM weights given by DM5. However, by observing the variations in net preference flows with respect to any selected PM in this case, Improved Speed and Quality of Repair (S3) emerged the most preferred water loss reduction strategy for the NSWB. By having the tallest bar in the top graph, it could be judged as the optimum water loss reduction strategy according to DM5's preferences with an aggregated optimum reduction score of 82.23%



Revenue Investment Operation Water Saved Water Qua Supply Re Affordability

Figure 4: Net preference flows of water loss reduction strategies & the Weights of PMs for DM5 Case.

Ranking Result for Group Decision Making Scenario

The rankings obtained for DMs (DM1-4) group case are shown in Figure 5 and 6 below. As shown, a collective judgment by all the DMs (DM1-4), Selective Mains and Service Line Replacements (S4) is the highest-ranking water loss reduction strategy alternative among all 7 operating measures with an aggregated optimum reduction score of 78.74%

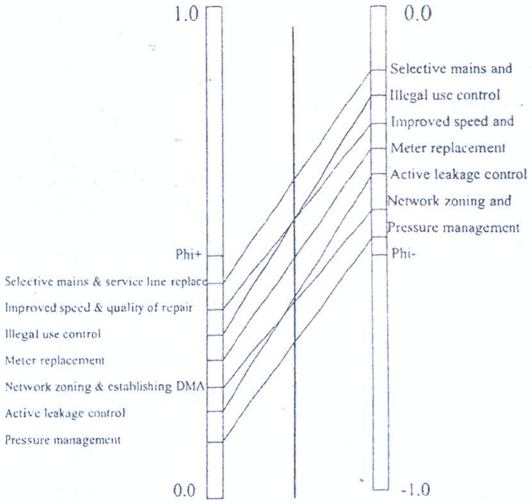


Figure 5: Partial rankings obtained for DMs (DM1-4) group case

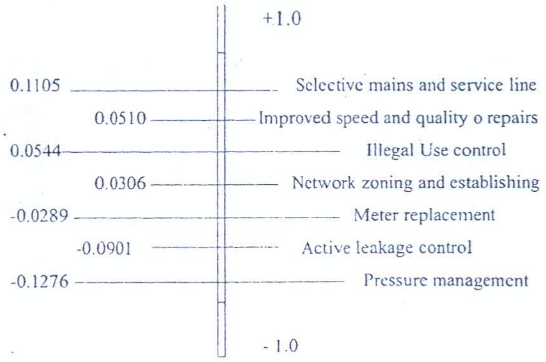


Figure 6: Complete rankings obtained for DMs (DM1-4) group case

GAIA-criteria plane Result for Group Decision Making Scenario

The GAIA-scenario plane for the group decision-making case (DMs 1-4) is shown in Figure 7,

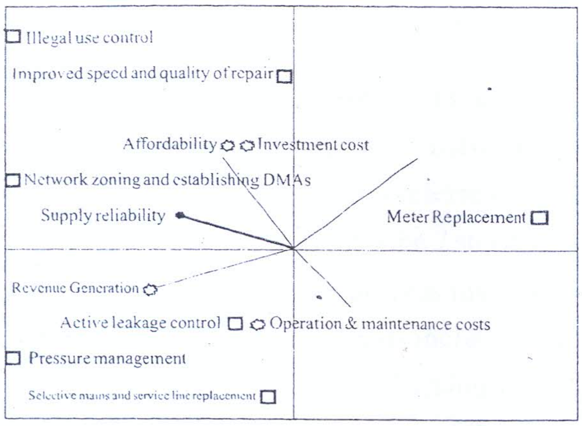


Figure 7: GAIA-Criteria Plane for group decision making (DM1-4) (Δ=78.9%)

yielding a decision quality value of 78.9%. Not quite distinct to DM5's case, though the two distinctive clusters of alternatives are apparent with Supply Reliability (EC6) showing up as the optimum water loss reduction strategy in relation to the collective preferences of all 4 DMs. It is also noted that DM 4's preferences match closely with the collective decision of the group DMs'. Though DM1 and DM3 also had similar preferences, they appear to be in conflict with the group's preferences. The top chart (Fig. 8) gives the net preference flows of the water loss reduction strategy for all 4 DMs together. And as in the case of individual DM case, the bottom chart indicates the PM weights assigned to each DM in the group, in the group decision making case, Selective Mains and Service Line Replacements (S4) is indicated as the optimum water loss reduction strategy, having the tallest bar in the top graph as indicated in Figure 8.For each of the scenarios, the optimum water loss reduction strategies derived are as follow:

DM1 - Illegal use control (S2) with an aggregated optimum reduction score of 100%.

DM2 - Improved speed and quality of repairs (S3) with an aggregated optimum reduction score of 93.59%

DM3 -. Illegal use control (S2) with an aggregated optimum reduction score of 83.67%.

DM4 - Selective mains and service line replacements (S4) with an aggregated optimum reduction score of 88.28%.

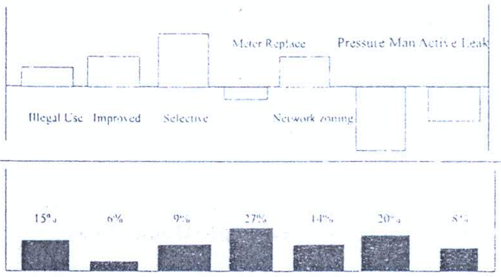
DM5 - Improved speed and quality of repairs (S3) with an aggregated optimum reduction score of 82.23%.

DM7 - Improved speed and quality of repairs (S3) with an aggregated optimum reduction score of 90.48%.

DM (1-4) - Selective mains and service line replacements (S4) with an aggregated optimum reduction score of 78.74%.

Walking Weights Results for Group Decision Making Scenario

Walking weights' display result for the group decision-making case (DM1-4) is shown in Figure 8



Revenue Investment Operation Water Saved Water Qua Supply Re Affordability

Figure 8: Net preference flows of water loss reduction strategies and the Weights of Decision

Makers (DM1-4).

Partial rankings, complete rankings and the GAIA-Scenario plane were used to determine the optimum (or most preferred) water loss reduction strategy among the 7 strategy options. The decision analysis process involved various decision-making situations including six single DM cases and one group decision-making case. Improved Speed and Quality of Repair (S3) and Selective Mains and Service Line Replacements (S4) emerged the most preferred water loss reduction strategy for both the individual and Decision Making Group considered in the study. Furthermore, as against the existing strategies being implemented by the NSWB (Illegal use control S2 and Establishing district meter areas (DMAs) and Network zoning S5), the emerged preferred water loss reduction strategy for both the individual and Decision Making Group would not only help the utility to save water and reduce water loss but would also help in maintaining and managing the strategic assets of the utility (NSWB) in order to forestall further deterioration of the utility's water supply network.

Robustness of the Results - Weight Stability Intervals

The multi-scenario analysis gives the weight stability intervals of the different actors (or scenarios) in a collective decision. This stability interval indicates within which bounds the weight of any actor/stakeholders can be modified without affecting the ranking, provided that the relative weights of the other actors are not modified. The weight stability intervals of the individual actors in DM5 and the Decision Making Group are as shown in Figure 9 and 10 respectively.

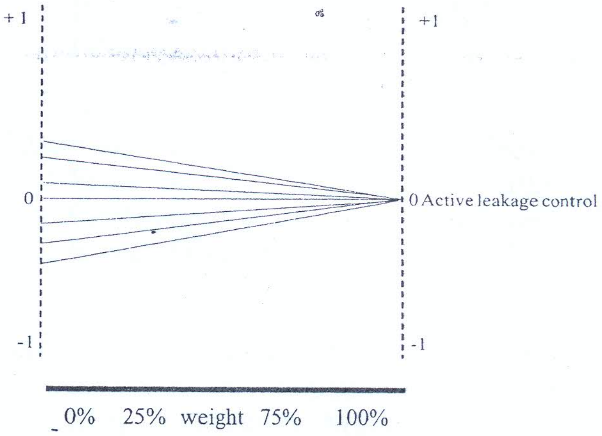


Figure 9: Weight Stability Intervals Result of Individual Making Scenario (Dm5

As shown in Fig 9 above, the weight stability interval result for the individual making scenario indicates that the weight of the strategy option (Active leakage control) at 0% cannot be changed without affecting the overall ranking while in Fig 10, the weight stability interval result for the group decision making scenario indicates that the weight of the strategy option (Pressure management) can be changed by 27% without affecting the overall ranking.

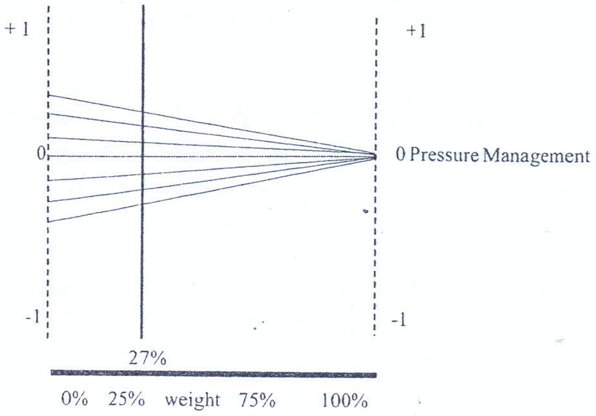


Figure 10: Weight Stability Intervals Result of Group Decision Making Scenario (DM1-4)

Conclusion

Based on the findings of the study, the following conclusions were drawn.

Two plausible management scenarios were identified to be effective for the water supply and allocation for Minna metropolis; these are Individual Decision Making and Group Decision Making Scenarios. In addition, results of analysis showed that for all the Decision making options and corresponding relative preferences in terms of partial and complete ranking as well as Geometrical Analysis for Interactive Assistance (GAIA) strategies both variable combinations of Improved Speed and Quality of Repairs (S3) and Selective Mains and Service line Replacements (S4) significantly allowed for water loss reductions by 82.23% and 78.74% respectively. It suffices to note also that the application of Multi-Criteria decision method is effective and suitable for the determination of probable robust water management scenarios. It could also be inferred that the involvement of stakeholders, especially the water users directly or indirectly in the management decision making can greatly help in water loss reduction substantially. The results also showed that establishment of preference elicitation could lead to bias when weights as assigned to the options and alternatives by the knowledge experts as indicated by the sensitivity analysis.

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