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Analytic Hierarchy Process Framework for Water Security Management in Egypt

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ABSTRACT

Water security is one of the main serious constraints for development in Egypt. Furthermore, it is essential to develop strategies for the water sector in an integrated way. However, this research develops a new integrated water security index (IWSI) based on the analytic hierarchy process (AHP) to highlight the evaluation of thewater security situation in Egypt. The new proposed index is strongly correlated with fifteen indicators that selected to evaluate the five main key components (Availability Water Security (AWS), Economic Water Security (EWS), Water-Related Disasters Security (WDS), Environment Water Security (EVWS), and Governance and Water Management Security (GWMS)). The developed integrated water security index (IWSI) evaluates the status of water security in Egypt. The study concludes that IWSI is considered a good water management tool to help decision-makers prioritize future water development plans and improve resource management. Moreover, it is highly recommended to continue improvement in water security index assessment for monitoring the rapid variability in its integrated indicators.

Keywords: Water Security Index, Water Resources, Analytic Hierarchy Process, Sustainable Development.

1.INTRODUCTION

Water security represents an important role in all human life to satisfy its continuity safely [1]. Egypt is currently overexploiting its water resources and facing growing water scarcity mainly due to population growth, deterioration of water quality with the impact of climate change, and development in the Upper Nile countries without sufficient coordination with Egypt. These require an accurate water safety assessment and define the impact of IWRM interventions on the water system. It is very important to have a tool that we can use to assess water security.

Analytical Hierarchy Process (AHP) is a relative measurement theory with absolute scales of tangible and intangible criteria based on the judgment of knowledgeable people and experts AHP reduce multidimensional problem to one-dimensional problem. Decisions are determined by a unique number for the best outcome or by a preference vector of the order for different possible outcomes [2].

Mei, et al. developed a quantitative and qualitative model of different policies based on AHP series of sub-indices. The model output facilitates Beijing water resources system dynamics management [3].

Mutikanga, et al. proposed AHP as a strategic planning tool for water leakage loss and water resource management. The study output introduced many alternative scenarios that focus on how to overcome infrastructure and assets damage to sustain water supply efficiency [4].

In addition, the researchers comprised AHP measurements and descriptions of their selected technical and environmental elements of a complex system of waterworks. Hence, the standard AHP has been extended as group AHP decisions in water sustainability assessment. Thus, it is better to consult a group of experts to avoid bias and groups make better decisions than individuals [5]

The main objective of thecurrent paper is to develop a new integrated water security index by using ananalytic hierarchy process framework to facilitate the required decision-support towards thebetter formulation of water security plans.

2.INTEGRATED WATER SECURITY DEVELOPING METHODOLOGY

The methodology of AHP for developing integrated water security is based on integrated processes, as shown in

Figure 1, starting with understanding management challenges in water-scarce conditions and outlining the water security main process framework to develop the required integrated water security

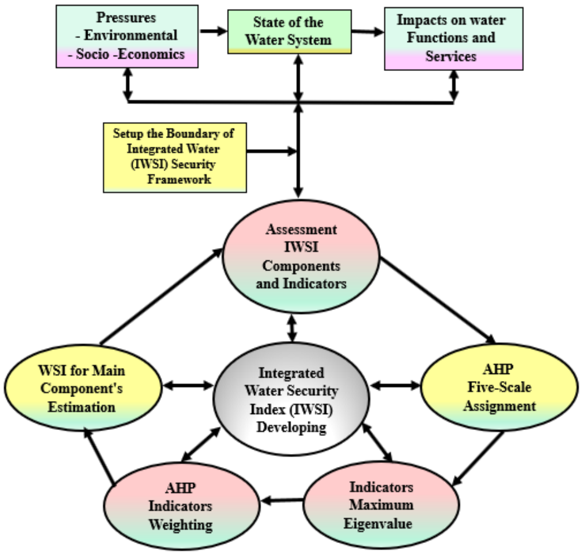

Figure 1: Study Overall Methodology

3. WATER SECURITY COMPONENTS AND INDICATORS

Five main sub-indexes: Availability Water Security Index (AWSI), Economic Water Security Index (EWSI), Water-Related Disasters Security Index (WDSI), Environment Water Security Index (WSI), and Governance and Water Management Security Index (GWMSI) are selected to develop the integrated water security index (IWSI) In additional to that, 15 indicators are selected to provide an interdisciplinary measure then these indicators evaluated concerning specific variables. Table 1 enlists five components, 15 indicators, variables, and their measuring guides.

4. FRAMEWORK ASSESSMENT AND DEVELOPING

AHP provides an interdisciplinary measure that priorities and distinguishes the selected indicators and links between their influence and the main components for developing thefinal evaluating score of the water security index. The methodology of theAHP framework involved four main steps: accurate indicators measuring, normalization, assigning weights, and aggregation. AHP assessment process can be summarized as follows [2]:

Step 1: Develop a hierarchical form that is split into criteria (standards), objective, and attribute levels.

Step 2: Develop the comparison matrix $A_{n\times n}$ and designate each part a_{ij} in conformance with the five-scale technique. The concept of assignment by the five-scale technique is revealed in Table 2.

Step 3: Calculate the significance ranking indicator r_i as follows:

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follows:

$$r_i = \sum_{j=1}^{n} a_{ij} (i = 1, \quad 2, \ldots, \quad n) \quad (1)$$

Where r_i is the significance ranking indicator, and a_{ij} is the part of the comparison matrix $A_{n\times n}$

Step 4: Calculate the decision matrix $B_{n\times n}$, and each matrix part is bij as the following way:

$$b_{ij} = \begin{cases} \dfrac{r_i - r_j}{r_{max} - r_{min}} x(k_m - 1) + 1 & r_i \geq r_j \\ \left[\dfrac{|r_i - r_j|}{r_{max} - r_{min}} x(k_m - 1) + 1\right]^{-1} & r_i < r_j \end{cases} \quad (2)$$

Where, bij is the part of the decision matrix $B_{n \times n}$, r_i is the significance classification indicator of indicator i, r_j is the significance classification indicator of indicator j, r_{max} is the maximum amount of the significant ranking indicator, and r_{min} is the minimum amount of the significant ranking indicator. km is defined as follows:

$$k_m = \frac{max\{r_i\}}{min\{r_i\}} \quad (i = 1, 2, \ldots, n) \quad (3)$$

Step 5: Calculate the optimum transferal matrix $C_{n\times n}$, and each matrix part is c_{ij}, as the following way:

$$c_{ij} = \frac{1}{n} \sum_{k=1}^{n} \left(lg \frac{b_{ik}}{b_{jk}} \right) \quad (i, j = 1, 2, \ldots, n) \quad (4)$$

Where c_{ij} is the part of the optimal transfer matrix $C_{n \times n}$, and bij is the part of the decision matrix $B_{n \times n}$.

Step 6: Compute the coherent quasi-optimal matrix $D_{n \times n}$ and each part of the matrix is d_{ij} as follows:

$$d_{ij} = 10^{c_{ij}} \quad (i, j = 1, 2, \ldots, n)$$

(5)

Where

d_{ij} is the part of the coherent quasi-optimal matrix and c_{ij} is the part of the optimal matrix transfer matrix $C_{n \times n}$.

Step 7: Calculate the eigenvector of the maximum eigenvalue for matrix $D_{n\times n}$. Later, the weight ω_i of the apiece indicator can be gotten after standardization.

$$\omega = (\omega_1, \omega_2, \ldots, \omega_1)^T \quad (6)$$

The weight vector that is combined with the weight of every indicator is as the following way:

Where w is the weight vector.

Step 8: After attaining IWSI are concluded by:

$IWSI = \sum(W_i \times I_i) / W_i$

Where, W and I refer to the weight and significance intensity of each indicator respectively.

Step 9: Index final score level in terms of the level of water security according to five main categories, Table 3.

Table 1: Water Security Components Outlines

Component	Indicator	Variable	Measuring Guides
Availability Water Security (AW)	Water Scarcity (AW1)	Freshwater sufficiency	m3/capita/year [3]
	Reliability (AW2)	Infrastructure Leakage Index	Metered Water and losses from Nonrevenue water [4]
	Water Accessibility (AW3)	Safely managed drinking water services	Percentage of population with access to clean water [5]
	Sanitation Accessibility (AW4)	Safely managed sanitation services	Percentage of thepopulation having access to sewage system [5]
Economic Water Security (EW)	Agriculture Water (EW1)	The productive use of water to sustain economic growth in food	Agricultural resilience, Dependency, and Use efficiency [6]
	Industrial Water (EW2)	The productive use of water to sustain economic growth in theindustry	Industrial water productivity and Industrial Footprint [7]
	Water for Energy (EW3)	The productive use of water to sustain economic growth in energy	The relative contribution of hydropower to energy supply [8]
Water-Related Disasters Security (WD)	Flood Disaster (WD1)	The capacity to cope with and recover from flood	-Economic loss caused by floods per year [9]
	Drought Disaster (WD2)	The capacity to cope with and recover from drought	Drought Resilience [10]
Environment Water Security (EVW)	Pollution Threats (EV1)	River basin management for sustainable surface water quality	-Total Suspended Solids -Potential Acidification [11]
	Bio-Diversity Threats (EV2)	River basin management for preventing watershed disturbance	Livestock density [12]
	Flow Regulation (EV3)	Sustainable water resources development	-River network fragmentation -Residency Time Change downstream from dam [13]
Governance and Water Management Security (GM)	Economic Growth Capacity (GN1)	Progress toward better economic impact on water security	GPP per capita [7]
	Affordability (GN2)	Ensure the vulnerable populations can pay for essential water services	Served operation income / Total income [14]
	National Budget Directed to Water (GN3)	The productive use of thenational budget in water and sanitation services improvement	Percentage of national budget directed to water and sanitation services [7]

Table 2: AHP Five-Scale Assignment Technique

Significance Intensity	Definition
1	The indicator i is similarly as significant as indicator j
2	The indicator i is lightly significant related to indicator j
3	The indicator i is noticeably significant related to indicator j
4	The indicator i is intensely significant related to indicator j
5	The indicator i is tremendously significant related to indicator j

Table 3: Integrated Water Security Categories

Component	AW	EW	WD	EV	GN
AW	1.000	5.000	0.250	1.000	1.000
EW	0.200	1.000	2.000	1.000	3.000
WD	4.000	0.500	1.000	1.000	6.000
EV	1.000	1.000	1.000	1.000	4.000
GN	1.000	0.330	0.167	0.250	1.000

Table 4: Geometric Mean Pairwise Comparison

IWSI	Security Level	Explanation
<1.5	Insecure Water	People suffer from a serious problem due to water security
1.5 – 2.5	Low Water Security	Insufficient management and policies to satisfy the target water security
2.5 – 3.5	Medium Water Security	Water security is relatively satisfactory to cover the basic needs.
3.5 – 4.5	High Water Security	Good management for attaining a suitable water security level.
>4.5	Very High-Water Security	The index shows a high level of security for all dimensions

5. RESULTS AND DISCUSSION

In the phase of required data collection, a detailed survey questionnaire was developed. The target group included operators, researchers, and regulators. The questionnaire focuses on pair-wise comparison matrices to determine both components and indicators weights. Table 4 illustrates the main components geometric mean pairwise comparison matrix.

It can be noted that water-related disasters main component has a superior value in the overall integrated security index weighted components due to its direct effect in satisfying various water needs especially in crises conditions such as measured in its involving indicators (flood and drought disasters). While, the availability of water security has the second-high weight Moreover, based on the developed maximum components' eigenvalue, the same AHP methodological process is also applied to develop the relative weight of every indicator involved in the five main components. Figure 2 illustrates the AHP results of indicators relative weights for each component.

Where the abbreviation (AW1, AW2, AW3, AW4, EW1, EW2, EW3, WD1, WD2, EW1, EW2, EW3.GN1, GN2, and GN3) are previously denoted in Table 1.

It is clear that drought and flood indicators have the highest weight value because of their serious impact on water-related disasters security and consequently the

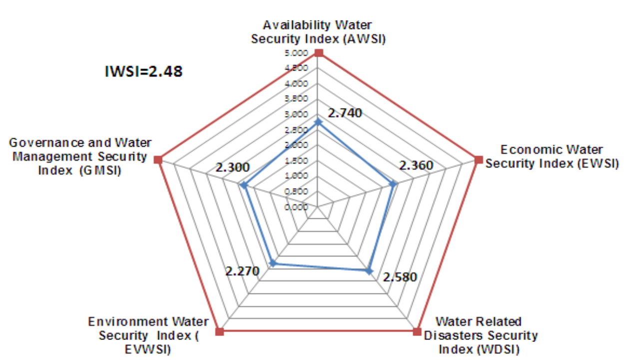

Figure 2: Indicators Relative Weights

After that, the normalized decision matrix $B_{n\times n}$ and each matrix part b_{ij} are developed as shown in Table 5.

Table 5: Geometric Mean Pairwise Comparison

As mentioned above, AHP processes are used to facilitate

Component	AW	EW	WD	EV	GN
AW	1.000	2.236	0.500	1.000	1.000
EW	0.447	1.000	1.414	1.000	1.732
WD	2.000	0.707	1.000	1.000	2.449
EV	1.000	1.000	1.000	1.000	2.000
GN	1.000	0.577	0.408	0.500	1.000

developing the relative weight of each component and their involving indicators. However, the coherent quasi-optimal matrix $D_{n\times n}$ is developed, Table 6.

Table 6: Geometric Mean Pairwise Comparison

Component	AW	EW	WD	EV	GN	Weighted eigenvalue
AW	0.184	0.116	0.222	0.122	0.210	0.210
EW	0.082	0.181	0.327	0.222	0.211	0.205
WD	0.367	0.128	0.231	0.222	0.299	0.249
EV	0.184	0.181	0.231	0.222	0.244	0.212
GN	0.184	0.105	0.094	0.111	0.122	0.124

value because of its importance as one of the dominant components for the management of various water aspects (scarcity, reliability, and water - sanitation accessibility).

predictive influence damage on all water security aspects. These can reflect the especially recent serious exerted efforts from the Egyptian governorate to overcome the impact probabilities of these crises.

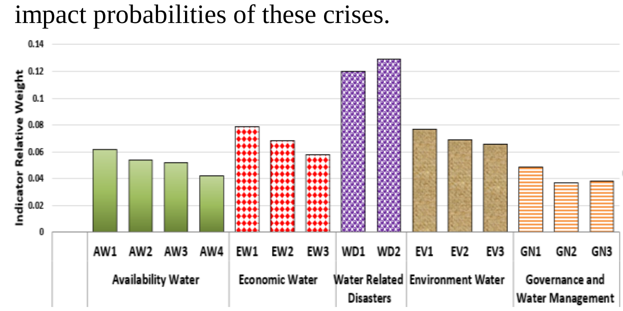

Figure 3: Developed Integrated Water Security Index for Egypt

Moreover, Figure 3 illustrates the results of the five main components sub-indices in addition to the overall developed Integrated Water Security Index for Egypt.

It can be noted that AWSI scores 2.74 out of 5 which means that is medium secured. Whenever EWSI Scores 2.36 that means the situation is low security. The index must be improved by raising agricultural efficiency and land productivity. In addition to that, WDSI scores 2.58

that means the situation is relatively secure. The involved analysis of this index leads to the high flood damage risk and the relatively low wastewater treatment coverage hurt this sub security index. Moreover, EVWSI scores 2.27 that means critical security situation in this index. This is mainly due to the high watershed disturbance due to the disconnection of the wetland and coastal lakes. On the other hand, GMSI scores 2.3, which mean the situation is near insecure; this is mainly due to some regulation does not apply to Egypt.

On the other hand, the overall integrated water security index for all of Egypt is calculated according to the five mentioned indices. IWSI scores 2.48 that means the water system is characterized as medium security.

6. CONCLUSIONS

-This paper aims to assess the water security index for Egypt and to develop a more robust approach for assessing the water security index.

- AHP approach was applied for the Egyptian case to analyze and evaluate the results, and highlight the necessary recommendations to better represent the water security in Egypt.
- The developed AHP model was also successfully used for determining the relative importance of the water safety components.
- The developed integrated water security index helps in highlighting the water challenges and their priorities for implementing the various Egyptian water sector sustainable development planning.

7. CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Mohamed A. Reda: Conceptualization, Methodology, Writing, Original Draft, Results and analysis, Validation

8. DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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