Journal of Water Resource and Protection, 2015, 7, 1280-1290
Published Online November 2015 in SciRes. http://www.scirp.org/journal/jwarp
http://dx.doi.org/10.4236/jwarp.2015.716104

Decision Making for Capacity Expansion of Water Supply Systems

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Received 21 May 2015; accepted 7 November 2015; published 10 November 2015

Abstract

This study developed a systematic decision-making process for water supply capacity expansion using the analytic hierarchy process. The decision-making criteria were categorized into environmental, economic, technical and socio-cultural aspects. Capacity expansion of three water resources (Kpong, Weija and Teshie plants) of Accra-Tema Metropolitan Area (Ghana) was studied as a test case. The research resulted in the environmental criterion with the highest priority weight (52.4%), followed by the economic (30.6%), technical (11.3%) and socio-cultural criteria (5.8%). The overall analysis ranked the Kpong plant with a score of 36.1% followed by the Weija and Teshie plants with scores 33.8% and 30.2%, respectively.

Keywords

Water Supply Capacity Expansion, Analytic Hierarchy Process, Sensitivity Analysis, Accra-Tema Metropolitan Area

1. Introduction

Potable water availability has become a global challenge due to increasing constraints on water supply facilities. The rise in global human population growth and rapid urbanization greatly contribute to the stress on water resources [1]. The United Nations (UN) estimated a rise in world population to 8.9 billion in 2050 [2]. Relatively, much of this demographic change will occur in the developing countries. The population of the developing region was estimated to increase by 58% of its current population over 50 years, as compared to 2% for the developed region [2]. These point to the fact that there will be an increase in competition for most natural resources among which water is the most essential, and authorities are expected to respond by appropriately sizing

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How to cite this paper: Alhassan, H., Naser, G., Milani, A.S. and Nunoo, S. (2015) Decision Making for Capacity Expansion of Water Supply Systems. *Journal of Water Resource and Protection*, **7**, 1280-1290.
http://dx.doi.org/10.4236/jwarp.2015.716104

water supply systems to help meet the demands for water. World Health Organization (WHO) and United Nations Children's Fund (UNICEF) indicated that about 87% of the world population had access to improved water sources [3]. Despite this progress, a staggering population of 884 million still live without access to improved sources. Inadequate water supply in some developing countries (in South Asia, Latin America, and Africa) makes many water utility managers employ intermittent water supply (IWS) as an alternative to continuous supply despite its serious water quality challenges [4]-[6]. Given the limitations on the water resources availability and the increasing demand for water, capacity expansion of the existing systems is unavoidable. While this study focused on the capacity expansion of water supply facilities, it employed a multi-criteria decision analysis (MCDA) approach in choosing the best alternative for capacity expansion out of a set of supply sources. The decision-making was completed using environmental, economic, technical and socio-cultural criteria. The Accra-Tema Metropolitan Area (ATMA), Ghana, was studied as a case to test the robustness of the proposed decision making tool.

2. Background

Many different factors are considered when sitting a new water supply facility. Such factors can be grouped as environmental, economic, technical and socio-cultural criteria. Recent studies have shown the effect of climate change on water resource availability and the impact that this change will have on urban water supply in near future. For instance, the tributaries to River Offin (Ghana) are drying up, and per capita freshwater availability in the country has reduced from 9204 m^3 in 1955 to 3529 m^3 in 1990 [7]. Access to improved water sources in Ghana is about 82% as of 2008 [3]. This, in accordance with the Millennium Development Goal target of 77% coverage, would be interpreted as Ghana having met its target. However, water utility providers present significantly lower figures. The Community Water and Sanitation Agency, which has the responsibility of rural water supply, reported coverage of 57% as of 2008. On the other hand, the Ghana Water Company Limited (GWCL), which has the responsibility of urban water supply, reported coverage of 58% as of 2008.

In water supply capacity expansion considerations, the design of a water supply system, its construction cost and the costs associated with energy consumption and chemicals (for treatment) are vital elements. Generally, the economics of a water supply system depends on its design and the technology employed. Research has shown a wide difference in construction costs between conventional water treatment of freshwater and modern technologies employed in desalting saline water. Research [8] found the cost of constructing a 19,000 m^3/day conventional treatment plant to be 8 cents/m^3 while that of reverse osmosis plant of the same capacity had a unit cost of 21 cents/m^3, both on a 70% capacity utilization. Energy and chemical consumption in urban water supply depend on quality of the source water and treatment technology. Generally, groundwater is expected to have a better quality than surface water; and thus, it does not require extensive treatment processes. However, in terms of energy consumption a contrasting relationship evolves—the analysis [9] revealed conventional surface water production unit energy consumption to be 0.371 kWh/m^3 while that of groundwater unit consumption was 0.482 kWh/m^3 (a rise of about 30%). Unit energy consumption cost for desalting water can be about eight times higher than the conventional treatment processes.

Technical and socio-cultural factors also play a very significant role in water supply capacity expansion decision-making. The pressure of competition pushes industries into developing efficient and flexible mechanisms of production such as the automation of machinery. By increasing the flexibility of the production process, a competent and elastic system is created that efficiently responds to changing environmental conditions and emerging treatment challenges. Potential security threats to a water supply system must be incorporated in the decision-making process. Following the September 11 terrorist attack on the United States, the security of water supply facilities has taken a different dimension. A physical, chemical or biological attack on water supply systems can have dire consequences on public health. This adds to natural security threats such as hurricanes, earthquakes and floods. In the past, adversaries viewed attacking water systems as a huge advantage in warfare. In contrary to Western countries, threat to water supply security in Africa predominantly comes from water vending cartels that vandalise water supply mains to interrupt supplies in order to sell water to communities at exorbitant rates. Water supply capacity expansion studies have been conducted since the mid-1900s. Many capacity expansion studies in the field of water resources and supply have often taken the form of mathematical modeling [10]-[12].

3. Multi-Criteria Decision Analysis (MCDA)

With the complexities of the modern era, water authorities and engineers are facing with making difficult decisions among various available alternatives. Considering the diverse impact and future ramifications that these decisions might have, it behooves on the decision-makers to make acceptable and reliable decisions through a rational approach, considering the multitude of constraints accompanying the alternatives. Decisions that defy basic rationality, experience, and knowledge of subject matter mostly end with unsuccessful results.

MCDA is a discipline that simultaneously considers multiple criteria and different alternatives and can be used as a decision aid in complex decision-making problems. MCDA is by no means a perfect panacea to the pain of decision-making. This is because the various MCDA tools have their inherent weaknesses and only complement knowledge and experience in making decisions. MCDA is broadly characterized into two classes of multi-attribute and multi-objective decision-making. The interdisciplinary nature of MCDA has been evident in its diverse application in different fields. The widely accepted practice of this classification fits the categorization into two facets of problem-solving: multi-attribute decision making is used for selection (evaluation) problems, while multi-objective decision making is employed for design with continuous variables [13]. Relevant literature [13]-[15] provides a list of various MCDA approaches. The list includes: the multi-attribute utility theory (MAUT); models based on outranking such as Elimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), distance-based models such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP). This research applies the AHP mainly due to its strength in decomposing a complex decision problem into simplified components (*i.e.*, goal, criteria, sub-criterion, etc.) in a hierarchy. It also has a unique ability of checking inconsistency in judgment, and can be used with either qualitative or quantitative data. Despite these advantages, AHP comes with some weaknesses. Key weaknesses of the AHP are possible rank reversal when an identical less optimal alternative is introduced, and the large number of pairwise comparisons to be made when decision criteria or sub-criteria are many [16].

4. Analytic Hierarchy Process (AHP)

AHP utilizes both rational and intuitive approaches to select the best choice from a plethora of alternatives based on the evaluation of multiple criteria. The methodology uses pairwise comparative judgements by experts to develop overall priorities in ranking alternatives. The process makes room for potential inconsistency in human judgements and provides avenues for improving the consistency [17]. **Figure 1** indicates the AHP decision-making process proposed in this research. The research conducted the following steps for AHP analysis [18]:

1) Problem Structure: It defines the decision problem into a hierarchy of goals, criteria, sub-criteria and alternatives.

2) Data Collection: This involves the pairwise comparison of the various elements in the decision hierarchical structure as per qualitative scale in **Table 1**.

3) Comparison Matrix: The pairwise comparisons of the criteria are arranged in a square matrix with diagonal elements being 1. The i^{th} row criterion is better than the j^{th} column criterion if element (i, j) has a value greater than 1, and vice versa. The value of the (j, i) element is the reciprocal of the value of the (i, j) element as illustrated in matrix $\boldsymbol{A}$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} = \begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \tag{1}$$

4) Element Priority: The computation of the principal eigenvalue and the corresponding normalized right eigenvector of the comparison matrix to obtain priorities of the various elements in the hierarchical tree. Mathematically this is represented as:

$$Aw = \lambda_{\max} w \tag{2}$$

where $\boldsymbol{w}$ is the normalized right eigenvector of the matrix $\boldsymbol{A}$ and $\lambda_{\max}$ is the principal eigenvalues. Symbolically this becomes:

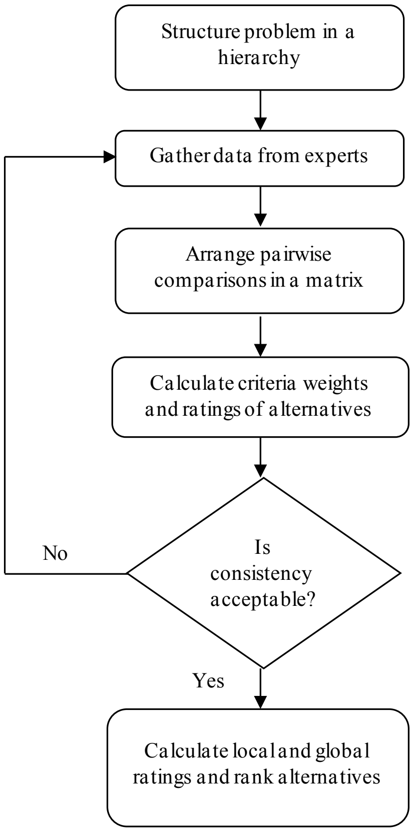


Figure 1. Flow diagram of the AHP methodology.

Table 1. Gradation scale for quantitative comparison of alternatives [16].

Judgment Options	Intensity of Importance
Equal	1
Marginally strong	3
Strong	5
Very strong	7
Extremely strong	9
Intermediate values to reflect fuzzy inputs	2, 4, 6, 8
Reflecting dominance of second alternative compared with the first	Reciprocals

$$\begin{bmatrix} 1 & w_1/w_2 & \dots & w_1/w_n \\ w_2/w_1 & 1 & \dots & w_2/w_n \\ w_n/w_1 & w_n/w_2 & \dots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \lambda_{\max} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{3}$$

5) Consistency Index: The consistency of the matrix of order n is evaluated based on the consistency index (CI) defined by:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{4}$$

Comparisons made by this method are subjective and the AHP tolerates inconsistency through the amount of redundancy in the approach. If this consistency index fails to reach a required level then answers to comparisons may be re-examined. Comparing CI with average random index (RI) gives the consistency ratio (CR). RI was derived from a sample of randomly generated reciprocal matrixes using the scale 1/9, 1/8, ⋯, 8, and 9. The CR value is supposed to be less than 0.1; otherwise the process would have to be repeated until such an acceptable value is obtained.

6) Local and Global Rating: The rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings with respect to each criterion. The local ratings are then multiplied by the weights of the criteria and aggregated to get global ratings.

5. Sensitivity Analysis

Sensitivity analysis describes how sensitive the final outcome is to changes in input data. This study conducted the sensitivity analysis in two ways: 1) using the built-ingraphical sensitivity analysis function in the *Expert Choice* software (http://expertchoice.com/); 2) by applying the approach proposed by [19] which determines the smallest modification in the weight of a criterion that can change the alternative ranking. The approach considers the change in relative (percentage) terms, and therefore coins the terminologies Percent Any (PA) and Percent Top (PT). The PA term represents the modification of a criterion that can change the order of ranking in any of the alternatives, while the PT term represents criteria weight modification that will cause the top ranked alternative to lose its position. It proceeds with the following definitions for *m* alternatives and *n* decision criteria.

1) Let $\delta_{k,i,j}\left(\text{for } 1 \le i < j \le m \text{ and } 1 \le k \le n\right)$ be the minimum change in the current weight w_k of criterion C_k such that the ranking of alternatives A_i and A_j will be reversed.

Also, $$\delta'_{k,i,j} = \delta_{k,i,j} * \frac{100}{w_k} \quad \text{for } 1 \le i < j \le m \text{ and } 1 \le k \le n \tag{5}$$

where $\delta'_{k,i,j}$ expresses changes in relative terms.

2) The PT critical criterion corresponds to the smallest $\left|\delta'_{k,i,j}\right|\left(\text{for } 1 \le i \le j \le m \text{ and } 1 \le k \le n\right)$.

3) The PA critical criterion corresponds to the smallest $\left|\delta'_{k,i,j}\right|\left(\text{for } 1 \le i < j \le m \text{ and } 1 \le k \le n\right)$.

4) The criticality degree of criterion C_k, D'_k, is the smallest percent amount by which the current value of w_k must change to alter the existing ranking. That is:

$$D'_k = \min_{1 \le i < j \le m} \min_{1 \le i < j \le m} \left\{\left|\delta'_{k,i,j}\right|\right\}, \text{ for all } n \ge k \ge 1 \tag{6}$$

5) The sensitivity coefficient of criterion C_k, sens(C_k), determines the most sensitive decision criterion. It is the reciprocal of its criticality degree for any $n \ge k \ge 1$. If one wishes to change the rating of alternatives A_1 and A_2 through weight w_1 of criterion C_1, the following relation is true:

$$\delta_{1,1,2} < \frac{\left(P_2 - P_1\right)}{a_{21} - a_{11}}, \text{ if } a_{21} > a_{11} \tag{7}$$

The following condition should satisfy the weight $w_1^* = w_1 - \delta_{1,1,2}$ to be feasible

$$0 \le w_1^* \text{ or} \tag{8}$$

$$0 \le w_1 - \delta_{1,1,2} \tag{9}$$

The quantity $\delta'_{k,i,j}\left(\text{for } 1 \le i < j \le m \text{ and } 1 \le k \le n\right)$, by which the current weight w_k of criterion C_k needs to be modified (after normalization) so that the ranking of the alternatives A_i and A_j will be reversed, is given as follows:

$$\delta'_{k,i,j} < \frac{\left(P_j - P_i\right)}{a_{jk} - a_{ik}} * \frac{100}{w_k}, \text{ if } a_{jk} > a_{ik} \tag{10}$$

Furthermore, the following condition should also be satisfied for the value of $\delta'_{k,i,j}$ to be feasible:

$$\frac{\left(P_j - P_i\right)}{a_{jk} - a_{ik}} < w_k \tag{11}$$

Criterion C_k is considered to be robust if all of its $\delta'_{k,i,j}\left(\text{for } 1 \le i < j \le m \text{ and } 1 \le k \le n\right)$, quantities are infeasible. In that case, any change in the weight of the criterion will not affect the original ranking of the alternatives.

6. Case Study and Data Collection

This research studied Accra-Tema Metropolitan Area (ATMA), Ghana, as a test case. ATMA mainly consists of the capital city Accra and its suburbs, the industrial city of Tema, Ashaiman, and other communities as shown in **Figure 2**. ATMA has a population of about 4 million. The city of Accra is the anchor of the ATMA region and has a total area of 200 km^2. The region has a tropical savannah climate with average annual rainfall in the region of 730 mm occurring between the two rainy seasons in the country. The average monthly temperature ranges between 24 and 28 degrees Celsius, with the highest temperature occurring during the dry harmattan season [20].

ATMA has two main sources of water supply, the Weija Water Treatment Plant (WTP), the Kpong WTP, and the nearly completed Teshie Desalination plant. The Weija WTP has its source from the Densu River while the Volta River feeds the Kpong WTP. The Teshie Desalination plant receives water from the Atlantic Ocean. The Weija WTP is located 4 km off the Accra-Winneba road, and is sited about 120 m above sea level with a designed capacity of 60 million gallons per day (MGD), and distributes water by gravity. The Kpong WTP is situated at Kpong along the Kpong-Akosombo road. It has an installed capacity of about 48 MGD. Unlike the Weija plant, it has no advantage of elevation and distributes water through high-lift pumping. The two treatment plants employ the multiple-barrier conventional approach for treating surface water. ATMA has a water supply deficit of 57 MGD and is putting a serious strain on consumers and the economic productivity of the region [21]. Potable water scarcity in the region has become a "normal" problem for some decades now, and this compels the Ghana Water Company Limited to ration water. The inadequate water supply greatly affects productivity and

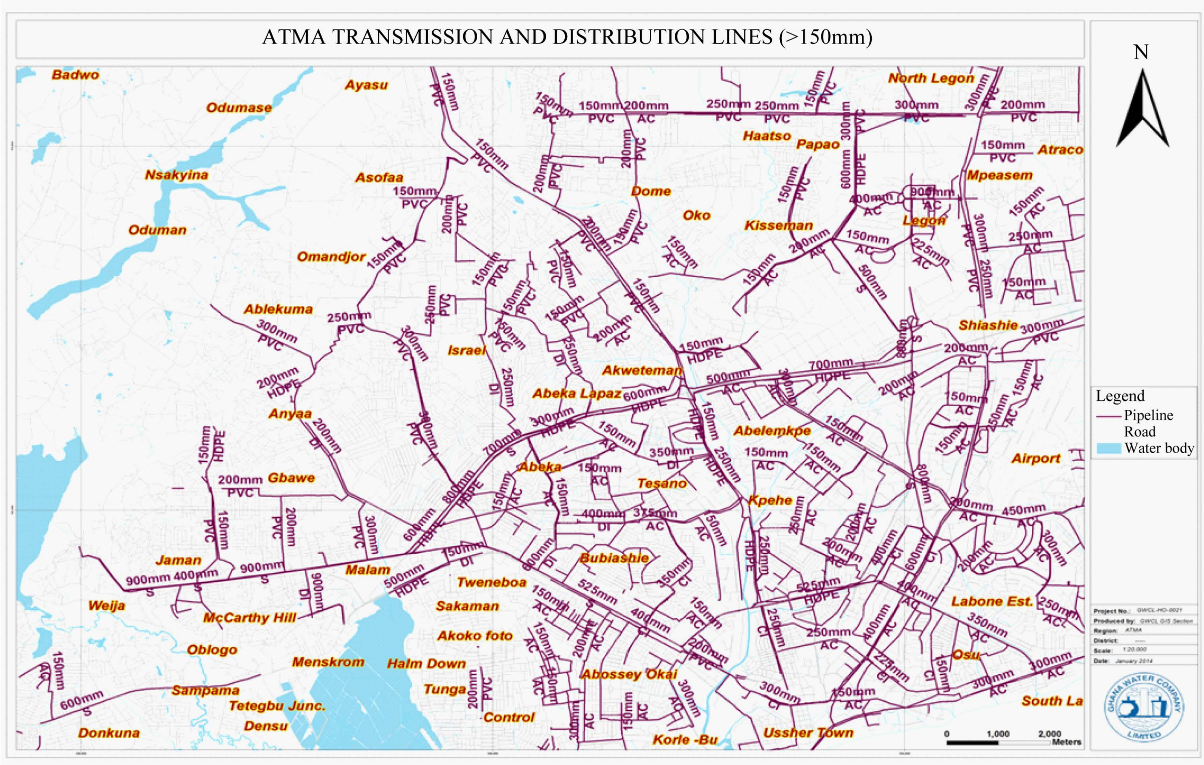


Figure 2. ATMA water distribution system (source: Ghana Water Company Limited).

has promoted the rampant water vending business of tanker and sachet water services with very doubtful water quality [22].

As per the AHP framework, literature was reviewed and expert advice solicited to identify the alternatives, criteria and sub-criteria as presented in the hierarchical structure in **Figure 3**. Considering the limited availability of local experts in the water supply industry in Ghana, 17 participants were recruited for this study. The participants are highly rated engineers and scientists drawn from the Ghana Water Company Limited and the Public Utility and Regulatory Commission (the regulatory body for urban water systems in terms of performance and pricing). A questionnaire was designed and initially evaluated and then approved by the two participating institutions before the data was collected. Due to the limited number of experts to technically evaluate the questionnaire, selection of the participants was facilitated with the help of the management of the two institutions, before the experts were contacted.

7. Results and Discussion

In trying to make the best decision for urban water supply capacity expansion in the ATMA region, the alternatives considered included the Weija WTP, the Kpong WTP and the Teshie desalination Plant. The main criteria considered bordered on environmental, economic, technical and socio-cultural perspectives. To enable a deeper evaluation of each criterion, the criteria were divided into sub-criteria as indicated in **Table 2**. Some sub-criteria could potentially be categorised under other criteria, but in this research consideration was given to their suitability to a criterion with respect to the decision problem. **Table 2** reveals that the environmental criteria had a priority score of 53.3% with respect to the goal, and this is followed by economic (31.1%), technical (10.3%) and socio-cultural (5.3%) criteria. Within the environmental criterion, the Teshie desalination plant, the Kpong and Weija WTPs scored 42.6%, 40.5% and 16.9%, respectively. The resource availability sub-criterion scored highest (26.5%) among the environmental sub-criteria. The priorities of the three plants under the environmental criterion reflect the pattern of reality—the Atlantic Ocean has an almost infinite capacity while the Weija and Kpong sources have capacities of 0.114 and 148 km^3, respectively [23] VRA 2014). Poor water quality, mainly eutrophication, and relatively lower volume of the Densu River contributed to the low score of the Weija WTP.

The economic criterion evaluates the relative sustainability and financial viability of the three alternative pro-

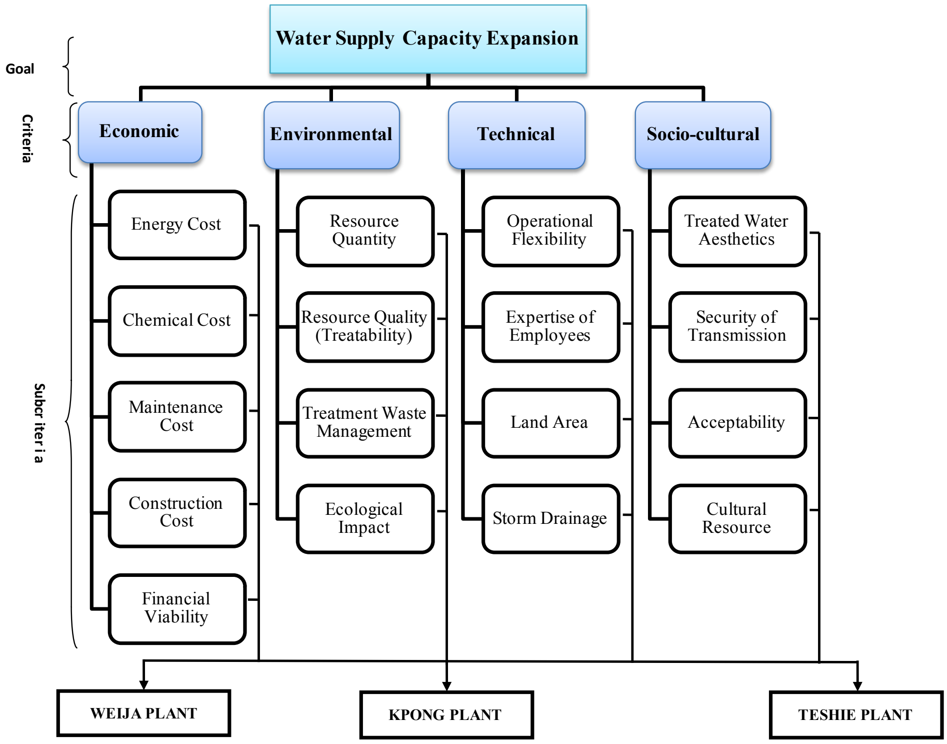


Figure 3. The AHP hierarchy for the capacity expansion project.

Table 2. Priorities of criteria and sub-criteria with respect to the alternatives.

Criteria	Sub-Criteria with Global (G) and Local (L) Weights		Alternatives		
			Weija	**Kpong**	**Teshie**
Environmental (53.3%)	Resource Availability (RA)	L: 0.507 and G: 0.265	0.0212	0.0404	0.2038
	Resource Quality (RQ)	L: 0.286 and G: 0.150	0.0421	0.0984	0.009
	Treatment Waste Management (TWM)	L: 0.082 and G: 0.043	0.011	0.0289	0.0032
	Ecological Impact	L: 0.125 and G: 0.066	0.0143	0.0445	0.0069
			16.9	**40.5**	**42.6**
Economic (31.1%)	Energy Cost (EC)	L: 0.302 and G: 0.092	0.0654	0.0201	0.0069
	Chemical Cost (CC)	L: 0.100 and G: 0.031	0.0024	0.0086	0.0195
	Maintenance Cost (MC)	L: 0.049 and G: 0.015	0.0092	0.0041	0.0016
	Construction Cost (CoC)	L: 0.147 and G: 0.045	0.0312	0.01	0.0037
	Financial Viability (FV)	L: 0.403 and G: 0.123	0.0834	0.03	0.0097
			62.6	**23.8**	**13.5**
Technical (10.3%)	Operational Flexibility (OF)	L: 0.339 and G: 0.038	0.013	0.0217	0.0035
	Expertise of Employees (EE)	L: 0.139 and G: 0.016	0.0063	0.0078	0.0016
	Land Area (LA)	L: 0.405 and G: 0.046	0.0105	0.0187	0.0166
	Storm Drainage (SD)	L: 0.117 and G: 0.013	0.0063	0.0048	0.0021
			32.0	**47.0**	**21.1**
Socio-Cultural (5.3%)	Treated Water Aesthetics (TWA)	L: 0.227 and G: 0.013	0.0018	0.0082	0.0031
	Security of Transmission (ST)	L: 0.308 and G: 0.018	0.0097	0.0024	0.0057
	Acceptability (A)	L: 0.205 and G: 0.012	0.0032	0.0075	0.0011
	Cultural Resource (CR)	L: 0.261 and G: 0.015	0.0065	0.0046	0.0039
			36.8	**39.4**	**24.0**

jects. Economically, the Weija WTP ranked highest (62.7%). This is due to its low utilisation of energy as a result of its ability to distribute treated water by gravity, despite having a relatively high chemical consumption rate. The high unit energy consumption cost of desalinating water in relation to conventional water treatment contributed to the poor economic performance of the Teshie desalination plant (13.5%). Under the technical criterion, the Kpong WTP obtained a weight of 46.9% followed by the Weija WTP and the Teshie desalination plant with weights of 32.0% and 21.1%, respectively. Relatively, the Kpong WTP is more operationally flexible and requires less expertise of operators due to its simple process treatment structure. It benefits from the good water quality of the Volta Lake and does not require pre-oxidation and chemical coagulant application, making treatment waste generation and filter backwashing less frequent. The large land available at the Kpong site and its good topography also contribute to its high score. Within the socio-cultural criterion, the Kpong WTP scored 39.2%, the Weija WTP scored 36.6% and the Teshie desalination plant scored 24.0%. High pollution levels of the Densu River and the employment inorganic chemical coagulants affect the taste of water produced at Weija. Good aesthetics of treated water from Kpong mainly contribute to its high score within the socio-cultural criterion, as consumers refer to water from the Kpong plant as being sweet [24].

The overall ranking of the criteria with respect to the goal of capacity expansion, as indicated in **Figure 4** ranked the Kpong treatment plant first with a score of 36.1%, followed by the Weija treatment plant with a score of 33.8% and the Teshie desalination plant ranked third with a score of 30.2%. The results also reveals an overall mean consistency index of 0.06. The economic criterion had the highest standard deviation value of 0.0141, while the technical criterion had the lowest standard deviation. The high standard deviation of the economic criterion could be due to the fact that it had ten pairwise comparative judgment questions as compared to six comparative judgment questions for all the other criteria. In harmony with Sheth (2009), this indicatesthat higher number of pairwise comparison questions can lead to a higher inconsistency in judgments.

To evaluate the subjectivity of the expert judgment, and to test the robustness of the decision solution, sensitivity analysis was performed. **Figure 5(a)** shows increasing the weight of the environmental criterion by 11.6% and simultaneously reducing the economic, technical and socio-cultural criteria by 12.7, 13.3 and 13.85 percent resulted in a change in the alternatives' ranking. Similarly, an increment in the weight of the economic criterion and simultaneous reduction in the weights of the others causes a change in ranking of the alternatives as shown in **Figure 5(b)**. However, no increment in the weights of the technical and socio-cultural criteria, as seen in **Figure 5(c)** and **Figure 5(d)**, causes a change in the ranking. This indicates that the decision is sensitive to the environmental and economic criteria while being robust to the socio-cultural and technical criteria.

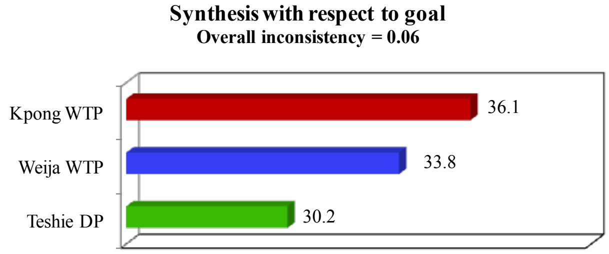
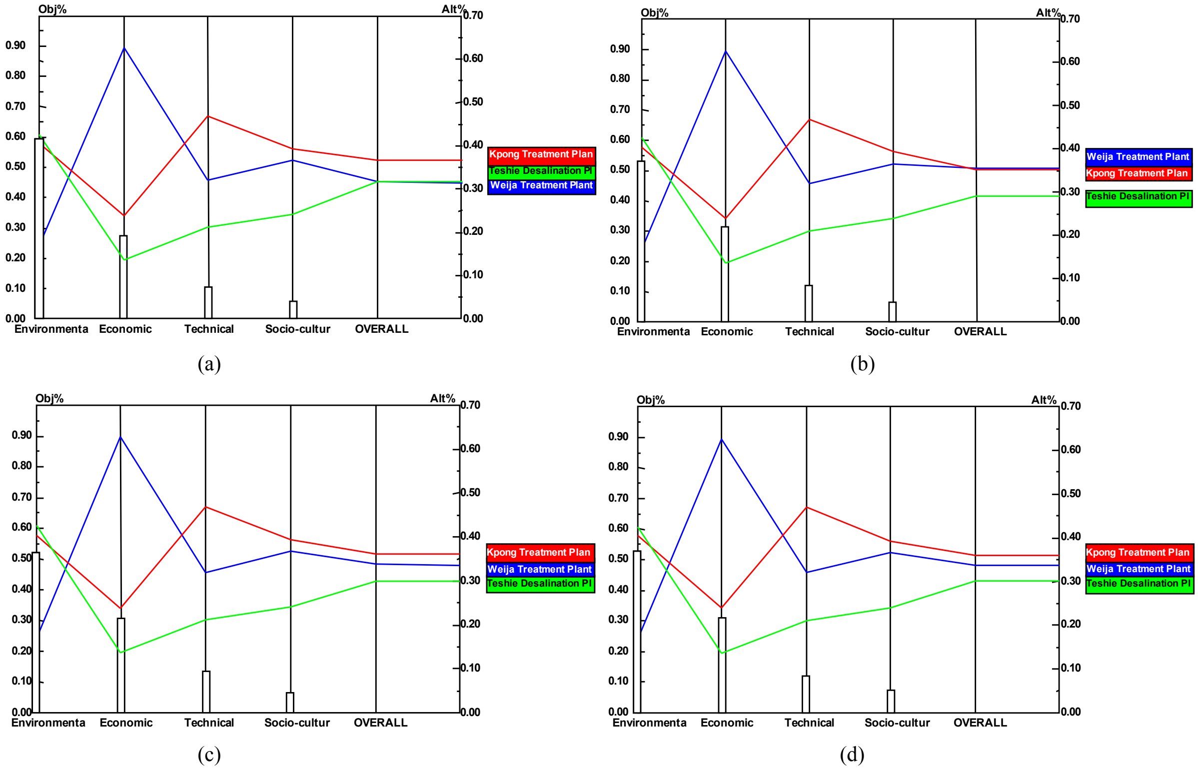


Figure 4. Overall ranking of alternatives.



(a) (b) (c) (d)

Figure 5. Performance sensitivity analyses.

From **Table 3** and **Figure 6**, the percent-top critical criterion is −36.0% under the RA sub-criterion. This indicates that an increase in the weight of the RA sub-criterion by 36.0% will make the Kpong WTP lose its position as being the best (top) ranked alternative to the Teshie desalination plant. The percent-any critical criterion is −19.5% under the RA sub-criterion, implying that an increase of 19.5% of the RA weight will cause some change in the order of the ranking of the any of the alternatives. **Table 4** shows the criticality degree (D'_k) and sensitivity coefficient values. As the table reveals, the resource availability sub-criterion is the most sensitive decision sub-criterion. The robust sub-criteria are the sub-criteria with all the $\delta'_{k,i,j}$ values indicated as not feasible (N/F).

8. Conclusion

The urban water supply source in the ATMA region of Ghana was evaluated as a case study under environmental, economic, technical, and socio-cultural criteria using the AHP model. The considered alternatives were the Weija WTP, Kpong WTP, and Teshie desalination plant. The case study identified the Kpong WTP as having a relatively high potential for expansion. It also outlined sets of critical factors that could be considered when decisions were to be made for expanding such water supply systems. The solution was identified as being sensitive to the environmental and economic criteria while being robust to the technical and socio-cultural criteria.

Table 3. Relative changes in sub-criteria weights ($\delta'_{k,i,j}$).

	RA	RQ	TWM	EI	EC	CC	MC	CoC	FV	OF	EE	LA	SD	TWA	ST	A	AR
K-W	N/F	41.0	N/F	76.7	−51.0	N/F	−453.2	−108.8	−43.3	N/F	N/F	N/F	−1529.4	N/F	−318.4	N/F	−1216.6
K-T	**−36.0**	65.7	N/F	N/F	N/F	−539.4	N/F	N/F	N/F	N/F	N/F	N/F	N/F	N/F	−1791.6	N/F	N/F
W-T	**−19.5**	N/F	N/F	N/F	61.0	−208.6	N/F	N/F	48.4	N/F	N/F	−586.1	N/F	−2744.4	N/F	N/F	N/F

Table 4. Criticality degrees and sensitivity coefficients.

	RA	RQ	EI	EC	CC	MC	CoC	FV	LA	SD	TWA	ST	AR
D'_k	**19.5**	41.0	76.7	51.0	208.6	453.2	108.8	43.3	586.1	1529.4	2744.4	318.4	1216.6
Sens (C_k)	0.0513	0.0244	0.0130	0.0196	0.0048	0.0022	0.0092	0.0231	0.0017	0.0007	0.0004	0.0031	0.0008

The abbreviations of sub-criteria listed in the table represent the respective sub-criteria as listed in Table 2, in their respective order.

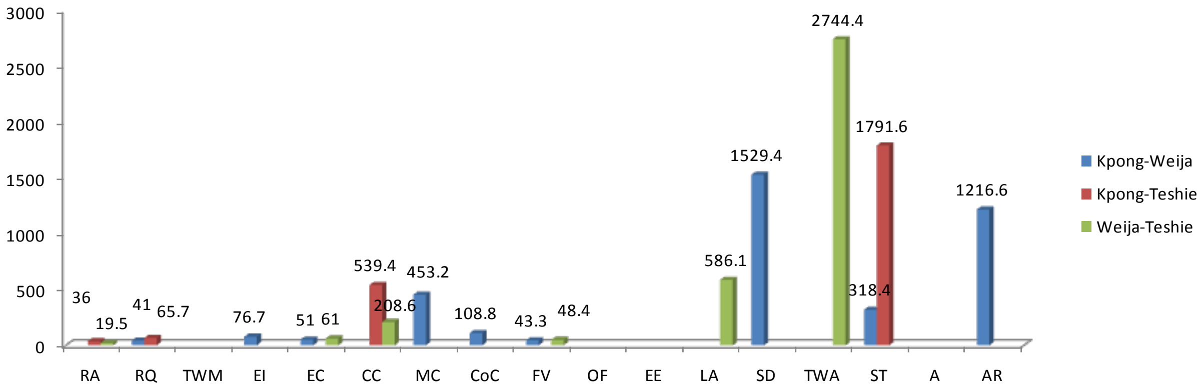


Figure 6. Graphical representation of relative changes in sub-criteria weights.

Despite the strengths of the AHP, some weaknesses were observed. The problem of inconsistency in the judgment of the participating experts during the administration of the questionnaire was observed to be associated with questions that had relatively large pairwise comparisons. Additionally, it was realised that the nature of the decomposition of the problem could also have an effect on the final result of the study. Thus, when different experts viewed the same problem from different perspectives, in terms of the problem decomposition, the outcome of such a study could be starkly different. It is, therefore, recommended that when possible interactions of different level criteria are identified, an advanced methodology like the Analytic Network Process (ANP) should be used. The established MCDA solution procedure may ultimately be applied to other water supply systems for decision-making.

Acknowledgements

The authors would like to acknowledge the assistance of management of the Ghana Water Company Limited and the Public Utility and Regulatory Commission of Ghana. Our sincere appreciation also goes to the anonymous reviewers of the article, as well as a financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC).

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