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Decision Support Tool for Selecting Appropriate Sustainable Rainwater Harvesting Based System in Ibadan, Nigeria

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***Abstract*— The approach to water management worldwide is currently in transition, with a shift from centralised infrastructures to greater consideration of decentralised and sustainable technologies, such as rainwater harvesting (RWH). However, in Nigeria, implementation of sustainable water management, such as RWH systems, is inefficient. Social, environmental and technical barriers, concerns and knowledge gaps exist, which currently restrict its widespread utilisation. This inefficiency contributes to water scarcity, water-borne diseases, and loss of lives and property due to flooding. Meanwhile, several RWH technologies have been developed to improve sustainable water management (SWM) through both demand and storm-water management. Such technologies involve the use of reinforced cement concrete (RCC) storage tanks, surface water reservoirs and ground-water recharge pits as storage systems for mitigating water supply problems in Ibadan. A framework was developed to assess the significance and extent of water management problems, match the problems with existing RWH-based solutions and develop a robust ready-to-use decision support tool that can quantify the costs and benefits of implementing several RWH-based storage systems. The methodology adopted was the mixed method approach, involving a detailed literature review, a questionnaire survey of relevant stakeholders such as: household respondents, Nigerian Architects and Civil Engineers and focus group discussion were also conducted. 18 selection attributes have been defined and three alternatives have been identified in this research. The questionnaires were analysed using SPSS, Excel and selected statistical methods to derive weightings of the attributes for the tool. Following this, three case studies were modelled using RainCycle software. From the results, the MDA model chose RCC tank as the most appropriate storage system for RWH.**

***Index Terms*— Rainwater harvesting, modelling, hydraulic assessment, decision support system.**

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I. INTRODUCTION

Rainwater harvesting (RWH) is important for sustainable development and has no proven adverse environmental impacts. It also provides convenience in terms of decreased distance to sources of supply and is less time consuming than surface and groundwater sources. RWH technology acts as a tool for poverty eradication, for improving women's livelihood as they are directly involved in water provision for households.

RWH primarily consists of the collection, storage and subsequent use of captured rainwater, either as the principal or supplementary source of water. It is applicable both for potable and non-potable purposes [1]. Some systems can provide water for domestic, institutional, commercial and industrial purposes, as well as agriculture, livestock, ground-water recharge, flood control processes and as an emergency supply for fire fighting [2].

RWH is a simple and ancient concept, which varies from small and basic systems of attaching a water butt to a rainwater downspout, to large complex systems of collecting water from many hectares to serve many people [3]. In a study, groundwater in a household well was recharged using rainwater harvested from rooftops [4]. This led to water conservation through reduced evaporation; the well thus yields water all year, compared to the control well that dried up during the dry season.

In the 20th century, there was a decline in RWH techniques around the world, partly due to the provision of large, centralised water supply schemes, such as dam building projects, groundwater development and piped distribution systems. However, in the last few decades interest in the use of harvested water has increased [5], with an estimated population of 100,000,000 people worldwide currently utilising a rainwater system [6].

Based on the status of relevant macroeconomic and human development indices, Nigeria is classified as a 'developing country'. A very topical catchphrase in Nigeria today is 'modernisation', which is viewed as key to addressing the poverty and underdevelopment status prevalent in the country [7]. Within this context, development of appropriate technologies plays a crucial role. While in the past there has been some scepticism regarding the suitability of modern Information Technology (IT) within an 'appropriate technology' framework, there is now a growing school of thought that sees advanced IT as actually underpinning the development effort in underdeveloped countries, such as Nigeria [8]. This is in the context of the continuing fall in prices and rise in availability of computing power. There is, therefore, a need to develop practical tools and methodologies to underpin and support sustainable development and management of the country's water resources, in the form of comprehensive decision-support systems (DSSs) that integrate data and stakeholder development priorities.

In spite of rapidly advancing computer technology and the proliferation of software for decision-support, relatively few DSSs have been developed, implemented, and evaluated in the field of water resource management in Nigeria. Such decision-support tools need to be structured to fit in with existing policy frameworks and responsibility allocation in Nigeria's water sector. They should be tailored to the local conditions prevailing in the country, and accommodate specific needs, as identified by stakeholders in a participatory, bottom-up development framework. By building a DSS, many needs of policy-makers and resource managers in the water sector must be met. These include the provision of mapping capability for land and water resources, a common digital database for information, a suite of spatial analysis tools, development of predictive models, and provision of a basis for the evaluation of management alternatives.

This paper describes the development of a computer based modelling and assessment tool for rainwater harvesting (RWH) in domestic, commercial, public or industrial buildings. The tool developed is an integrated platform of related evaluation techniques, including Whole Life Cycle Cost Analysis and Multi-Attribute Utility Theory. The tool uses data including cost and quantities of materials for building a RWH storage system and quantifies the cost and benefits of alternative RWH-based systems that can improve project management. This tool is novel, given its integration of the analytical techniques mentioned above and application for selecting the most appropriate RWH-based sustainable water management systems. The implementation of the tool is envisaged to provide an objective platform for the quantification of the costs and benefits of RWH-based systems prior to implementation.

Overview of Decision Support System for Rainwater Harvesting

A GIS-based decision-support system (RHADESS) was developed to indicate the areas of SA suitable for RWH [9]. Increasing agricultural demand in SA was met by storing excess runoff for runoff harvesting [10]. The study highlights the potential benefits from multi-scale adoption of runoff harvesting by modelling runoff. A method for estimating the amount of rain required to flush for any roof type was developed [11]. This implies that the first 1 mm of rain after each dry spell must be diverted or flushed, since the rainfall in this region is erratic and unevenly distributed. This diverting device helps improve water quality.

A GIS was recommended as a hydro-spatial hierarchical method in dry areas for siting small water harvesting reservoirs [12, 13]. Furthermore, a web-based GIS-hydrologic modelling system for selecting the most suitable location for building water-harvesting reservoirs was developed [14]. This process was applied in a 300-km^2 area of Israel-Lebanon [15]. While these GIS tools have been developed to facilitate siting of water harvesting reservoirs, comprehensive water supply management at a community scale is yet to be developed by the decision support tool.

A GIS-based Decision-Support System (DSS) for identifying potential sites for RWH was developed in Tanzania [16]. The GIS-based DSS uses remote sensing, and limited field survey to identify potential sites for RWH technologies. The model builder in the Arc View GIS was used as a platform for the parameters and weight of factors. The results from testing and validation of the developed DSS indicated that the tool could be reliably used to predict potential sites for RWH technology in semi-arid areas.

Whole Life Costing Techniques

Whole life costing (WLC) is about identifying future costs and referring them back to present day costs using standard accounting technologies, such as present value (PV). Different methodologies exist for discounting future costs, but PV is the simplest and most commonly used discounting method available and is appropriate for application to RWHS, which may have different time patterns of expenditure (e.g. irregular maintenance items). It is worth noting that discounting cost to a PV has limitations and is sensitive to discounting rates and assumptions of future costs and timing of these costs. WLC details include:

1. Capital costs.
2. Operating costs in the RainCycle software consists of the following items: discount rate, electricity cost, mains water cost, disposal cost and decommissioning cost.

II. MULTI-ATTRIBUTE UTILITY THEORY

Multi-attribute utility theory (MAUT) is subdivided into additive models and multiplicative models [17] (Cho, 2003). The additive MAUT model is also called simple multi-attribute ranking technique (SMART) (Wang and Yang, 1998) [18]. This theory allows compensation between criteria i.e. the gain on one criterion compensates for the loss on another (Fulop, 2005) [19]. The ranking value x_j of alternative j is obtained simply as the weighted algebraic mean of the utility values associated with it, as shown in equation 1.1

$$x_j = \sum_{i=1}^{m} w_i u_{ij}, j\ 1, \ldots\ldots, n \ldots\ldots\ldots\ldots\ldots (1.1)$$

where:

m is the number of attributes and *n* is the number of alternatives;

x_j is the overall multi-attribute utility value of alternative *j*;

w_i is the importance weight of attribute i;

u_{ij} is the marginal utility of attribute i with respect to alternative j.

Criteria are ranked in their order of importance and points are assigned to them to reflect their relative importance. However, the comparison of the importance of attributes is meaningless if the range of utility value of alternatives is not well reflected. Hence, a variant of SMART named SWART was proposed (Edwards and Baron, 1994) [20]. This involves the use of swing which in the course of the comparison of the importance of the criteria also considers the amplitude of the utility values (i.e. the changes from the worst utility value level to the best utility level among the alternatives).

In deriving the utility value u_{ij} of an alternative with respect to an attribute, the most commonly used method is proportional scoring (Levin and McEwan, 2001) [21]. This is the linear re-scaling of each alternative to a common utility scale. The utility scale ranges from 0 to 1. The highest possible score for any alternative is 1 while the lowest possible score is 0. The proportional scoring utility function is shown in equation 1.2 (Levin and McEwan, 2001) [21].

$$U_{ij}(y) = \frac{y - \text{Lowest Value}}{\text{Highest Value} - \text{Lowest Value}} \quad \text{.......}(1.2)$$

where:
y is the measured quantity or assigned unit of the alternative for the attribute under consideration, which is also called consequence.
$U_{ij}(y)$ is the utility score of the alternative for the attribute.
Equation 1.2 represents the utility function for a benefit attribute i.e. as the benefit quantity increases; and/as its utility score increases. For a cost attribute, the marginal utility function is presented in equation 1.3 i.e. as the cost quantity increases, its utility score decreases.

$$u_{ij}(y) = \frac{\text{Highest Value} - y}{\text{Highest Value} - \text{Lowest Value}} \quad \text{.......}(1.3)$$

The steps involved in SMART are:

1. Identify the relevant criteria (attributes).
2. Assign numerical variables to each of the attributes and specify their restrictions (importance weights).
3. Construct utility functions and measure the utility values for the individual alternatives with respect to the attributes.
4. Evaluate the individual utility values and importance weights using the simple additive utility function shown in equations 1.2 and/or 1.3
5. Aggregate the utilities and weights using equation 1.1
6. Carry out sensitivity analysis to ensure the reliability and validity of the outcome of steps 1 to 5.
7. Choose the alternative with the highest overall multi-attribute utility (ranking) value.
8. Report the whole analysis

III. THE MULTI-CRITERIA DECISION ANALYSIS MODEL (MDAM)

A detailed review of MCDA methods for water supply problems was conducted by Lade *et al*. (2012) [21].
The reviewed of existing decision analysis modelling tool revealed few RWHS models exist and there seems to be insufficient attention to Decision-Support Tools (DST) for integrated urban water management. To integrate RWH into the development and management of water resources in Nigeria, there is a need to develop tools and methodologies that will both assist planners with the identification of areas suitable for RWH, and quantify associated hydrological impacts of widespread adoption.

Overview of Main Features

Figure 1 presents a hierarchy structure for selecting water supply alternatives. The factors considered are:

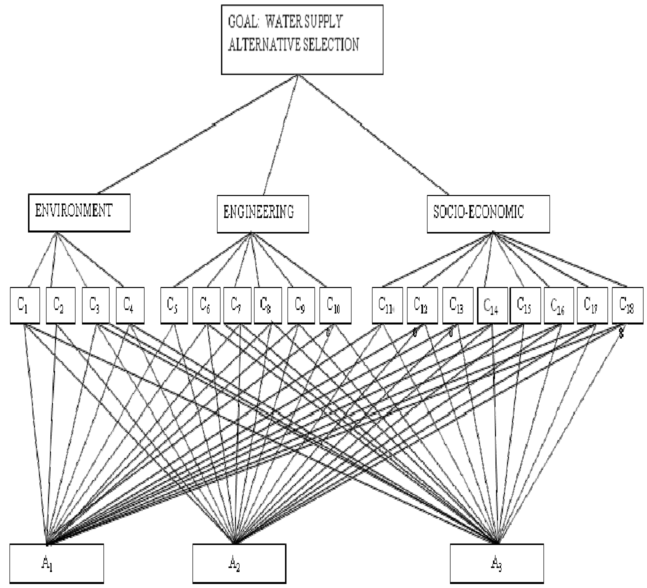

Fig. 1 Hierarchy structure for the selection of water supply alternatives

Environment

Socio-economic

C_1 _ Maximise water quality.
C_2 – Minimise evaporation loss rate.
C_3 – Minimise seepage loss rate.
C_4 – Maximise accessibility/repair.

Engineering

C_5 – Maximise water saving efficiency.
C_6 – Minimise area utilisation .
C_7 _ Minimise risk of structural failure.
C_8 _ Minimise impact of structural failure.
C_9 _ Minimise ground area required.
C_{10}- Minimise system stabilisation time
C_{11} _ Maximise usability/customers satisfaction.
C_{12} _ Maximise reliability.
C_{13}– Maximise culture.
C_{14}– Minimise construction cost.
C_{15} –Minimise pumping cost.
C_{16}– Minimise maintenance cost.
C_{17} – Minimise unit cost.
C_{18} – Maximise payback period.
The alternatives are:
A_1- RCC water tanks.
A_2- Surface water reservoirs.
A_3- Ground-water recharge pits.

The proposed multi-criteria decision analysis model (MDAM) intends to provide a systematic platform for knowledge-based decision-making in the selection of RWH-based systems. The framework is a quantification tool of the cost and benefits of implementing each of the identified RWH-based storage systems. Questionnaires were used to measure the importance of functions of alternative RWHS to water supply and the scores of alternatives with respect to qualitative attributes. The implementation of the framework, like many other decision analysis methods [16] [22], consists of the following stages: definition, evaluation and selection stage. The process flowchart of the stages involved in the implementation of the framework is shown in Figure 2.

Definition Stage

In order to select the right system to address the identified water supply problems, a clear definition of the selection attributes of alternative RWHS is required. It is necessary to define discriminating attributes as objective measures which will measure how well each alternative achieves the implementation goals [17] [23]. In addition, it was stated that attributes [18] [24] should be:

- Able to discriminate among the alternatives and to support the comparison of the performance of alternatives.
- Operational and few in number.

Hence, 18 selection attributes have been defined and three alternatives have been identified in this research. The 18 selection attributes represent mitigation of 18 significant effects of the lack of adequate water supply facilities in the current practise of water management which any of the identified alternative RWHS can provide. The selection attributes along with the function that can satisfy them and the RWH-based storage systems that can provide the functions are shown in Figures 3 and 4.

Evaluation Stage

The evaluation stage involves quantifying the consequence of each alternative RWHS with respect to each selection attribute; derive the marginal utility from the consequence and aggregate the overall multi-attribute utilities of alternatives. The marginal utilities of the alternatives with respect to the attributes are finally aggregated into overall multi-attribute utilities of the alternatives, after combining with the weightings of the attributes. This is shown as the marginal utility quantifier in Figure 3. The expected cost is then converted to marginal utility of each alternative with respect to attribute using marginal utility function.

Selection Stage

Selection stage is the stage of comparing the overall multi-attribute utilities and choosing the best alternative. The alternative with the highest overall utility will be most preferable for implementation in the typical project whose data are entered into the model. The model input, process and output are shown in the conceptual framework presented in Figures 3 and 4. The input data will be entered into the model by end-users.

The sensitivity analysis was carried out on the model output by varying key parameters, such as importance weightings, to prove the reliability of the model under varied preferences [19] [25]. This is because different decision-makers may have different preferences for MCA attributes (Figure 2). If further analysis is needed, the framework process will return to definition stage. If no further analysis is needed, the best alternative will be chosen.

Layout of the Model

Spreadsheet models are usually written for end-users with limited computer experience; hence they should be well structured [20] [26]. A structured spreadsheet is developed with no overlapping blocks of cells using separate self-contained sections. The self-contained sections are housed in separate sheets and linked in a multiple sheets model. The functional sections in this model are input, process and outputs, which are the sections, involved in the calculation operations of the model. The functional and non-functional sections of the model are housed in separate worksheets. Figure 5 shows the layout of the implemented model.

Input of the Model

The input data into the model are grouped as foundational input and user input. The foundational input data include weightings, scores and costs of alternative RWH-based water supply systems used for building the model. The user input data are site-specific data, such as daily rainfall, catchment area, runoff coefficient, first-flush volume, rainwater filter coefficient, water demand, pump power rating, capital cost, construction cost, maintenance cost and unit cost generated using the RainCycle model.

In-process Calculations

These are the calculation operations carried out by the model on the input data to generate the output. Formulae were coded into the spreadsheet to estimate the ground area to be utilised by the storage tank and the formula derivations are presented.

Estimating ground area utilised by the storage system
Ground area of:
RCC tank = $(2R + 1)^2$
Surface reservoir = $(R + 1)^2$

$$\text{Groundwater recharge pit} = \frac{\text{Capacity of tank } (m^3)}{\text{Diameter of pit (m)}}$$

Diameter of 1 pit = 0.912 m
where:
R is the radius of tank (m).

Output of the Model

These are the products of the calculations carried out by the model. The in-process calculations described in the previous section and other calculations based on the principles of multi-attribute utility theory and whole life costing generated expected costs of alternatives with respect to attributes, utilities of alternatives with respect to attributes, and multi-attributes utility values. The default output and default graphical representation of model output are shown in Figures 6 and 7, respectively.

Model Information and User Guide

A separate model information worksheet was added to the model to give end-users the basic information about the model configuration and references for further information on some of the key components. A user guide section was added to help end-users navigate the model and enhance its efficient usage. This was added as an additional worksheet. It is a step-by-step guide of how to input data into the model and interpret the output.

Model Validation

Validation is a key part of model development processes which increases the confidence level and value of the model [21] [27]. The developed sustainable RWH model was presented to building and construction experts in Ibadan for their comments, as a means of validating the model and its application. The findings of the validation process are presented.

Analysis of Expert Responses

Of the eight experts contacted**,** six responded to the survey. The experts were actively involved in water related projects and material selection. They possess relevant qualifications and their total combined construction industry experience is 125 years. The respondents were asked to comment on the model in a structured, semi-closed questionnaire. All the responses received were largely positive. Most experts agreed that the model addresses an important problem in sustainable RWH evaluation and selection. Concerning its capability in performing its intended function accurately, all the experts were of the opinion that it is capable. This suggests that the model would be regarded as a useful tool for sustainable RWH storage system selection.

In terms of the model's completeness, the experts are of the opinion that the model is comprehensive and detailed, addressing all relevant criteria for selecting a RWH system. With regard to comprehensibility, most experts found the model to be clear and simple to understand and implement. Most experts are of the opinion that the model would not be too costly to implement at current resource levels. Two experts commented that "the benefits of using the model justify any resource requirements". The various approaches for evaluating the selection criteria were found suitable. The scale for rating the methods was also found to be appropriate. Issues of concern raised relate to the implementation of new cost effective materials for building the storage tank and alternative sources of power supply such as solar units in the near future.

On the whole, the experts were in favour of the model, suggesting that the model would be regarded as valuable tool for selecting sustainable RWH storage systems. This represents a positive contribution to the body of knowledge and practise of sustainability in the construction industry. The model can now be recommended to practitioners, subject to future modifications that can improve its acceptability and performance.

CONCLUSION

The cost and benefits of implementing each of the identified RWH-based storage systems (reinforced concrete cement, surface reservoir and ground water recharge pits) have been investigated using a computer based modelling tool. 18 selection attributes have been defined and three alternatives have been identified in this research. The 18 selection attributes represent mitigation of 18 significant effects of the lack of adequate water supply facilities in the current practise of water management which any of the identified alternative RWHS can provide.

The implementation of the integrated decision analysis model in the Microsoft Excel operating environment has been presented. The model input data are site-specific and most of them can be obtained from project documents, such as engineering bill of quantities, household plan and reservoir elevation. This research revealed that out of the three alternative storage systems: RCC tank, surface reservoir and groundwater recharge system, the MDA model developed chose RCC tank as the most appropriate system for rainwater storage.

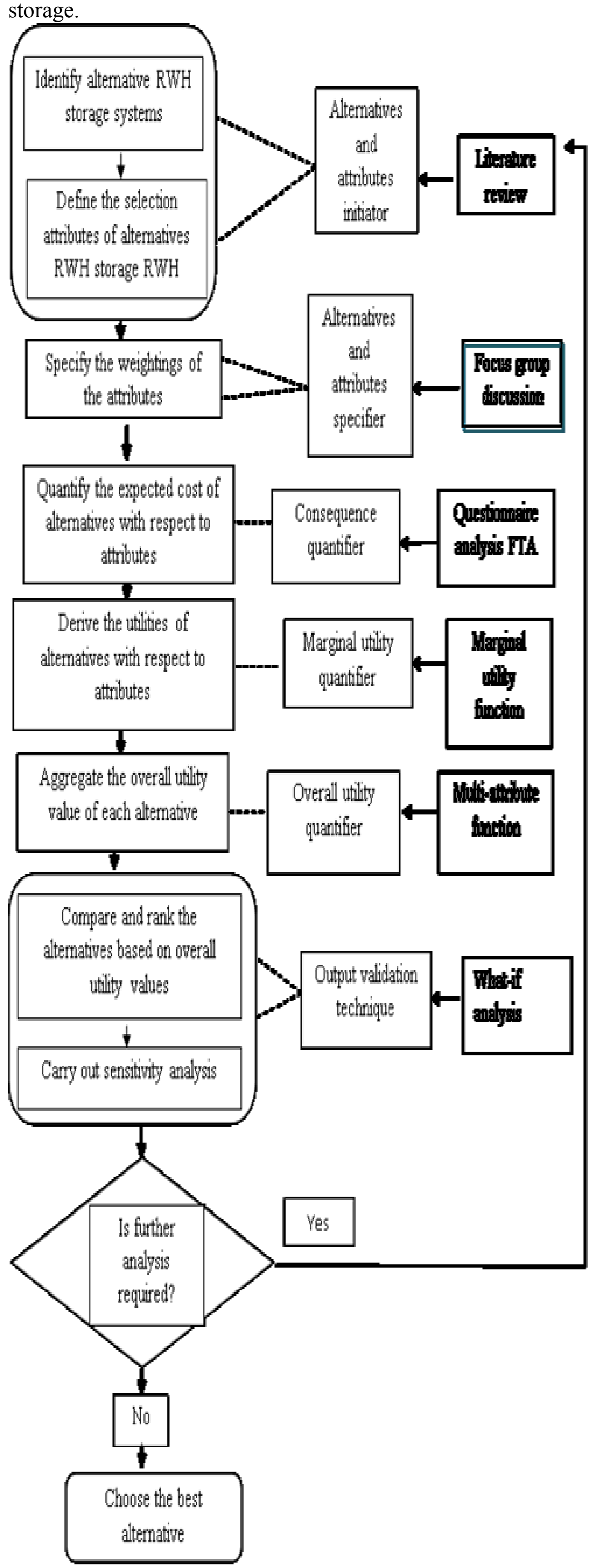

Fig. 2 Process flowchart of framework implementation

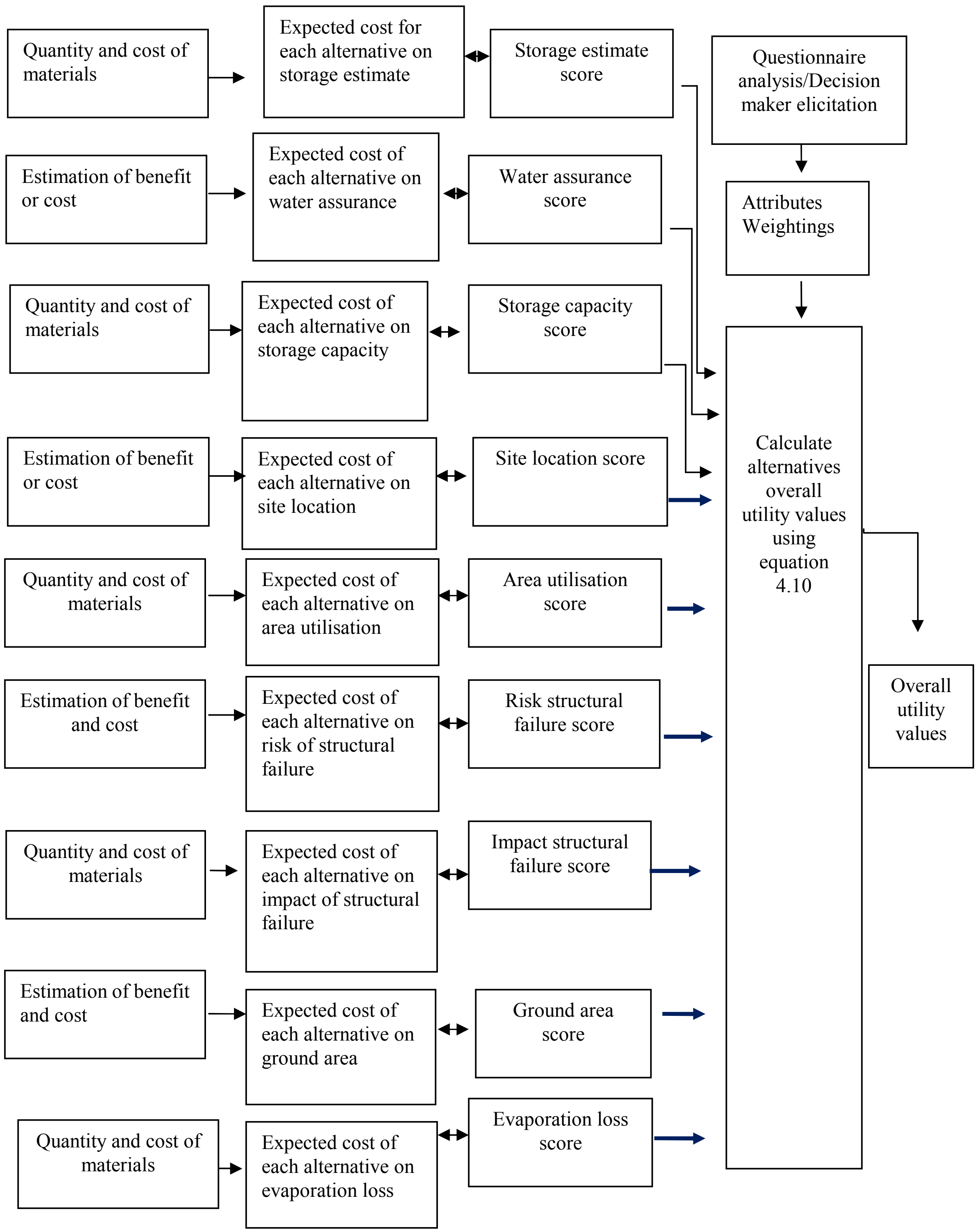

Fig. 3 Architecture of integrated decision analysis model

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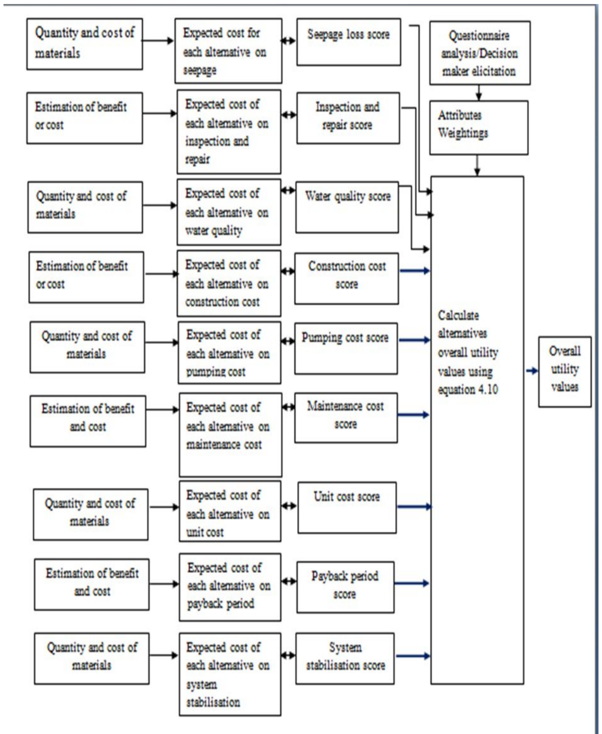


Fig. 4 Architecture of integrated decision analysis model

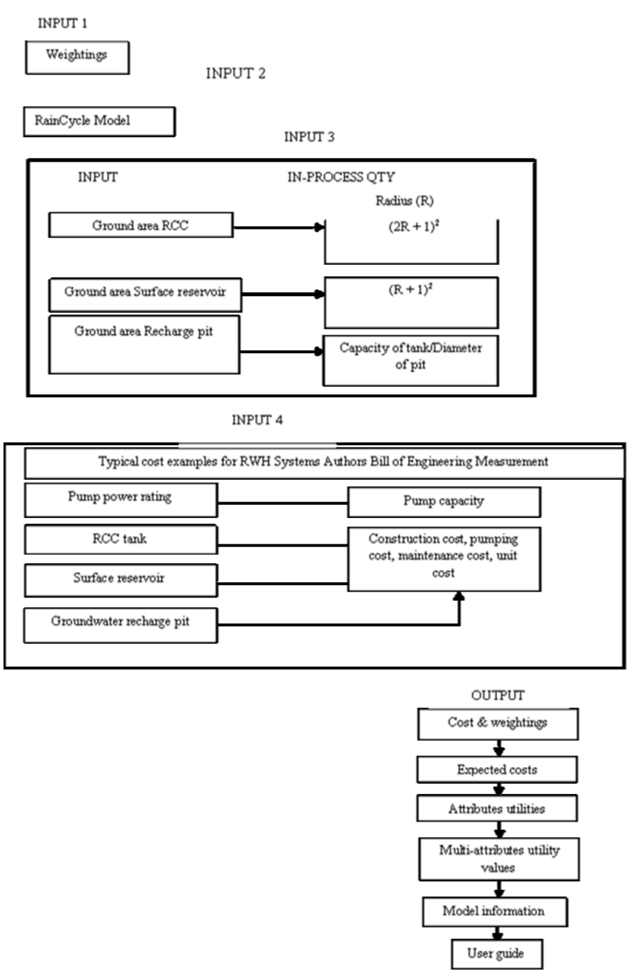
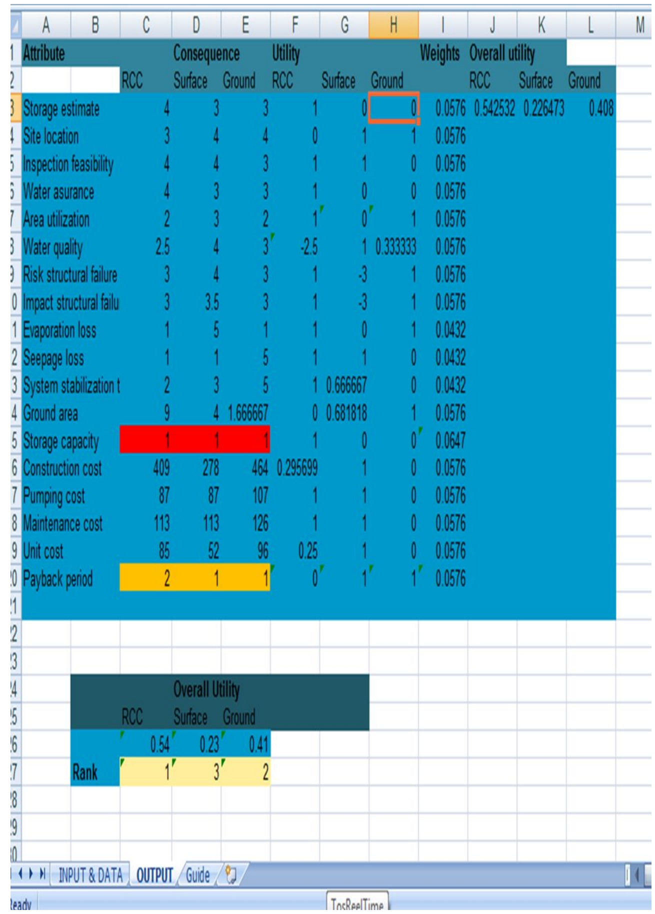


Figure 5 Integrated decision analysis model layouts



Attribute	Consequence RCC	Consequence Surface	Consequence Ground	Utility RCC	Utility Surface	Utility Ground	Weights	Overall utility RCC	Overall utility Surface	Overall utility Ground
Storage estimate	4	3	3	1	0	0	0.0576	0.542532	0.226473	0.408
Site location	3	4	4	0	1	1	0.0576			
Inspection feasibility	4	4	3	1	1	0	0.0576			
Water asurance	4	3	3	1	0	0	0.0576			
Area utilization	2	3	2	1	0	1	0.0576			
Water quality	2.5	4	3	-2.5	1	0.333333	0.0576			
Risk structural failure	3	4	3	1	-3	1	0.0576			
Impact structural failu	3	3.5	3	1	-3	1	0.0576			
Evaporation loss	1	5	1	1	0	1	0.0432			
Seepage loss	1	1	5	1	1	0	0.0432			
System stabilization t	2	3	5	1	0.666667	0	0.0432			
Ground area	9	4	1.666667	0	0.681818	1	0.0576			
Storage capacity	1	1	1	1	0	0	0.0647			
Construction cost	409	278	464	0.295699	1	0	0.0576			
Pumping cost	87	87	107	1	1	0	0.0576			
Maintenance cost	113	113	126	1	1	0	0.0576			
Unit cost	85	52	96	0.25	1	0	0.0576			
Payback period	2	1	1	0	1	1	0.0576			

Overall Utility	RCC	Surface	Ground
	0.54	0.23	0.41
Rank	1	3	2

Fig. 6 Default multi-criteria decision analysis model output

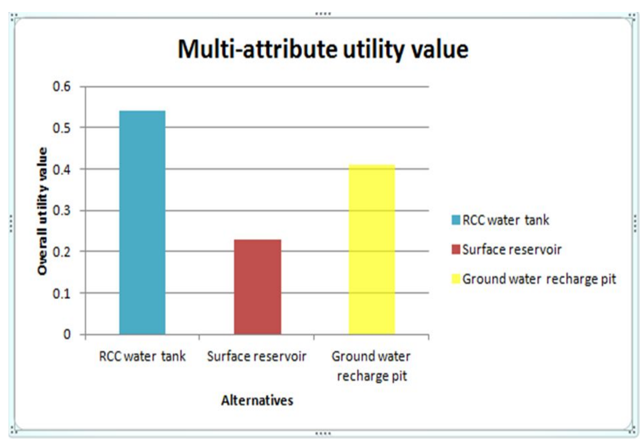


Fig.7 Default graphical representation of model

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