Integrated Performance Evaluation Indicators for Water Supply Systems

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ABSTRACT

Water supply systems (WSSs) process optimization can be considered as one of the highest importance priorities in core public infrastructures management challenges. The primary goal of water service is to operate this valuable asset with the utmost efficiency possible at an acceptable cost throughout its life. Achieving this objective primarily requires assessing the existing performance of all components of the WSS using distinct performance indicators (PIs). Various international water bodies have developed detailed performance assessment frameworks based on multiple indicators to comprehensively cover all WSSs. On this basis, the present study proposes a conceptual WSSs performance evaluation framework linking various water collection, treatment, and distribution processes with their PIs groups and corresponding categories. However, multi-attribute utility theory (MAUT) was used to provide a stepwise approach, starting abroad range of quantitative and qualitative drinking water performance evaluation process depending on specific operating conditions. Meanwhile, the integrated performance evaluation indicators (IPEI) for elven extended Cairo drinking WSSs were developed to determine the overall complex interrelationship between the targets evaluating indicators sets. The results of this study are a very useful entry point for water services providers to put forward their basis selection, ranking of WSSs critical elements, and consequently developing the required future plans.

Keywords: Water Supply Systems, Infrastructures Management, Multi-Attribute Utility Theory, Integrated Performance Evaluation Indicators.

1. Introduction

Drinking water must meet specific standards and criteria for public health and be free of pathogenic bacteria. The basic duty of water companies is to provide safe drinking water that meets the quality requirements as prescribed by law. The most important issue when managing and planning the operation of a drinking water distribution system is to meet the needs of consumers. A reliable distribution system means ensuring water of the required quality and pressure for all consumers at all times. [1]. One perceived benefit is that water supplies gain consumer trust. However, besides this main goal, water companies focus on how to operate the entire water supply system economically and sustainably. They try to focus on designing and building new water supply elements to achieve better efficiency and efficient operation of existing systems. In addition, the current state of the individual components of the system and its behavior must be continuously evaluated. Only a detailed knowledge of the current state of the system can plan a substantial investment or repair [2].

As illustrated in Table (1), many international agencies such as the Canadian Standards Association (CSA,2010); National Research Council (NWC,2012); Asian Development Bank (ADB,2012); Office of the Water Services (OFWAT,2012); World Bank (WB,2011); National Research Council (NRC,2010); International Water Association (IWA,2006); and American Water Works Association (AWWA,2008) are grouped water supply system performance indicators (PIs) in different categories [3].

Table (1) Number of water supply performance indicators categories

PI Category/ Subcategory	WB	OFWAT	ADB	NWC	NRC	IWA	AWWA	CSA
Water Resources	11	2	15	26	5	4	-	5
Physical/Asset	1	-	2	2	-	15	-	7
Personnel/Staff	11	-	1	-	-	26	11	17
Water quality/Public health	2	-	13	7	3	5	1	7
Operational	4	4	10	5	10	39	8	6
Quality of service/Customer service	17	4	2	12	8	34	2	4
Economic/Financial	35	14	11	21	7	47	9	16

Generally, most of these PIs are mainly involved in Water quality, finance, customer service, and the operation of a WSS. The importance given to these PIs indicates that these are the most important categories and also have strong interactions with each other. In addition, many studies selected some of these indicators and tried to weigh them to assess their interrelationship and consequently reach the appropriate condition performance evaluation of various water supply system components. As illustrated in Table (2), these studies used many approaches such as Elimination Et Choix Traduisant la REalite (ELECTRE); Analytical Hierarchy Process (AHP); the technique for order preference by similarity to ideal solution (TOPSIS); and Multi-Attribute Utility Theory (MAUT) for developing the final evaluating performance score.

Table (2) Description of Performance Evaluation Methods in WSS

Method	Theory	Concept	Goal	Reference
ELECTRE	Outranking Theory	- Compare the alternatives pairwise for each criterion - Over strength preferring	Outranking models	[4]
AHP	Hierarchical Theory	-Importance of the criterion -Assigned weight	Value measurement models	[5]
TOPSIS	Classification Theory	-Measure how good alternatives reach determined goals	Aspiration and reference level models	[6]
MAUT	Utility Theory	-Weighting criteria in addition to its values with respect to its relevant attributes	Eliciting single-attribute evaluations models	[7]

The present study aimed at focusing on elven different water supply systems at Cairo governorate which areserved by elven major WTPs: Tebien, Kafr El Elow, North Helwan, Madi, Fustat, El Ruda, Rud El Farg, El Ameria, Mostrud, Shubra El Khema, and El Marg. Meanwhile, the main study’s objective is to develop an integrated performance evaluation indicator (IPEI) based on multi-attribute utility theory (MAUT) applications. In this study, the chosen MAUT because of the additive utility function can be considered as one of the most widely used whereas the alternative with the highest utility performance is required to be the most appropriate

2. Study area

Cairo water company (CWC) produces drinking water with a daily amount exceeding six million cubic meters through elven WTPs to cover various Cairo governorate water requirements [8,9]. These WTPs mainly depend on surface water sources from theNile River and its canals. The present research focuses on WSSs in various locations of the Cairo governorate in Egypt. Generally, water is provided to various Cairo districts through six major WTPs located at the south and west Cairo water company’s sector

(Tebien, Kafr El Elow, North Helwan, Madi, Fustat, El Ruda). While the northern and eastern Cairo districts are mainly provided with potable water from Rud El Farg, El Ameria, Mostrud, Shubra El Khema, and El Marg WTPs, Figure (1).

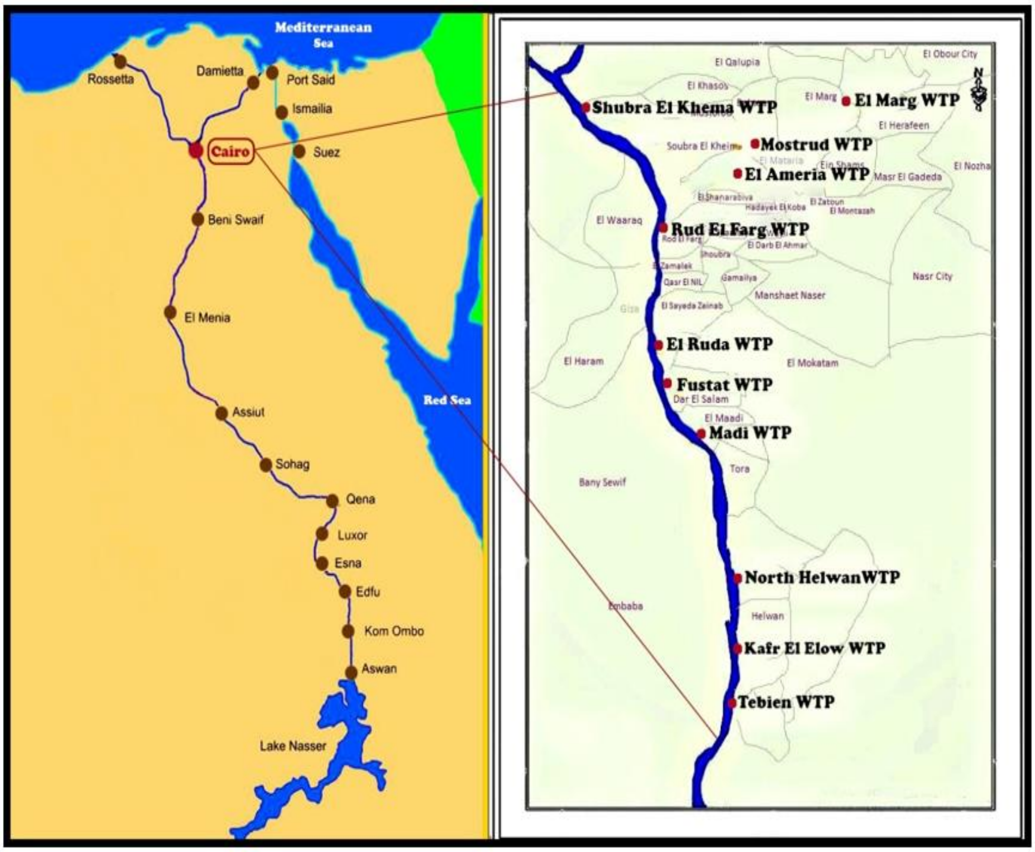

Figure (1) Study Area

3. Study Methodology

The main water supply process can be summarized in three consecutive stages: surface water collection (intakes), water treatment processes, and water distributions. However, to satisfy the optimum target efficiency of the mentioned main processes, this study focuses on their main affecting components and also the corresponding measuring indicators [10,11,12]. Moreover, this research rearranged performance according to six main components and twenty-eight indicators, Table (3).

Table (3) Water supply systems evaluating components and indicators 101

Component	Indicator
Operational (O)	Chemicals doze regimes (O1)
	Daily pump running time (O2)
	WSS power consumption to water supply (O3)
	Process control systems (O4)
Quality of Supply(Q)	Water quality tests performed (Q1)
	Quality of supplied water (Q2)
	Microbiological water quality compliance (Q3)
	Physical-chemical water quality compliance (Q4)
Reliability (R)	Non-revenue water by volume (R1)
	Water losses per km (R2)
	Speed of repair of bursts (R3)
	Inefficiency of use of water resources (R4)
	Water consumption per capita (R5)
	Subscriber meter replacement (R6)
Sustainability (S)	Network repair rate (S1)
	Water service connection repair rate (S2)
	Employees per water service connection (S3)
	Training per employee (S4)
	Total employees per water subscribers (S5)
	Average unit energy consumption (S6)
Economic Efficiency (E)	Energy costs ratio (E1)

	Collection ratio (E2)
	Operating cost coverage ratio (E3)
Customer service (C)	Continuity of supply (C1)
	New connection efficiency (C2)
	Non-Billing complaints (C3s)
	Water quality complaints (C4)
	Billing complaints (C5)
	Subscribers receiving continuous supply (C6)

In addition to that, MAUT theory is applied for this study to allocate relative weights to the various indicator. The basic assumption of MAUT is that there is a real function or utility of value (U), determined by the set of possible alternatives that the decision-maker seeks, either consciously or not, to maximize [13,14].

Each alternative result in an outcome, which may have a value on a number of different dimensions. MAUT seeks to measure these values, one dimension at a time, followed by an aggregation of these values across the dimensions through a weighting procedure. In this study, each main component weight is used in conjunction with its indicators evaluation value to produce the final integrated performance evaluation indicators. The MAUT applying main steps are:

I- Rank the different components and indicators in order of importance.

II- Rate the different components and indicators on a scale from zero to one, while reflecting the ratio of the relative importance of one indicator over the next.

III- Normalize these weights on a scale from zero to one.

IV- Determine indicators values for each component by using single-attribute utility functions on linear normalized scales.

V- Calculate the IPEI for each water supply system by obtaining the weighted linear sum for the main components.

Equation (1) shows how the utility values can be determined for each indicator. While Equation (2) focuses on the normalized criteria values determination from single-attribute utility functions on normalized scales.

$$U_j = \sum_{k=1}^{n_k} w_k n_{kj} \tag{1}$$

$$n_{kj} = f_k\left(s_{kj}\right) \tag{2}$$

where

U_j = utility of indicator j

w_k = weight of the k_{th} indicator

n_{kj} = normalized criterion k value for indicator j

s_{kj} = value of criterion k for indicator j

$f_k(x)$ = single-attribute utility function on a normalized scale.

Equation (2) shows that single-attribute utility functions on normalized scales are used to determine values for each indicator. However, these utility functions can be linear or nonlinear, depending on the specific indicator.

The sum of decomposed weights for all indicators should equal one, and the preference scores should range from 0 to 10. The mathematical expression of the performance evaluation indicator (PEI) will be shown in Equation (3):

$$PEI = \sum_{i=1}^{n} \sum_{j=1}^{m} [(w_{c,i} \times w_{p,i/j})(u_{i/j,r})] \tag{3}$$

Where, w_{cri}=PEI of the component; $w_{c,\ i}$=relative weight of the i_{th} indicator; $w_{p,\ i/j}$ represents the relative weight of the j_{th} indicator under the i_{th} component; n=number of components; m=number of indicators under the i_{th} components; and u_{i}/j,r=preference score of the j_{th} indicator under the i_{th} component for the actual water supply system.

replacing $w_{c,I}$ x wp,$_{i/j}$ by the indicator decomposed relative weight $w_{d,i/j}$, Equation (3)can be expressed using Equation (4) as follows:

$$PEI = \sum_{i=1}^{n}\sum_{j=1}^{m}[(w_{d,i/j}\ )(u_{i/j,r})] \qquad (4)$$

where, $w_{d,\ i/j}$ represents the decomposed relative weight of the j_{th} indicator under the i_{th} component.

Moreover, a distinctive factor (U_t) was introduced in the model Equation (5) in order to accommodate the maximum and minimum values of PEI for each indicator.

$$PEI = U_t\sum_{i=1}^{n}\sum_{j=1}^{m}[(w_{d,i/j}\ )(u_{i/j,r})] \qquad (5)$$

After that, the statistical analysis is also applied to provide a range of maximum and minimum integrated performance evaluation index (IPEI) values. Meanwhile, comparing the maximum and minimum IPEI values with the mean values of any component under the same WSS generates another constant (C_t) to estimate probable maximum and minimum IPEIs. Equation (5) can be rewritten as shown in Equation (6) in order to estimate the overall maximum and minimum IPEI values of water supply system components.

$$IPEI_{cri(t)max/min} = U_t\sum_{i=1}^{n}\sum_{j=1}^{m}[(w_{d,i/j}\ )(u_{i/j,r})] \pm C_t \qquad (6)$$

Where, $C_t = 0.70$; considering -ve and +ve signs for maximum and minimum IPEI, respectively.

After that, a determination for each water supply systems integrated performance evaluation class is implemented according to the IPEI main distinctive categories [15], Table (4).

Table (4) IPEI Main Categories

IPEI	WSS Performance Level
$0 \leq IPEI \leq 1.0$	Critical performance
$1.0 < IPEI \leq 2.0$	Extremely unexpected performance
$2.0 < IPEI \leq 3.0$	Poor unexpected performance
$3.0 < IPEI \leq 4.0$	Moderately unexpected performance
$4.0 < IPEI \leq 5.0$	Slightly unexpected performance
$5.0 < IPEI \leq 6.0$	Moderate expected performance
$6.0 < IPEI \leq 7.0$	Almost performed
$7.0 < IPEI \leq 8.0$	Good expected performance
$8.0 < IPEI \leq 9.0$	Very good performance
$IPEI > 9.0$	Excellent performance

4. Results and Discussion

At the initial stage, the relative weights of all components and their involved indicators are determined based on the previous literature reviews output, preliminary assessment of the technical condition of WSSs elements, and expert groups interviews [10, 11, 12.13], Figure (2). Moreover, to deal with uncertainty issues, probability distributions of preference scores were adjusted based on 12 scores for each indicator. In addition, the mean of the most and least preferences as well as the average scenario scores were calculated for each indicator. These produce three sets of scenario scores for each indictor and consequently used to feed the required data for fitting the probability distributions for these three sets of scenario scores for each indicator.

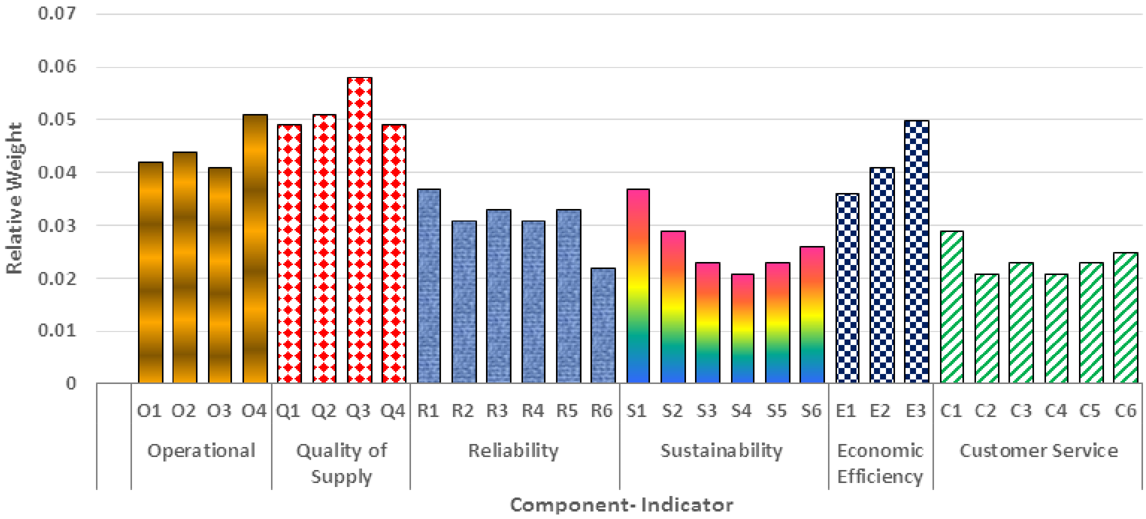

Figure (2) Components and Indicators Relative Weights

It can be noted that there is no parameter that has been assigned more than 6% as a relative weight. These can be explained the complexity of the interrelation between the huge number of evaluating components and indicators. On the other hand, it is obvious that the supply quality component (S) has the maximum total relative weight due to its involving in many indicators related human safety health. While the second important relative weight is reliability component because of its important in measuring and controlling the required fraction of the demand rate and consequence evaluating the shortages that result from failures of WSSs physical facilities elements. In terms of various evaluating indicators corresponding weights, the heights of them are: microbiological water quality compliance, process control systems, quality of supplied water, operating cost coverage ratio, and water quality tests performed.

After that, in order to show how different components and indicators response with respect to assigning relative weights in-service operation target WSSs scenarios, the recorded mean preference scoring values of each indicator are assessed to measure preferences or utility in terms of anticipated condition. However, equation (5) is applied to calculate the PEI of the eleven study's WSSs under each of the six-performance evaluating component, Figure (3). Meanwhile, the distinctive factor (U_t) is set a value of 0.90 when PEI ≥ 5; U_t = 1.10 when PEI < 5.

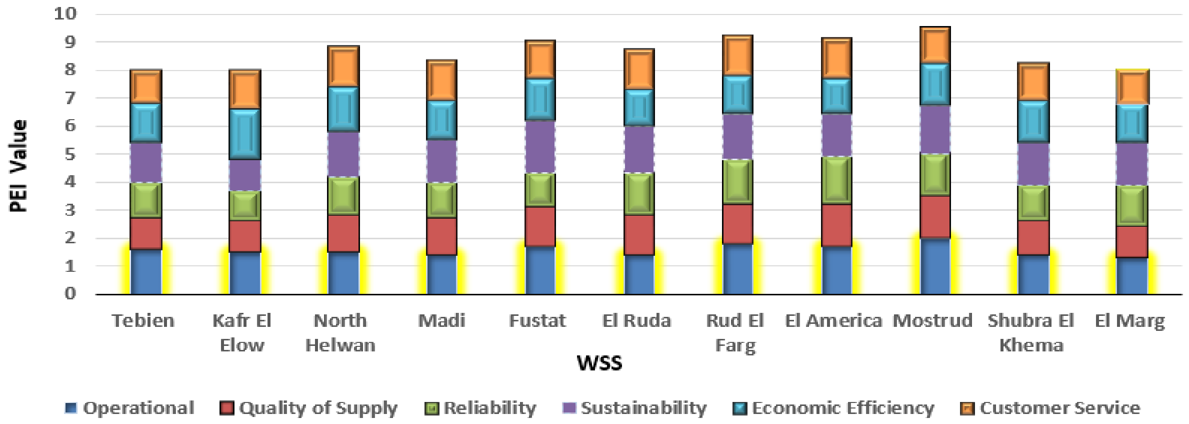

Figure (3) Performance evaluation indicator components

According to PEI values results that based on mean values of components, indicators, it can be noted that four of WSSs (Mostrud, Rud El Farg, El America, and Fustat) have a high relative performance evaluation indicator compared with the other WSSs. On the other hand, the current condition of all individual components of the WSSs and its behavior reflect their high operation levels, durability, sustainably, and economic efficiency.

At the next step, equation (6) is applied to calculate the maximum and minimum water supply system IPEI values. Figure (4) illustrates the results that classified by each as components for both two main Cairo water supply sectors (North and East – South and West).

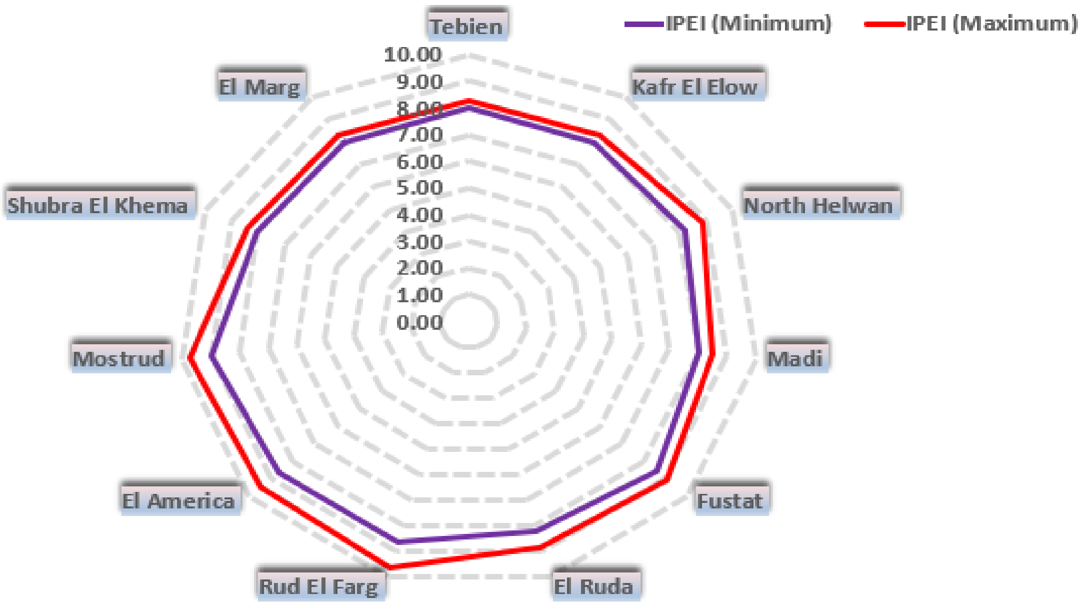

Figure (4) Water supply systems integrated performance evaluation indicator

As shown in Figure (4), a slightly small difference ranges are noted between the calculated maximum and minimum IPEI values at the same WSS. In addition, the most of north and east Cairo water supply system have a relative superior in IPEI values compared with corresponding south and west Cairo WSSs. Moreover, the IPEI are ranged from maximum value 9.50 at Mostrud to 8.00 the minimum value at El Marg. However, two high categories (excellent and very good) of performance are including all study’s WSSs.

5. Conclusions

- The presented study develops a performance indicator for evaluating Cairo water supply systems main elements: water intake, water treatment plants, and water distribution network.

- The Multi-Attribute Utility theory was applied for quantitative and qualitative performance evaluation measures.

-Furthermore, the preferences obtained using MAUT are the possibility of examining the importance and attractiveness of separate WSSs indicators, develop single-attribute index, and determine the overall integrated index for combinations of involved components levels.

- The developed integrated indicators result revealed that north and east Cairo WSSs are classified in high performance evaluation relative the corresponding south and west WSSs.

- However, the proposed performance indicator can be used from operators for WSS critical elements tracing to help them in adjusting the overall water supply process.

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