Journal of ENVIRONMENTAL Treatment Techniques

J. Environ. Treat. Tech.
ISSN: 2309-1185

Journal web link: http://www.jett.dormaj.com
https://doi.org/10.47277/JETT/9(4)768

# Assessment of the Integrated Water Resources Management in Egypt

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Received: 28/08/2021 Accepted: 30/09/2021 Published: 20/12/2021

## Abstract

Egypt's water requirements are increasing due to the growing population, improved living standards, and agricultural land expansion to ensure food security. The proper planning and integrated water resources management in Egypt is a complex process that requires considering many different aspects: Available water resources, the water requirements from the various sectors, and water quality. As for water resources, the current deficit reaches up to 20 billion cubic meters per year, mainly covered by reusing agricultural drainage water in irrigation through mixing stations, with a significant negative impact on health and environmental standards. As for urban water and sanitation, the rapid population increase puts immense pressure on the existing network and the government to expedite its infrastructure assets to cope with such an increasing pace. The development of Integrated Water Resources Management (IWRM) was particularly recommended in the ministers' final statement at the International Conference on Water and the Environment in 1992 (so-called the Dublin principles). This concept aims to promote changes in practices that are considered fundamental to improved water resource management. This paper provides a comprehensive assessment of IWRM concept implantation in Egypt and pays particular attention to the concept implementation results against its objectives, key lessons, and recommendations to improve current and future sector financing options for modern water. At present, the IWRM concept, given the network's complexity and limited staff availability, is limited to integrating irrigation and drainage service delivery. The proposed GWSI proved to be a suitable, efficient, and effective tool for such dynamic allocation.

**Keywords**: Multi-Criteria Analysis, IWRM, GIS, Water Accounting, Water Resources Management

## 1 Introduction

The concept and principles of IWRM vary from country to country according to their needs and institutional arrangements. In the current definition, IWRM Integrated Water Resources Management (IWRM) is defined as "a process which promotes the coordinated development and management of water, land and related resources to maximize economic and social welfare equitably without compromising the sustainability of vital ecosystems" [1]. In general terms, the IWRM has been widely acknowledged as an efficient way of managing water resources sustainably [2]; [3]. The IWRM perspective is guided by a country-specific interpretation of four principles defined by the 1992 International Conference on Water and the Environment [4]. Rests upon three principles that together act as the overall framework:

Social equity ensures equal access for all users (particularly marginalized and more inferior user groups) to an adequate quantity and quality of water to sustain human well-being.

Economic efficiency: bringing the most significant benefit to the greatest number of users possible with the available financial and water resources.

Ecological sustainability: requiring that aquatic ecosystems are acknowledged as users and that adequate allocation is made to sustain their natural functioning.

IWRM practices depend on the context; at the operational level, the challenge is to translate the agreed principles into concrete action. In line with the current global trend to meet the challenges and problems facing water resources, Egypt has embedded its definition of the IWRM within its national water strategy [5]. The IWRM in Egypt; is defined as the process that aims for good water and land management and other related resources to achieve the maximum desired economic benefit with society's welfare without threat to vital economic systems' stability. From a local context, IWRM pays special attention to the following principles:

Freshwater is a limited source but necessary to sustain life. Therefore, its development must be taken seriously into account its quantity and quality.

Development and management of water: through full partnership methodology, which includes the authors of the plans and policies, users and relevant stakeholders at all levels, be directed to achieving economic and social development to serve the objectives of stability in Egypt.

Decentralized water management systems and decisions: include the organizational structure to support and improve the administrative facilities and the consistency and harmony (horizontally and vertically) and local governmental and non-governmental institutions' participation.

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Table 1: IWRM Comparative analysis summary Table

| Country | Drivers for IWRM | Interventions | PROS | CONS |
|---|---|---|---|---|
| Spain | - Economic crisis in the early century<br>- Rural sufferance<br>- Drought<br>- Water-saving (to alleviate droughts, reduce water scarcity and increase water sustainability) | - Conversion of open canals into a pressurized delivery scheme<br>- On-farm drip irrigation<br>- Expand WUA | - Increased agricultural productivity, competitiveness, and export<br>- Higher farmers income<br>- Increased labor productivity<br>- Greater economic water productivity<br>- Higher employment | - No water saving<br>- Unexpected rise in energy costs penalizing pressurize systems (sectoral disconnected water & energy policies) |
| Australia | - Drought<br>-Environmental degradation<br>- Upstream-downstream inequity<br>- Soil salinity build-up<br>- Water-saving for future | - Purchasing' water rights' from farmers<br>- Subsidize farmer to adopt modern irrigation methods with high application efficiency | - Establishing a 'cap' limit thus saving water<br>- Establishing quotas' water rights' for farmers<br>- Allow trading of 'water rights' so that water would be allocated towards the highest water values | - No water saving (Jevons paradox; disregarded water accounting to quantify return flow properly) |
| China | - Unsustainable water resources management: excessive water consumptior<br>- Establishment of balance between supply and demand for ecosystem restoration | -- Adoption of 'National Water Saving Action Plans'<br>- Establishing quotas' water rights' for farmers | - Adoption of 'Consumption-Based Water Management' with extensive use of Remote Sensing for the determination of field 'water consumptive use' or evapotranspiration (ET) | - No water saving at the Macro level |
| Jordan | - Increase land and water productivity<br>- pursuing improvement of distribution efficiency and total irrigation performance | - Annual quota of water consumption<br>- Substitution of open-canal distribution networks with pressurized pipe networks<br>- Operations of the irrigation network are decentralized through WUAs | - A positive, spontaneous response by farmers in adopting modern on-farm irrigation systems (drip, sprinklers, sub-surface) and greenhouses<br>- Increased export of fruits and vegetables<br>- Achievement of high economic water productivity | - No water Saving (Jevons paradox)<br>- Increased competition for water<br>- Lag in benefit uptake by small farmers due to land fragmentation. |

***2.1 IWRM Assessment at the international level***

Experience shows that for IWRM to have a meaningful impact, a considerable political will, strategic planning, and investments from the outset should be supported. In the following table, a summary from similar drought countries is made to present a comparative analysis and lesson learned for the Egyptian case.

***1.2 Assessment of IWRM at the national level***

Several field meetings took place during the year 2018 to conduct a bilateral meeting with some officials to discuss the questionnaire and get their feedback. Egypt's IWRM concept responds to an acceptance that the country is approaching its available water limits and that supply levels may become increasingly variable due to climate change. However, the options for increasing the supply are limited. Looking at the 2016/2017 water balance as the tipping point, any demand increase in one sector will have to be met by a decrease in demand by another. In effect, this is a trade-off between the need for drinking and industrial water and the agricultural water demand. Given their high economic values and socio-economic transformation potential, the demand for potable and industrial water will eventually take priority over agriculture. Therefore, the critical issue can be thought of as not the overall water balance itself but rather the "food balance" in food security.

Clearly, and although potentially controversial and politically costly, the IWRM concept's implied rationale and indeed the implementation process confirms that a new water allocation paradigm is unavoidable. The principles involved are well captured in the 2050 vision, which includes: the provision of adequate water in both quality and quantity for different development purposes, such as agricultural, industrial, navigational, tourism purposes, and the like. However, the challenges, both technical and political, are immense. Demand is rapidly increasing due to a growing population and a growing demand for water by agriculture; horizontal expansion in the desert areas; industrial growth; and rapid urbanization - all of which increase competition for water from multiple uses at the time of climate change. Upon completing the meetings, other meetings with a reference group took place in May 2019 to discuss the consolidated responses outlined in Table 2 below.

***1.3 Applying Multi-Criteria Analysis to assess IWRM***

The approach shall use the 5-point system to assess quantitative and qualitative indicators. The assessment shall be made twice per year by a reference group including representatives from the governorate, central government, and academia. The objective shall be to create a water governance framework at a local level, composed of a traffic-light system of specifically agreed sector governance indicators and complimented by an action plan with investment and financial requirements. The disbursement of such financial flows and delivery of required water resources shall be linked with the achievement of the agreed indicators. The governorate water council will annually discuss the governorate water action plan. A governorate should score (A, equivalent to an 85%-point score on weighted average) in the following fiscal year to be eligible for the previous year's full water quota.

Table 2: Egyptian Case IWRM Consolidated Results of the assessment

| **Relevant Evaluation Question** | **Conclusive Answers** |
|---|---|
| How do water service providers perceive IWRM as currently applied, and how should it be implied in the future? | At present, the IWRM concept, given the network's complexity and limited staff availability, is limited to integrating irrigation and drainage service delivery. Nonetheless, many stakeholders acknowledge the need to embrace the broader concept while availing adequate tools such as Smart Decision Support Systems, water management by flows, and transferring control at lower levels to WUAs. |
| How successful has the effort to integrated irrigation and drainage been from an institutional and operational perspective? | Central Stakeholders generally acknowledge that the process has been complex and indeed constrained in some cases. The main reason cited at the mid-level concerns the difference between irrigation service provision - which is the responsibility of an Irrigation Sector - and drainage –an EPADP. Therefore, it was also acknowledged that this has led to significant difficulties in melding mandates, reporting lines, management structures, critical decision-making, and employment packages. Indeed, the irrigation and drainage directorates should be implemented at the main canal hydrological boundary. |
| To what extent does the current MWRI structure facilitate or constrain IWRM? Since IWRM concerns all water-using sectors and services, how should other ministries be reflected in the institutional landscape? | |
| To what extent are service providers constrained or enabled by the shift towards IWRM? | Constraints were more broadly reported, and all in some way concerned inadequate coordination at the field level. Successful mixing of bulk irrigation and drainage water is, for instance, was reported. However, the responsible parties reported severe shortfalls in terms of both the finance and personnel needed to operate, maintain, repair, and replace the electro-mechanical equipment concerned at the field level.<br>Similarly, concerning irrigation, financial shortfalls were reported for the increasingly urgent need to fix existing problems concerning tail escapes and gates in the irrigation channels and increase the canal system's physical distribution as a water-saving measure. |
| To what extent do the current financing arrangements facilitate or constrain successful IWRM, and if the latter, what solutions might be appropriate? | |
| To what extent does the available equipment and its maintenance help or hinder IWRM? | |
| What are the pressing research priorities as perceived by the service providers? | Central Stakeholders identified various research priorities, and they include the need:<br>to adopt a more appropriate IWRM concept to meet water use and allocation challenges expected in the future.<br>To better understand water's role in the national economy and what this will mean for IWRM when competition for water becomes an ever-intensifying reality rather than a matter for future consideration.<br>An Integrated policy, legal and regulatory framework to meet the challenges of increasing competition for water following IWRM principles.<br>Broad implementation of tile and controlled sub-surface drainage.<br>To understand better the potential role of desalination.<br>To identify better options for coastal zone management. |
| What are the service providers' opinions and priorities concerning inter-agency cooperation and the integration of irrigation and drainage functionality? | There is an embryonic acknowledgment of the need for inter-sectoral cooperation and coordination and an appropriate institutional approach to these ends. |
| What data and information resources are available and used by service providers when implementing and practicing IWRM? | The water sector is characterized by a large amount of potentially significant water management data. However, its integration is a challenge given data inconsistency and, to a certain extent, the absence of unified. It was also reported that the kind of data needed for water productivity monitoring is there, somewhere in the institutional landscape, but is not used by the water sector itself. |
| What gaps, if any, need filling in the legal and regulatory framework to make their work easier? | See above re-research needs. |

The following table shows the proposed financial appropriations per score (Table 3). The starting point shall be the current water allocations. For Egypt, the total water shortage could be measured by various options. The case at hand will be calculated as the difference between system input (freshwater resources, shallow Ground Water, desalination, and rainfall) and the total system uses (including potable water, industrial water, agriculture water, and evaporation); for more details, check Table 3. From the above table, we could deduce that the water shortage differs from one governorate to another and varies in terms of availability. This difference could have two reasons: either the governorate's consumption side is inaccurate for various reasons such as (illegal agricultural water consumption, illegal industrial water consumption or unaccounted for, or erroneous water withdrawal for potable purposes). The other option, supported by the "zero-summation" of the water shortage check, is that the excess water is flowing out of the system to another governorate (considered outflow discharge).

In that case, the system shortage should be recalibrated to 0% instead. In our analysis, we shall use the two options and other indicators to assess the overall system productivity and propose an objective function to optimally redistribute water resources, at the governorate level, based on water productivity and efficiency, to implement IWRM on a practical level.

### *1.4 Water Balance automated system*

A visual- basic macro worksheet to represent the water balance at the governorate level to assist rapid decision making; is developed. Figure 1 shows an example of the model prepared for sohag Governorate. Also, the model can produce regional water balances (Figure 2**Error! Reference source not found.**).

The model also includes (in orange boxes) the calculations related to system efficiencies per sector and type of use (Potable water efficiency, Agricultural use Efficiency, Total System Efficiency, and Governorate Stress Indicator). Also, average water shares for agriculture, municipal, and total water resources are automatically calculated by the model. Finally, the economic rate of return per sector is calculated as well. This tool could be handy to decision-makers to quantify overall water management indicators and assess progress.

### *1.5 System Application*

A merging between multi-criteria analysis (MCA), Geographic Information systems (GIS), and optimization systems shall be introduced to present the proposed mechanism. The system will be based on the concept of water security and the work implemented by the Asian Development Bank (ADB) water Security Index (ADB,2020) [17] yet adopted to the National Water Resources Plan 2037 (NWRP 2037).

Table 3: Overall governorate-based water balance

| I | Governorate | Water Diversion Nile BCM | Total System renewable resources BCM | Drain & WW reuse BCM | Shallow GW BCM | Total System input (BCM) | Total system uses BCM | Total system shortage/surplus BCM | % Water Short-age |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Cairo | 2.457 | 2.457 | 0.000 | 0.000 | 2.457 | 2.069 | -0.39 | -15.8 |
| 2 | Alexandria | 2.414 | 2.416 | 0.230 | 0.000 | 2.646 | 3.331 | 0.68 | 25.9 |
| 3 | Port Said | 0.670 | 0.676 | 0.236 | 0.000 | 0.912 | 0.502 | -0.41 | -45 |
| 4 | Suez | 0.442 | 0.466 | 0.261 | 0.000 | 0.727 | 0.387 | -0.34 | -46.8 |
| 5 | Damietta | 0.710 | 0.719 | 0.324 | 0.000 | 1.043 | 1.992 | 0.95 | 91 |
| 6 | Dakahlia | 5.193 | 5.271 | 1.558 | 0.000 | 6.829 | 5.276 | -1.55 | -22.7 |
| 7 | Sharqia | 5.166 | 5.468 | 1.172 | 0.200 | 6.840 | 7.530 | 0.69 | 10.1 |
| 8 | Qalyubia | 2.251 | 2.415 | 0.522 | 0.013 | 2.950 | 2.518 | -0.43 | -14.7 |
| 9 | Kafr sheikh | 3.702 | 3.703 | 1.185 | 0.000 | 4.888 | 4.808 | -0.08 | -1.6 |
| 10 | GHARBIA | 2.916 | 3.072 | 0.585 | 0.041 | 3.697 | 2.990 | -0.71 | -19.1 |
| 11 | Monufia | 1.889 | 2.082 | 0.673 | 0.098 | 2.853 | 2.949 | 0.10 | 3.4 |
| 12 | Beheira | 5.863 | 8.515 | 1.85 | 1.540 | 9.960 | 12.422 | 2.38 | 24.7 |
| 13 | Ismailia | 2.171 | 2.210 | 0.560 | 0.045 | 2.815 | 2.691 | -0.12 | -4.4 |
| 14 | GIZA | 1.189 | 1.846 | 0.525 | 0.200 | 2.571 | 5.100 | 2.53 | 98.4 |
| 15 | Beni Suef | 2.295 | 2.310 | 0.496 | 0.060 | 2.866 | 2.375 | -0.49 | -17.1 |
| 16 | Fayoum | 2.690 | 2.690 | 0.990 | 0.000 | 3.680 | 3.425 | -0.26 | -6.9 |
| 17 | Minya | 3.409 | 3.684 | 0.745 | 0.400 | 4.829 | 3.350 | -1.48 | -30.6 |
| 18 | Asyut | 2.164 | 2.362 | 0.250 | 0.108 | 2.720 | 3.017 | 0.30 | 10.9 |
| 19 | Sohag | 2.438 | 2.567 | 0.339 | 0.090 | 2.996 | 3.027 | 0.03 | 1.1 |
| 20 | Qena | 1.420 | 1.678 | 0.411 | 0.100 | 2.189 | 2.283 | 0.09 | 4.3 |
| 21 | Aswan | 1.991 | 2.002 | 0.000 | 0.000 | 2.002 | 2.280 | 0.28 | 13.9 |
| 22 | luxor | 1.220 | 1.223 | 0.238 | 0.100 | 1.561 | 1.225 | -0.34 | -21.5 |
| 23 | Red Sea | 0.000 | 0.064 | 0.000 | 0.000 | 0.064 | 0.104 | 0.04 | 63.1 |
| 24 | New Valley | 0.000 | 2.590 | 0.000 | 0.000 | 2.590 | 2.591 | 0.00 | 0 |
| 25 | Matrouh | 0.330 | 1.791 | 0.000 | 0.000 | 1.791 | 0.662 | -1.13 | -63.1 |
| 26 | South Sinai | 0.500 | 0.695 | 0.600 | 0.070 | 1.365 | 0.921 | -0.36 | -32.5 |
| 27 | North Sinai | 0.010 | 0.071 | 0.000 | 0.015 | 0.086 | 0.101 | 0.02 | 17.6 |
| **TOTAL** | | 55.5 | 63.34 | 13.51 | 3.08 | 79.93 | 79.93 | 0.0 | 20.7% |

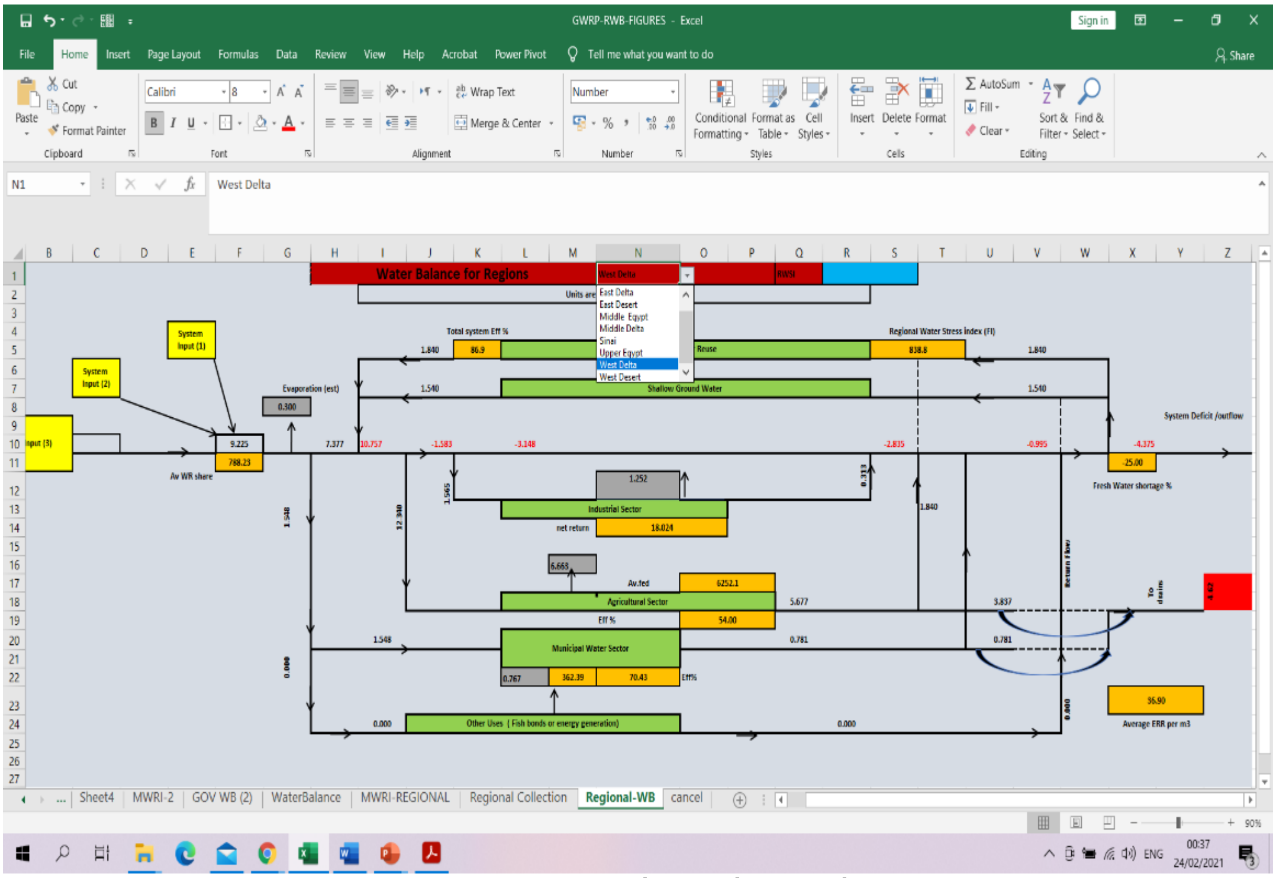


Figure 1: Upper Egypt Regional Water Balance example

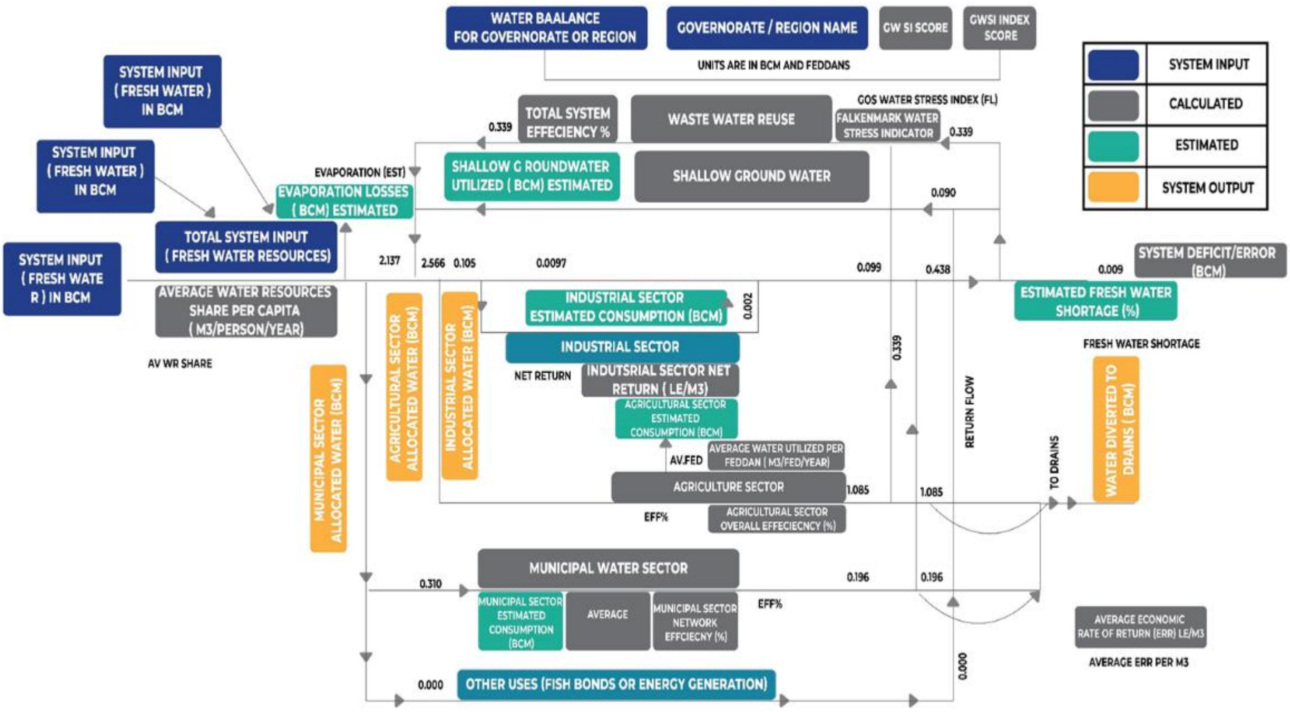


Figure 2: Water Balance Model Outline

It should be noted that the "water security" concept is evolving in respect to time to become the goal of implementing IWRM (Beek, E. van and W. Lincklaen Arriens, 2014) [38]. If we could consider that IWRM is a process, water security would be its ultimate goal (Grey, D. 2019) [39]. One of the most widely cited and used definitions of water security is this:

"the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments and economies." (Grey, D. and C. W. Sadoff. 2007) [40].

## 2 Methodology inputs

To best design the model, the following input data are collected, calculated, or estimated.

**System Input data**: which contains all data related to the water resources inputs (freshwater resources, reuse, and shallow groundwater).

**System total uses**: which contains all data related to water resource uses (potable water, industrial uses, agricultural uses, evaporation, etc.).

**System water efficiency key indicators**: which include data related to water efficiency indicators (such as water allocation per feddan, water allocation per person, wastewater coverage, NRW in the potable water network, Average Irrigation efficiency, percentage of reused water)

**Water productivity indicators**: which include data related to the overall water productivity, and either calculated at governorate level based on ready economic reports, or calculated from Agricultural Sector Model of Egypt ASME, or estimated if no data is available (for the sake of illustration).

### *2.1 Objective Function*

Any optimization method consists of a 1- objective function, 2- boundary conditions, 3- penalty function. in the case of water allocation based on IWRM and water security, the objective function shall be based on an MCA as follows

Water shortage Allocation at governorate level (Governorate Water Security Index- GWSI) = X1(Quality water security) + X2(Urban water security) + X3(Rural water security) + X4 (Economic and equity water security). Each item shall represent one pillar of the NWRP and shall be calculated as a percentage of governorate level indicators achievement.

**X1** = Weighted (WQI)*Weighted (Water shortage index). The highest score governorate or region shall be given 100, and the rest shall be relatively assigned to it.

**X2** = Weighted NRW * Weighted WW coverage * Weighted Industrial Water eff * Fresh water index. The highest score governorate or region shall be given 100, and the rest shall be relatively assigned to it.

**X3** = Weighted Irrigation Efficiency Index * Weighted Water Conveyance Index * Water Availability for agriculture index * Weighted reuse index. The highest score governorate or region shall be given 100, and the rest shall be relatively assigned to it.

**X4** = Weighted Economic agriculture return index * Weighted Economic Municipal return index * Weighted Economic Industrial return index * Water Equity Indicator. The highest score governorate or region shall be given 100, and the rest shall be relatively assigned to it.

For the weights of X1-X4: this could be assigned based on the importance of each indicator in the whole water cycle, or, as a start, be all given equal weight (25% each). Then, each governorate's scores will be calibrated based on their results, and water deficit/ freshwater delivery shall be redistributed based on their overall score (GWSI). Table 4 detailed the selected indicators and their description. The suggested approach is to implement it at the basin level (main canals), then at the governorate level, to ensure adequate and realistic water allocation. Figure 3 summarizes the proposed procedure.

Table 4: Proposed Governorate Water Security Index indicators

| Indicator | Acronym | Description | Data source | Index |
|---|---|---|---|---|
| Water Quality Index | WQI | Shall be calculated as the total number of passed samples in the water distribution network (No of approved /Total Number of tests) | Field reports | X1 |
| Water Shortage Index | WSSI | Total system resources / Total system uses | Calculated | X1 |
| Potable Water efficiency Index | PWEI | 1/Non-Revenue Water % | Calculated | X2 |
| Wastewater Coverage Index | WWCI | Wastewater Coverage % | Calculated | X2 |
| Industrial Water Efficiency index | IWEI | Industrial water efficiency (as a % of onsite reuse). | Estimated | X2 |
| Fresh Water Index | FWI | 1/ ratio of fresh water to total water resources | Calculated | X2 |
| Irrigation Efficiency Index | IIEEF | Irrigation Efficiency | Calculated | X3 |
| Water Conveyance Efficiency Index | WCEI | Conveyance Eff | Calculated | X3 |
| Water availability for Agriculture Index | WAA | 1/ (average water consumption per feddan / national average) | Calculated | X3 |
| Water reuse index | WREI | Reuse resources/ total resources | Calculated | X3 |
| Economic Rate of Return for water in agriculture | ERRA | ERR per cubic meter of water in the agriculture sector | Calculated | X4 |
| Economic Rate of Return for water in Municipal Sector | ERRM | ERR per cubic meter in the municipal sector | Calculated | X4 |
| Economic Rate of Return for water in Industrial sector | ERRI | ERR per cubic meter in the industrial sector | Calculated | X4 |
| Water Equity Index | WEQI | 1/ (average water consumption per person / national average) | Calculated | X4 |


Figure 3: Proposed methodology

Table 5: Governorate Water Security index Outlook

| Level | | Indicator(s) | Means of Verification | Weighting System |
|---|---|---|---|---|
| Governorate Level | | Governorate Water Security Index | | Sum (P1,P4) |
| Specific Objectives: NWRP pillars | | | | |
| P1 | Improve Water Quality | Water Quality Index Score reaches xx % in the three sectors (water TP, WW TP, main canal) | Quality surveys, sampling, and periodical reporting | 25% |
| P2 | Rationalize Water Use | Water losses per municipal sector reach xx %<br>Water Efficiency at field level reaches xx %<br>Overall water productivity reaches xx LE.M3 across all sectors<br>Annual cost (or expenditures) of transferring water per unit area (feddan) decrease by xx% | Official reports | 25% |
| P3 | Enhance Availability of Fresh Water Resources | Water reuse (conditioned that water quality is acceptable) reaches xx %<br>Increase of non-traditional water production (rainfall – Groundwater) by xx % | Governorate Water Balance and flow measurements across main canals | 25% |
| P4 | Improve the Enabling Environment for IWRM (planning and implementation) | The water council approves a revised IWRM policy<br>No public hearings were conducted for IWRM approval<br>% of population satisfaction increase by xx %<br>% of WUA/BCWUA achieving 90% success in equal water delivery at canal tails<br>The number of complaints in the different general directorates decreases by xx%<br>Number violations and what has been removed increase by xx% | Official reports<br><br>A public survey by the Information and Decision Support Center (ISDC) | 25% |

## 3 Water Balance Model and GWSI results analysis

Following the water balance model's preparation and establishing the GWSI matrix, the following section shall analyse the results obtained from the model and procedure against the National Water Resources Plan 2037 objectives and follow the IWRM goals. Table 5 provides the GWSI matrix logical framework approach that addresses the water shortage and competitiveness at both governorate and sub-regional levels. While Table 6 shows the GWSI index to the Egyptian governorates at a national level. Finally, Table 7 shows the GWSI at the regional level.

Table 6: Summary table for all GWSI indices and final scores

| Governorate | Region | X1 (Water Quality security) | Weighted X1 | X2 (Urban Water Security) | Weighted X2 | X3 (Rural Water security) | Weighted X3 | X4 ( Economic Water Security) | Weighted X4 | GWSI |
|---|---|---|---|---|---|---|---|---|---|---|
| Cairo | Capital | 0.307 | 0.088 | 0.355 | 0.097 | 0.56 | 0.07 | 14.4 | 0.250 | 0.5 |
| Alexandria | West Delta | 0.700 | 0.200 | 0.914 | 0.250 | 1.59 | 0.20 | 7.8 | 0.135 | 0.8 |
| Port Said | East Desert | 0.517 | 0.148 | 0.193 | 0.053 | 0.34 | 0.04 | 1.4 | 0.023 | 0.3 |
| Suez | East Desert | 0.808 | 0.231 | 0.127 | 0.035 | 0.30 | 0.04 | 1.2 | 0.020 | 0.3 |
| Damietta | Delta East | 0.412 | 0.118 | 0.403 | 0.110 | 0.33 | 0.04 | 3.1 | 0.054 | 0.3 |
| Dakahlia | Delta East | 0.719 | 0.205 | 0.413 | 0.113 | 0.46 | 0.06 | 4.3 | 0.074 | 0.5 |
| Sharqia | Delta East | 0.440 | 0.126 | 0.390 | 0.107 | 0.36 | 0.05 | 6.4 | 0.111 | 0.4 |
| Qalyubia | Middle Delta | 0.523 | 0.149 | 0.375 | 0.102 | 0.37 | 0.05 | 3.6 | 0.062 | 0.4 |
| el-sheikh Kafr | Middle Delta | 0.853 | 0.243 | 0.327 | 0.090 | 0.29 | 0.04 | 2.7 | 0.046 | 0.4 |
| GHARBIA | Middle Delta | 0.876 | 0.250 | 0.371 | 0.101 | 0.39 | 0.05 | 3.2 | 0.055 | 0.5 |
| Monufia | Middle Delta | 0.816 | 0.233 | 0.380 | 0.104 | 0.36 | 0.05 | 2.7 | 0.046 | 0.4 |
| Beheira | West Delta | 0.760 | 0.217 | 0.304 | 0.083 | 0.17 | 0.02 | 4.9 | 0.085 | 0.4 |
| Ismailia | East Desert | 0.544 | 0.155 | 0.161 | 0.044 | 0.39 | 0.05 | 6.6 | 0.115 | 0.4 |
| GIZA | Middle Egypt | 0.375 | 0.107 | 0.296 | 0.081 | 0.39 | 0.05 | 12.1 | 0.211 | 0.4 |
| Beni Suef | Middle Egypt | 0.741 | 0.212 | 0.306 | 0.084 | 0.36 | 0.05 | 4.2 | 0.072 | 0.4 |
| Fayoum | Middle Egypt | 0.737 | 0.210 | 0.290 | 0.079 | 0.17 | 0.02 | 5.8 | 0.100 | 0.4 |
| Minya | Middle Egypt | 0.870 | 0.248 | 0.170 | 0.046 | 0.37 | 0.05 | 3.5 | 0.061 | 0.4 |
| Asyut | Middle Egypt | 0.809 | 0.231 | 0.245 | 0.067 | 0.21 | 0.03 | 2.2 | 0.038 | 0.4 |
| Sohag | Upper Egypt | 0.841 | 0.240 | 0.240 | 0.066 | 0.21 | 0.03 | 2.5 | 0.043 | 0.4 |
| Qena | Upper Egypt | 0.801 | 0.229 | 0.209 | 0.057 | 0.14 | 0.02 | 1.6 | 0.028 | 0.3 |
| Aswan | Upper Egypt | 0.623 | 0.178 | 0.214 | 0.059 | 0.13 | 0.02 | 1.5 | 0.026 | 0.3 |
| luxor | Upper Egypt | 0.611 | 0.174 | 0.198 | 0.054 | 0.17 | 0.02 | 5.0 | 0.087 | 0.3 |
| Red Sea Governorate | East Desert | 0.224 | 0.064 | 0.180 | 0.049 | 0.00 | 0.00 | 0.4 | 0.007 | 0.1 |
| New Valley | West Desert | 0.234 | 0.067 | 0.165 | 0.045 | 0.26 | 0.03 | 0.8 | 0.013 | 0.2 |
| Matrouh | West Desert | 0.273 | 0.078 | 0.099 | 0.027 | 1.95 | 0.25 | 0.5 | 0.009 | 0.4 |
| North Sinai | Sinai | 0.364 | 0.104 | 0.124 | 0.034 | 0.04 | 0.00 | 2.2 | 0.038 | 0.2 |
| South Sinai | Sinai | 0.089 | 0.025 | 0.077 | 0.021 | 0.58 | 0.07 | 3.7 | 0.065 | 0.2 |

Table 7: Summary table for all GWSI indices and final scores at Regional Level

| Region | Water Diversion Nile (BCM) | Total System fresh resources (BCM) | Average WR m3/per/yr | Total area irrigated (000 FED) | Total System input (BCM) | The total system uses BCM | Total system shortage BCM | Total System efficiency | Faulkner Mark Indicator (FI) | RWSI |
|---|---|---|---|---|---|---|---|---|---|---|
| **Capital** | 2.5 | 2.5 | 251.0 | 19.6 | 2.5 | 2.1 | -0.4 | 56.8 | 251.0 | 0.6 |
| **East Delta** | 11.1 | 11.5 | 733.5 | 1685.8 | 14.7 | 14.8 | 0.1 | 69.1 | 721.4 | 0.5 |
| **East Desert** | 3.3 | 3.4 | 1054.3 | 522.4 | 4.5 | 3.7 | -0.8 | 50.9 | 1027.3 | 0.4 |
| **Middle Egypt** | 11.7 | 12.9 | 490.5 | 1882.2 | 16.7 | 17.3 | 0.6 | 66.9 | 476.1 | 0.6 |
| **Middle Delta** | 10.8 | 11.3 | 597.7 | 1525.5 | 14.4 | 13.3 | -1.1 | 59.7 | 578.5 | 0.6 |
| **Sinai** | 0.5 | 0.8 | 1343.4 | 118.6 | 1.5 | 1.0 | -0.4 | 47.3 | 1183.6 | 0.2 |
| **Upper Egypt** | 7.1 | 7.5 | 659.6 | 1047.6 | 8.7 | 8.8 | 0.1 | 52.8 | 649.8 | 0.4 |
| **West Delta** | 8.3 | 9.2 | 788.2 | 1973.7 | 12.6 | 15.8 | 3.1 | 86.9 | 838.8 | 0.6 |
| **West Desert** | 0.3 | 4.4 | 6160.9 | 409.7 | 4.4 | 3.3 | -1.1 | 23.0 | 2179.8 | 0.3 |
| **SUM** | 55.5 | 63.3 | | | 79.9 | 79.9 | 0.0 | | | |

Table 7 shows that although the water balance at the national level is a closed system, certain discrepancies and anomalies exist at the regional level. The justification is that the regional boundaries are not totally in line with hydrological delineation boundaries. As the network is highly connected with no clear separation points, return flow from one region to the other could exist and create the variance spotted in the above table.

The following graph shall show the relationship between GWSI, an average return rate, and water shortage to understand better the above table presented in figures Figure 4 to Figure 7.

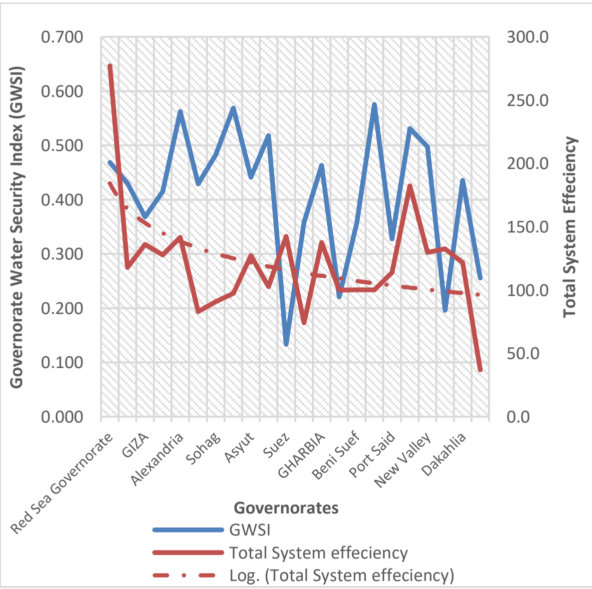


Figure 4: Relationship between GWSI and total system efficiency

Except for Suez and Cairo (where a considerable concentration of industrial activities affected the overall GWSI), a clear, directly proportional link between total system efficiency and increased GWSI confirms the index measure's effectiveness suitability IWRM and water management at strategic levels.

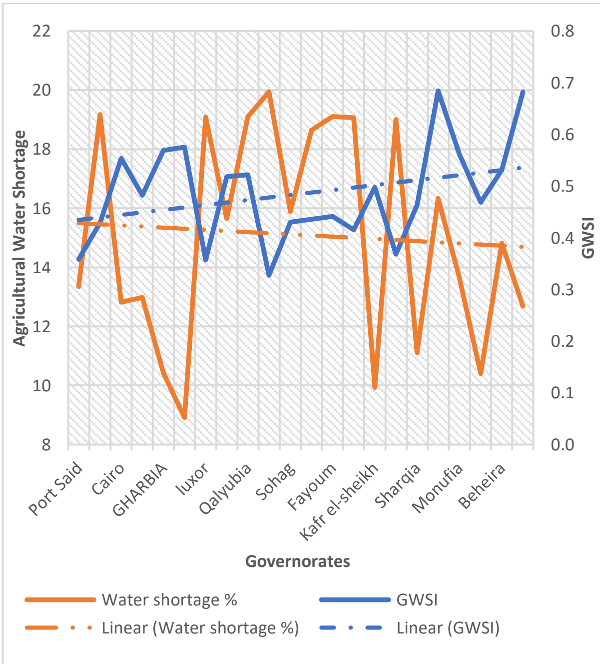


Figure 5: Relationship between GWSI and Agricultural Water Shortage percentage

The above figure shows an inverse proportional relationship between water shortage in agriculture and GWSI scores in most governorates. This correlation is accurate, except in urban governorates like port said, or in matrouh and new valley, where surface water is not their primary source of water feeding. It is noted that the two trend lines intersect at a water shortage level of 15% (water availability for agriculture of 85%) considered the optimum water allocation at the current water availability levels.

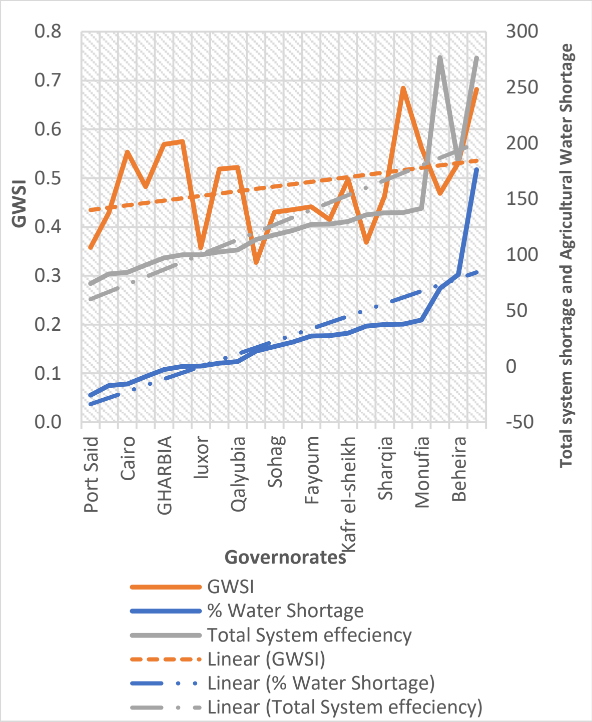


Figure 6: Relationship between GWSI, total system water shortage, and agricultural water shortage

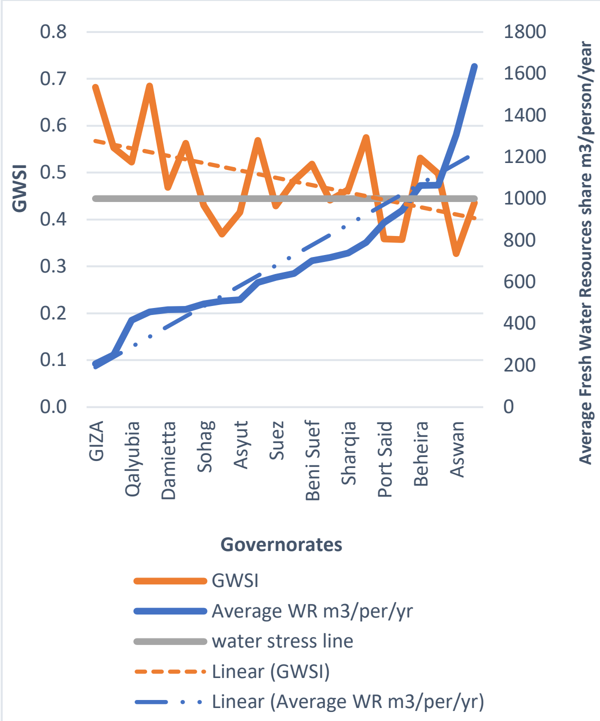


Figure 7: Relationship between GWSI and average water resources share per person at governorate level

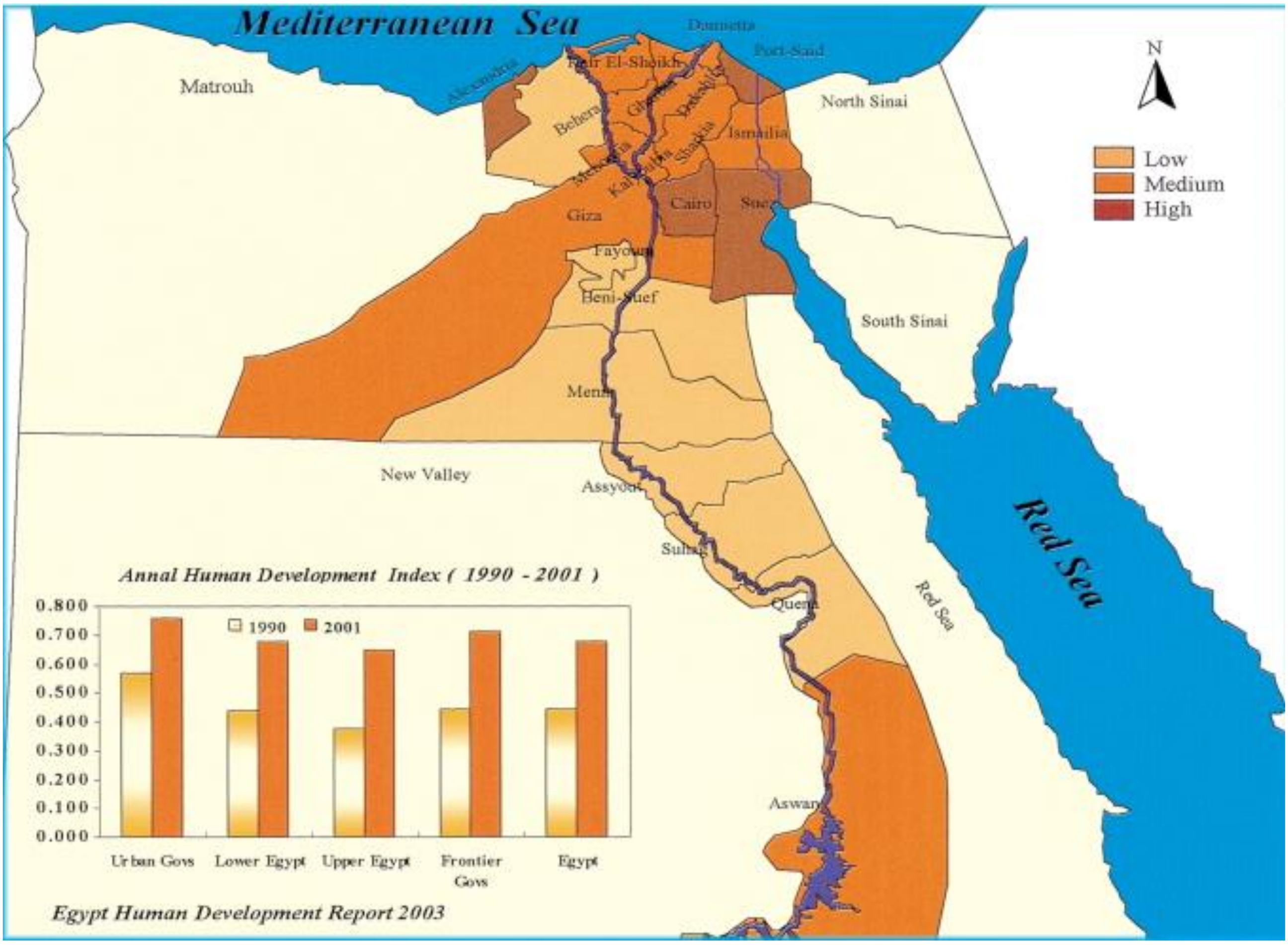


Figure 8: HDI index of Egypt

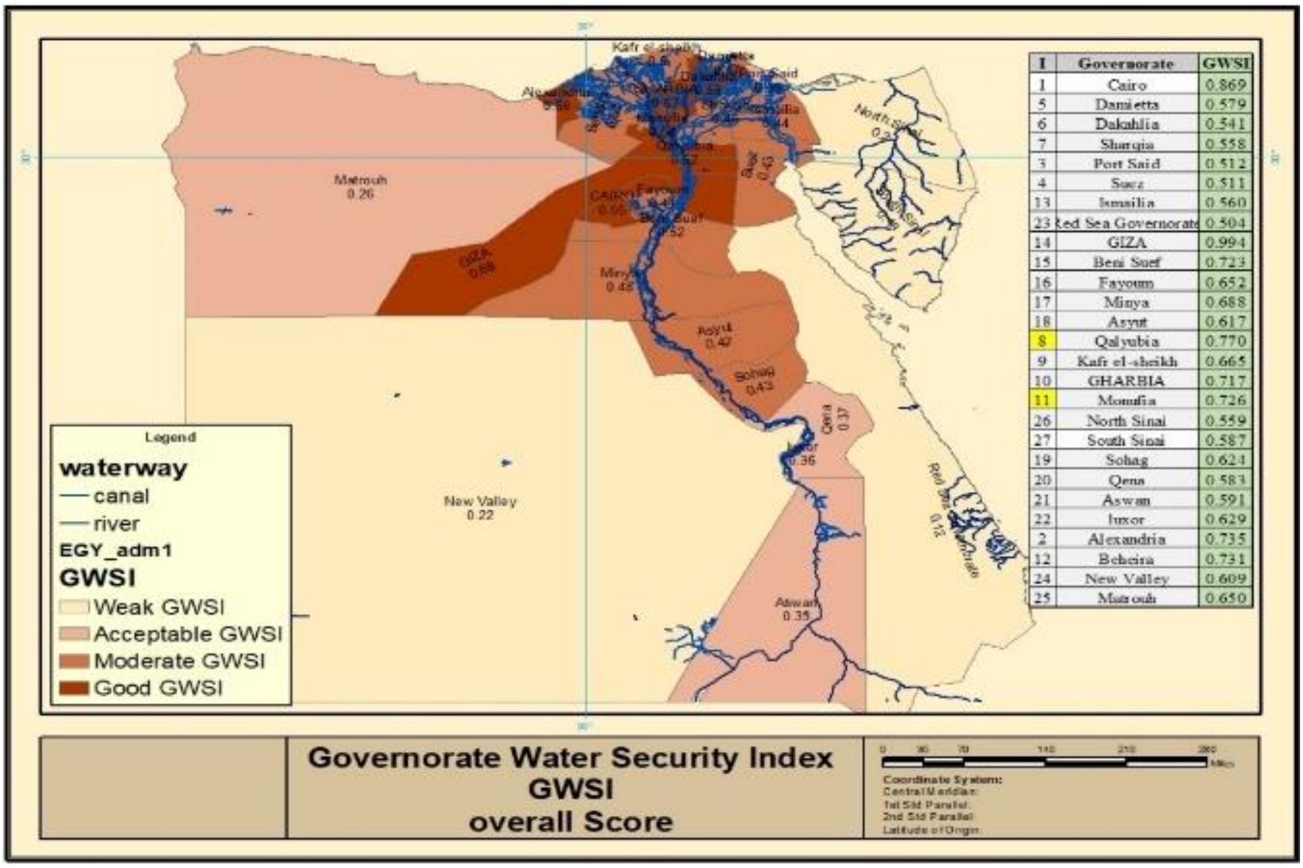


Figure 9: GWSI index representation

The above figure confirms findings made earlier regarding the directly proportional link between shortage levels and increases water security. From the above figure (Figure 7), it is apparent that a clear inversely proportional link between the water security index and the average share of water resources per governorate. The optimal figure is at the cross point of two curves equal to 1000 m3/year/person, which is also the international threshold for water stress. Table 8 confirms that the use of GWSI matches the objectives of the NWRP 2037.

Table 8: Relationship between GWSI and main IWRM indicators

| Indictor | Relationship with Governorate Water Security |
|---|---|
| Total System Efficiency | Directly Proportional |
| Agricultural Efficiency | Directly Proportional |
| Total System shortage % | Directly Proportional |
| ERR per $m^3$ (Water Productivity) | Directly Proportional |
| Self Sufficiency | Directly Proportional |
| Water Availability | Inversely Proportional |

## 4 Using GIS as a tool for Water Accounting and Decision Support Systems

Many have characterized Geographic Information Systems (GIS) as one of the most powerful of all information technologies because it focuses on integrating knowledge from multiple sources and creates a crosscutting environment for collaboration. GIS is a system for managing, analysing, and displaying geographic knowledge and representing various information sets. The integration of GIS and mathematical models could provide an excellent ground to apply the concepts of water account in a user-friendly manner. To be better understand what does it mean, we have to look at the general terms defining the water accounting (WA) concept; which is a systematic quantitative assessment of the status and trends in water supply, demand, distribution, accessibility, and use in specified domains, producing information that informs water management, governance, and science, supporting sustainable development outcomes for society and the environment (FAO, 2012, 2016) [41] [42]; Therefore, through GIS software to provide a suitable spatial analysis tool for decision making, a spatial-based quantitative and qualitative assessment of water supply and demand trends could be applied. The produced analysis could provide an excellent, user-friendly, easily understood framework to decision-makers and politicians without the need to understand the whole background dynamics, equations, and interlinkages. Set of tools to collect, store and recuperate information by transforming and organizing data gathered from the real world into a particular set of goals. In the following figures (Figure 8 to Figure 12), an illustration of GIS abilities to visualize data for better decision making and analysis shall be provided.

## 5 Analysis at Governorate Levels

Figure 8 shows the representation of GWSI over the GIS Decision Support System (GIS-DSS). The figure deduced that the index increases as we go downstream the Nile River (which is inversely proportional with the total amount of water available). This relationship means that, contrary to initial assumptions, the GWSI increases where water availability decreases, forcing the local level decision-makers to obtain more efficient and conservative measures to secure their local needs. Figure 9 shows the UNDP Human development report's outcomes, matching the Human Development Index (HDI) and the GWSI. When comparing the two figures, a close, directly proportional link between the GWSI, which in return means a development in the concept of IWRM as proven earlier, and the HDI, which in return means a development in social and economic aspects. According to the UNDP website [43], the official definition of the HDI is "The Human Development Index (HDI) is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The standard of living dimension is measured by gross national income per capita". Figure 10 shows the weighted Urban Water Security Index, an analysis of the water and wastewater sector development, and water productivity in the Municipal sector. The figure shows that the delta region and middle Egypt score relatively better than upper Egypt and border governorates. This analysis suggests that further development in this sector should be directed to upper Egypt and Sinai to ensure equal distribution of services, positively affecting overall water security and IWRM. Figure 11 shows the same analysis, yet for the rural water security index, mainly concerned with agricultural development and water productivity in the agricultural sector. The results show that better water productivity and management occur in the eastern delta region and middle Egypt. Therefore, from the above figure, investment dedicated to irrigation improvement, financed via the private sector and local banks, could focus on that region with higher productivity. In comparison, infrastructure investment projects could further focus on the western delta region to improve the overall efficiency agricultural level. Figure 12 shows the Economic and Institutional water security index, mainly concerned with economical water productivity and socio-economic development. The figure shows a general weakness in this aspect, which is relevant to the overall national performance in economic water productivity. This weakness suggests a further look at the means to enhance the economic rate of return per unit of water.

## 6 Analysis at Regional Level

At the regional level, the regional WSI assessment would help redistribute water based on regional water productivity and subsequently reassign water investment financial allocation on a more structured approach. The reason for suggesting the redistribution of water at the regional level, rather than governorate level, is the following: i) it is challenging at such an early stage, and due to anomalies noted in the water balance, as well as the uncertainty of main canals capability to hold additional flows, to set a new reallocation at governorate level without a deep-dive analysis that is beyond the scope of this study, and ii,) dealing with nine regions, for water distribution is far less complicated than dealing with 27 Governorates. Also, it matches the government plans for stepwise decentralization of water management.

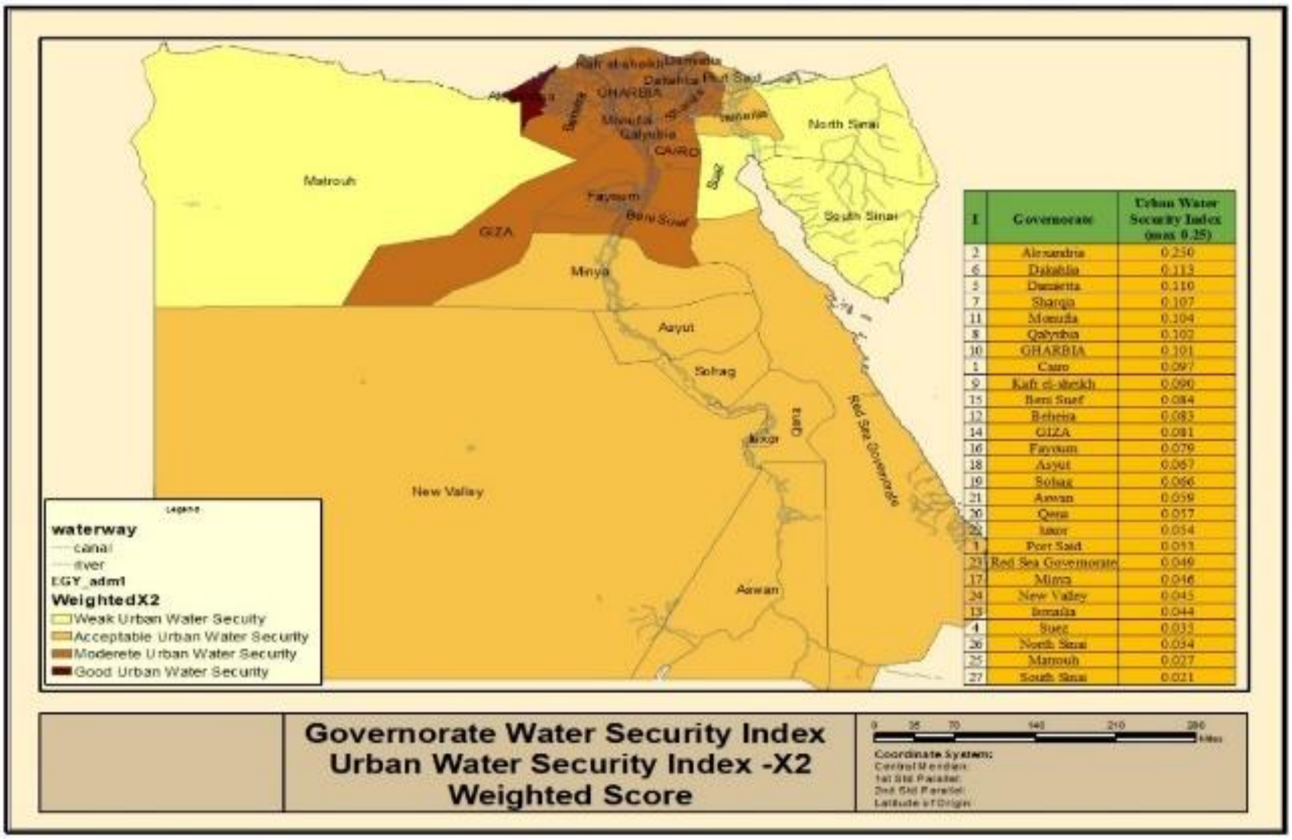

Figure 10: Urban Water Security Index – X2 results over the GIS-DSS

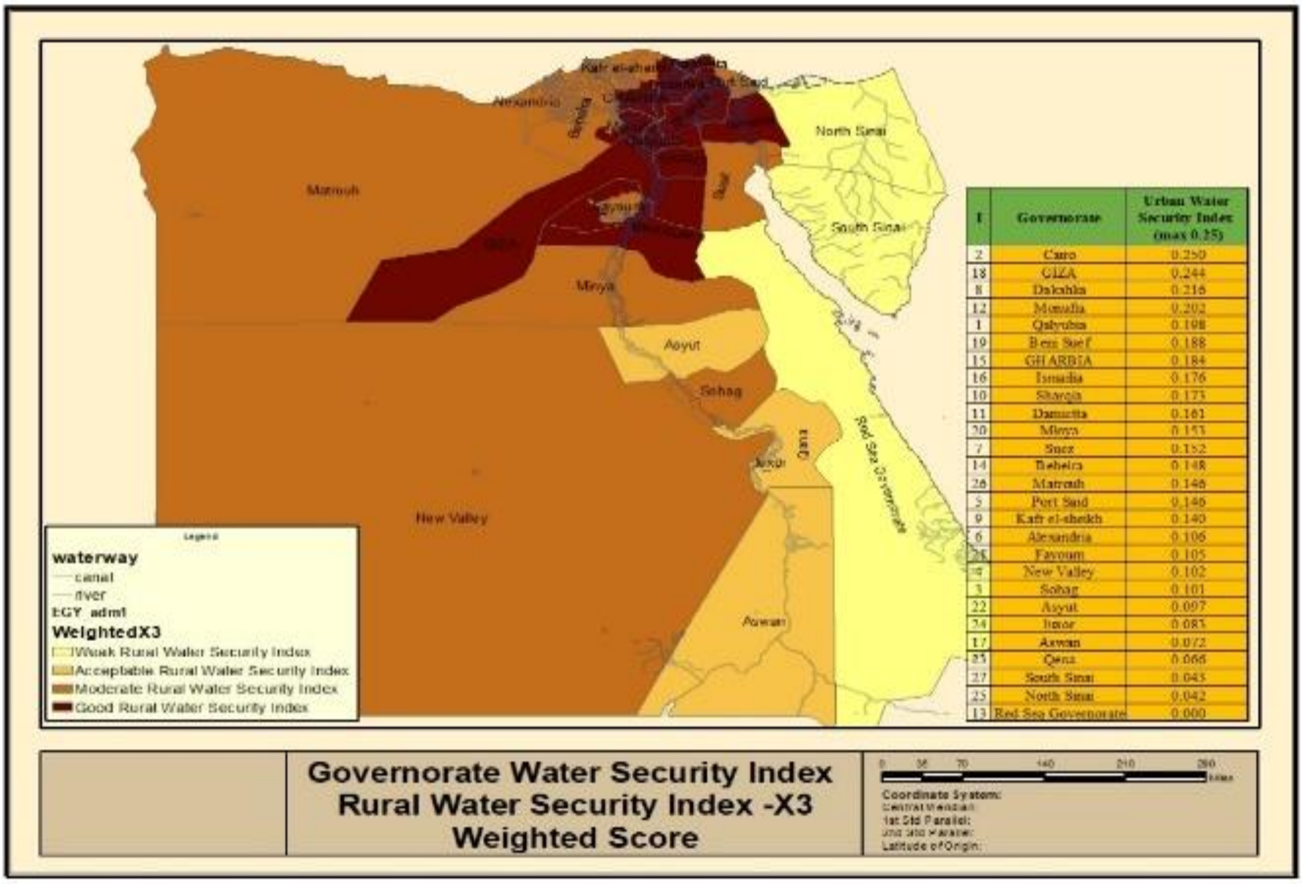


Figure 11: Rural Water Security Index – X3 results over the GIS-DSS

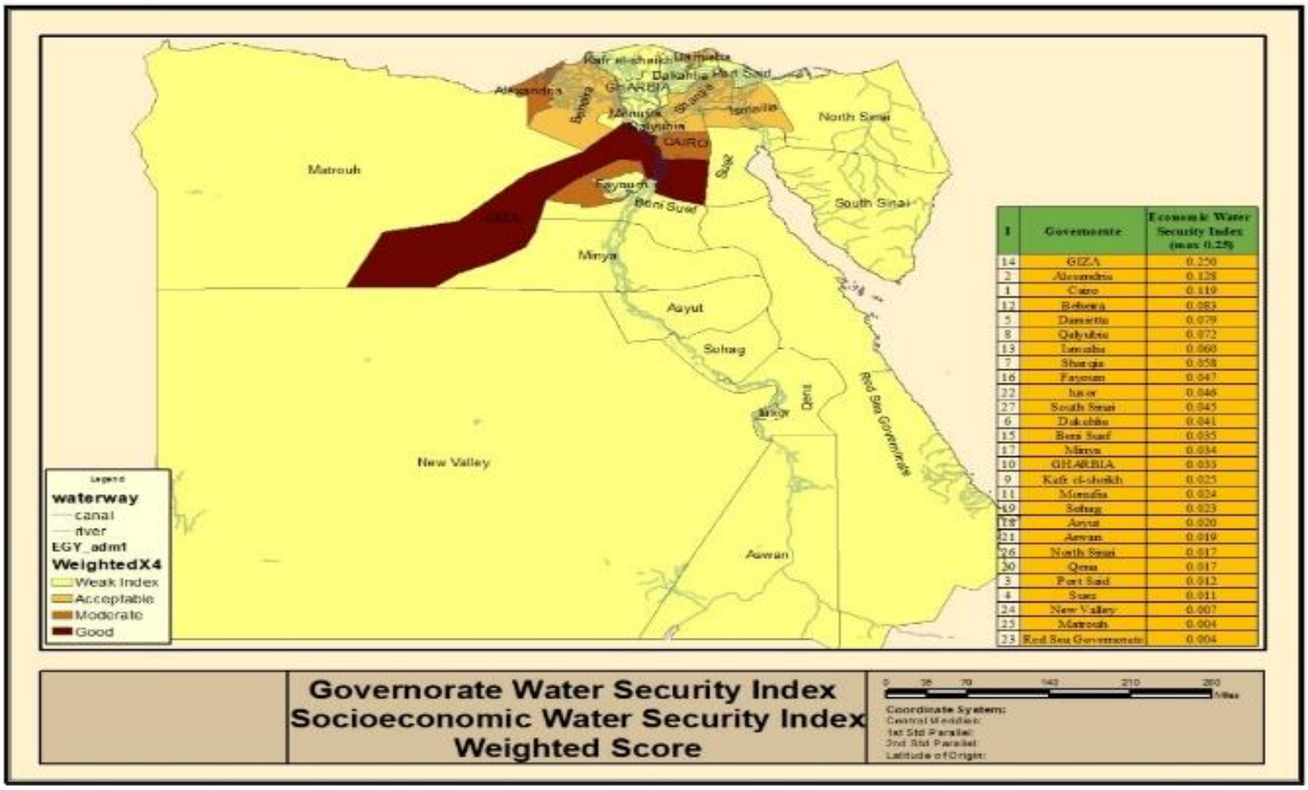


Figure 12: Economic and Institutional water Security Index – X4 results over the GIS-DSS

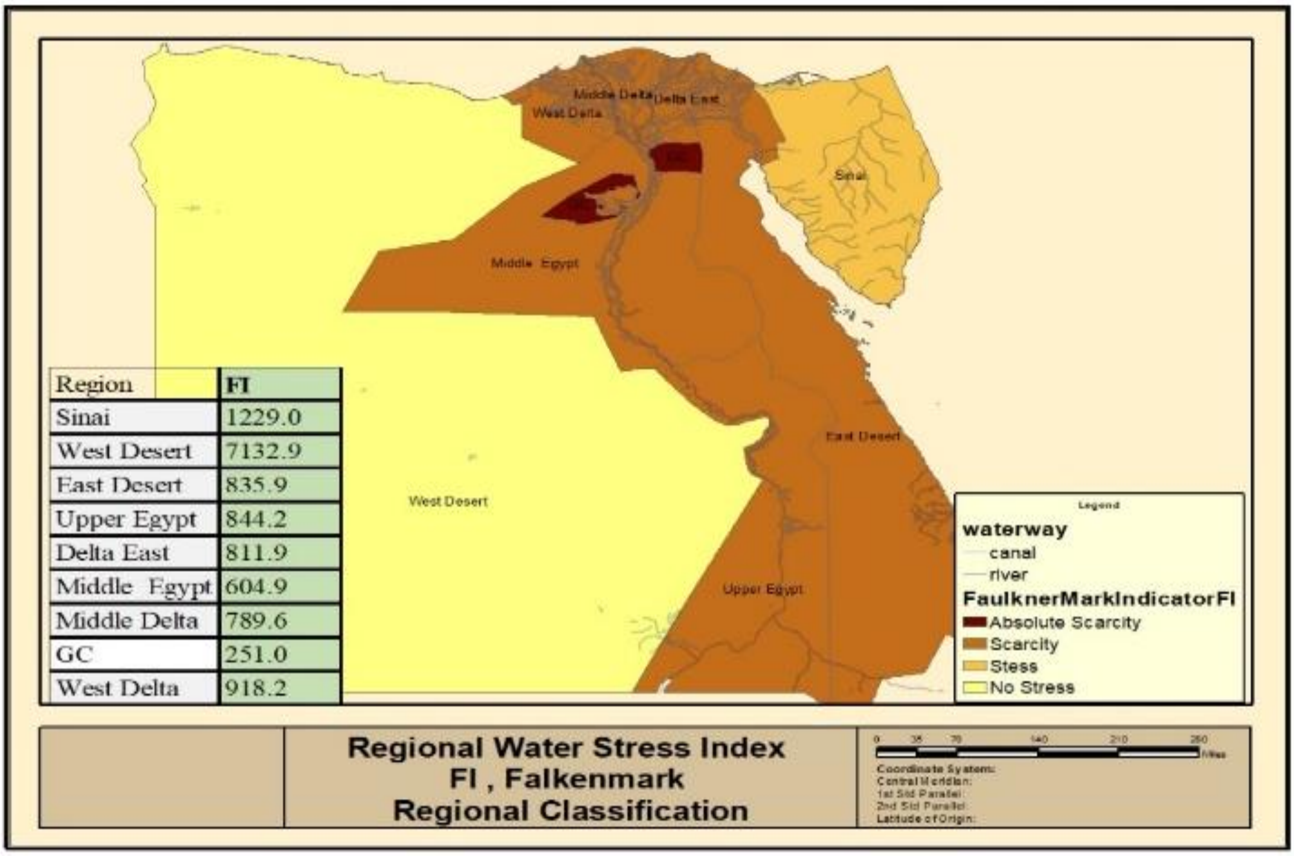


Figure 13: Regional Water Stress Index

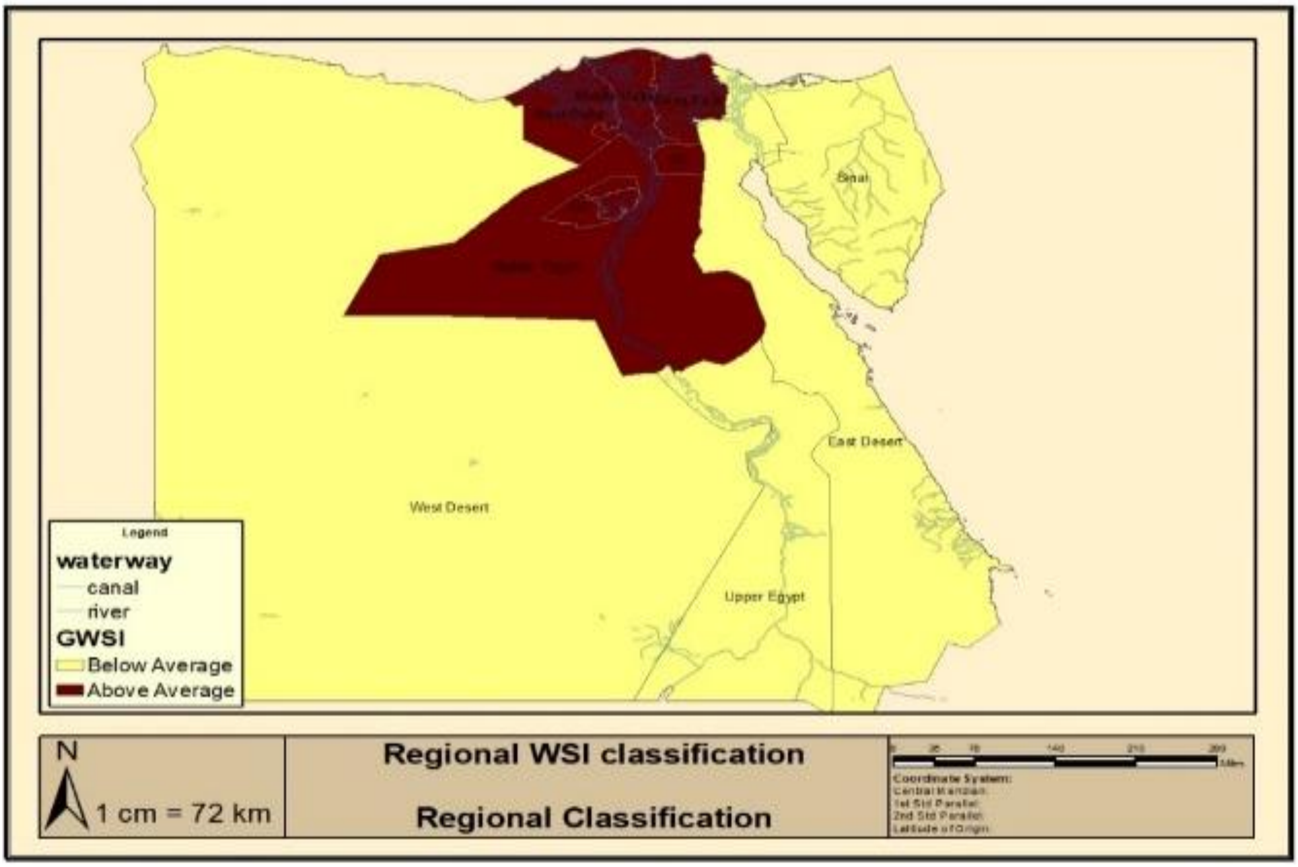


Figure 14: Regional based WSI classification over GIS DSS

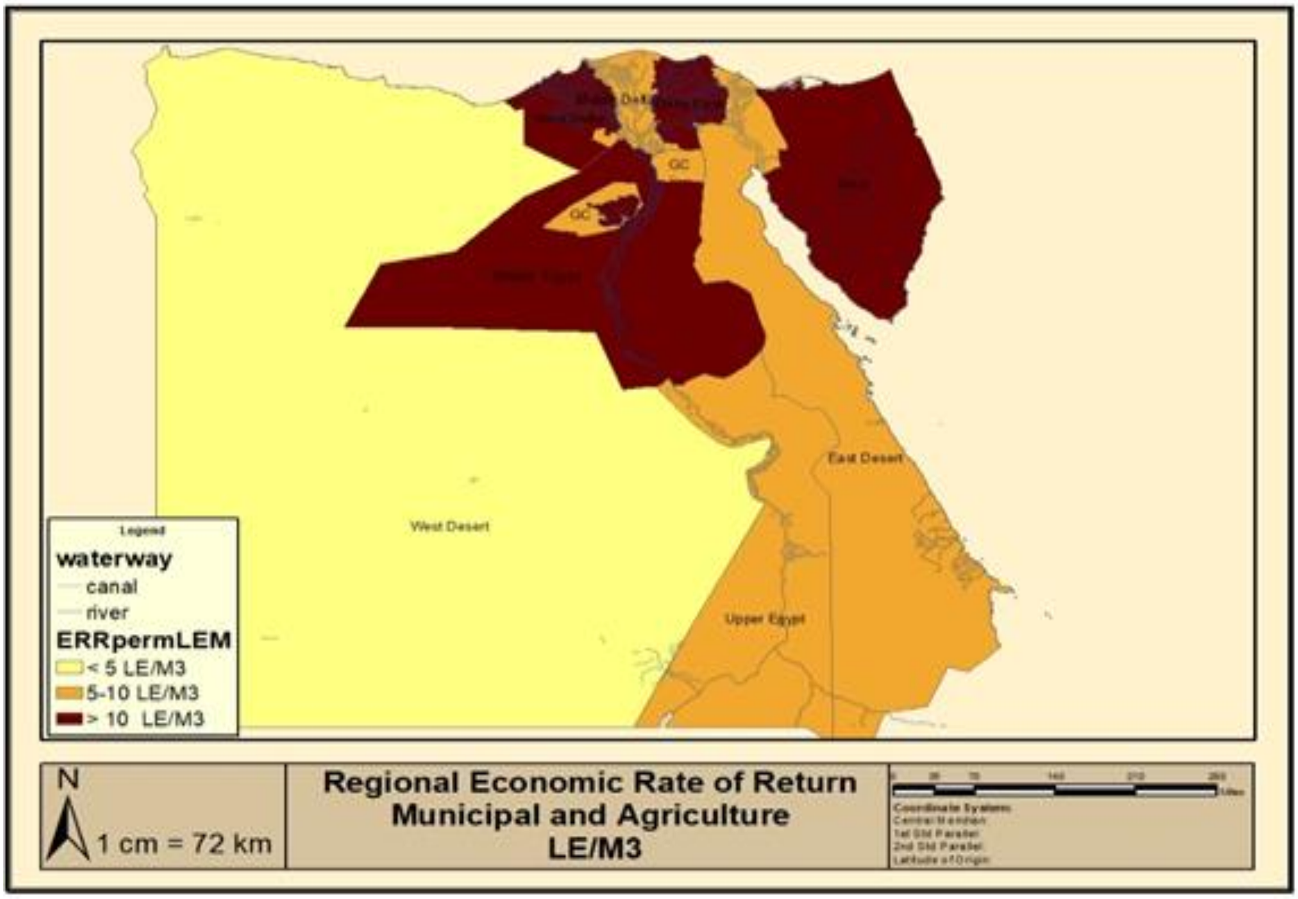


Figure 15: Regional Economic Water Productivity per unit of water

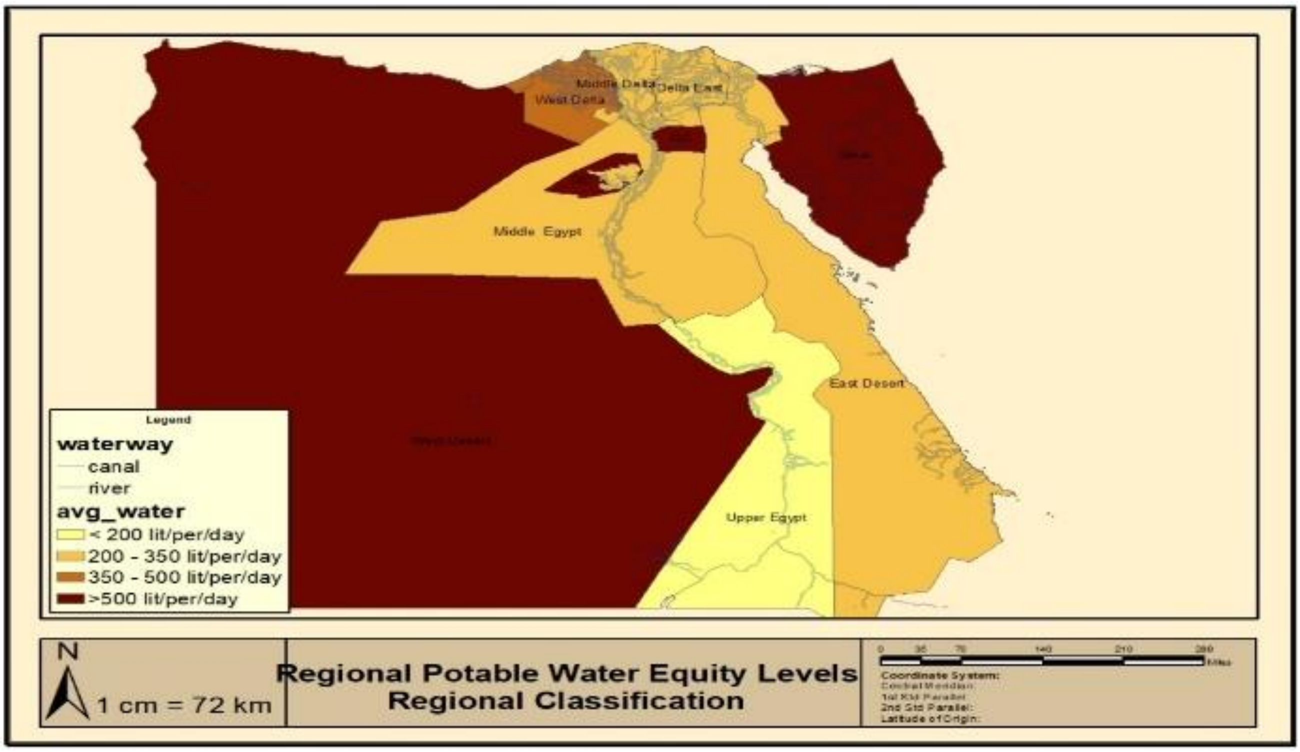


Figure 16: Regional Municipal Water Efficiency and Equity analysis

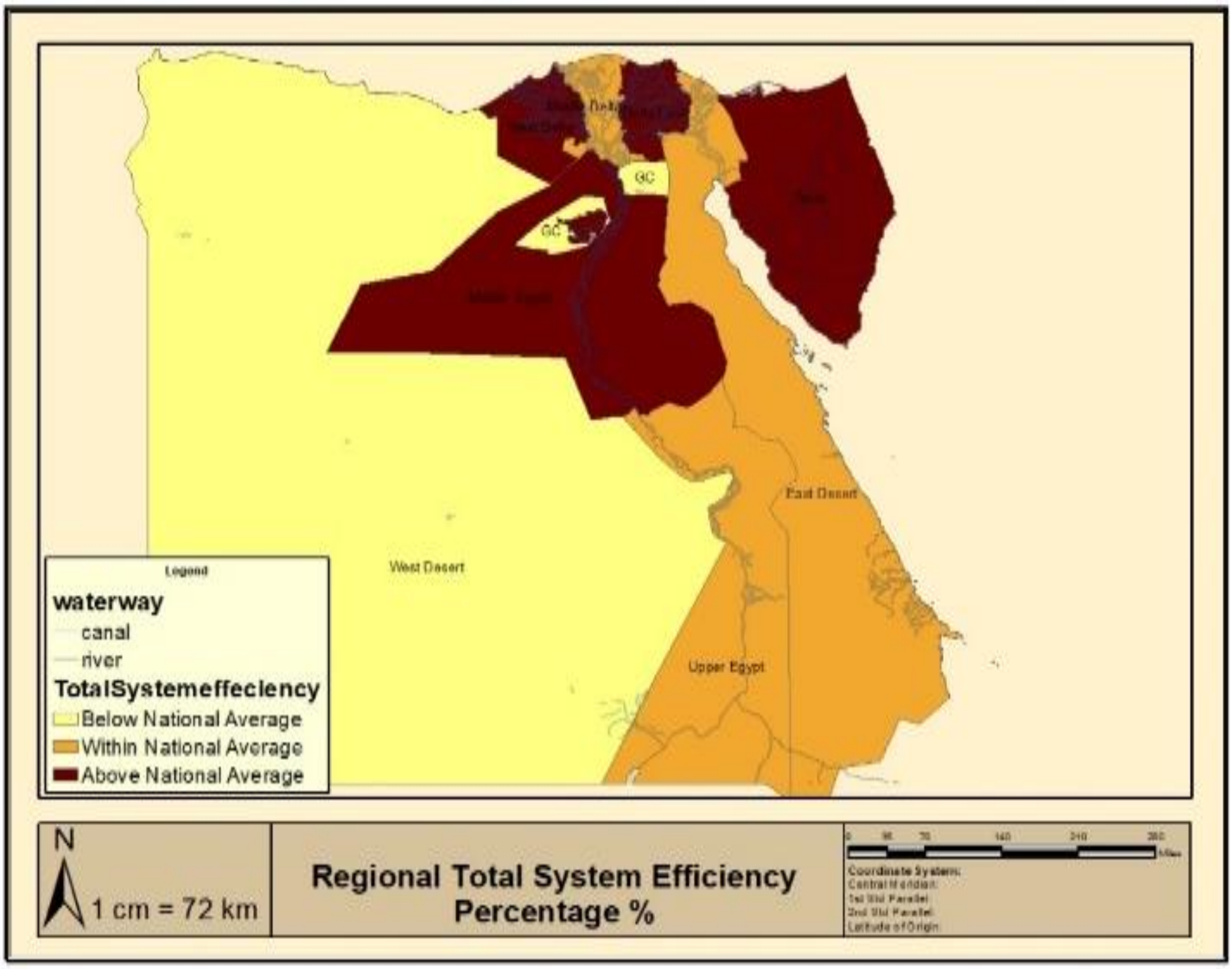


Figure 17: Regional Based Total System Efficiency

The following figures (Figure 13 to Figure 17) illustrate GIS abilities to visualize data for better decision-making and analysis shall be provided. Among the merits of implementing a GIS-based Decision Support System is its ability to conduct variable types of analysis and spatially linking them through time and space. In the above figure, an assessment of the Water Stress Index, also known as, Falkenmark Index (National Index is 630), clearly shows the high variance between different regions (results varied between 7000 and 251). The above figure could be easily deduced that greater Cairo faces the highest scarcity level (absolute scarcity). The high level of population concentration in the region and limited surface water, followed by the middle Delta. This deduction suggests increasing water availability projects (treated wastewater reuse) in the greater Cairo area. The following figure (Figure 14) shows the regional Water Security Index.

The results are divided into two categories which are above and below national averages. The results confirm the previous deduction regarding better water management and water productivity in the Delta region, followed by middle Egypt, than the rest of the country. The following figure (Figure 15) shows the economic water productivity at the regional level per unit of water. The above figure shows relatively higher productivity in middle Egypt, western and Eastern Delta, followed by Sinai and middle Egypt scoring above national averages. The above figure excludes the industrial sector's economic returns and only looks at the agriculture and municipal financial returns, which hold more than 90% of uses. The reason for that is when adding industry and services, and in the absence of a precise figure, a high distortion occurs in values which gives a false impression. The results could guide decision-makers to focus public finance for the municipal sector towards upper Egypt and middle Delta. In contrast, possibilities for economic productivity and private sector participation in water-based projects could be easier to fund in the more productive regions.

Figure 16 shall provide a quick analysis of municipal water efficiency and distribution equity for the municipal sector. The municipal water analysis shows a vast disparity between average water allocations in different regions. Although it should be noted that municipal water does include industrial and other non -domestic usages, and it was difficult to obtain figures related to the percentage of domestic use per governorates. Nevertheless, by applying for a thumb role, nearly 2/3 of municipal water uses goes to domestic usages in governorates. Industrial usage still shows in the above figure that areas such as greater Cairo and west Delta do have a very high-water consumption the rest of the country. This conclusion suggests that investment projects related to network improvement and potable water efficiency should be focused on the greater Cairo and west delta region in the first stage. This approach improves their municipal water efficiency levels and

assists in mitigating their high-water scarcity issue without reallocating new resources either from limited fresh water resources or expensive new resources (such as desalination).
Finally, Figure 17 provides the regional-based values of the Total System Efficiency.
Total System Efficiency, Bos 1979 [16] =

$$TSI = \frac{Total\ Water\ Uses}{Renewable\ Fresh\ water\ availabilities} \qquad (Eq. 1)$$

The above figure shows the results in three different levels (below - above) national TSI value of 88-95 %. The above figure shows the results in three different levels (below - above) national TSI value of 88-95 %. The results confirm the conclusions mentioned above regarding the relationship between system efficiency, water productivity, economic productivity, and Successful implementation of IWRM. Also, the clear, directly proportional relationship between the GWSI and TSI confirms the efficiency of the proposed procedure and system to analyse and assess the implementation of IWRM at both governorate and regional levels. Finally, with the application of IWRM GIS- DSS, the combination of Multi-Criteria Analysis (MCA), mathematical modelling, and GIS applications; provides an excellent, user-friendly tool for decision-makers to manage physical and monetary resources at a strategic level optimally.

## 7 Conclusions

Due consideration of the findings and conclusions capture above could be clustered into five actionable themes.

(i) The institutional challenges embedded have been significantly underestimated in terms of institutional reforms and enabling environment;
(ii) Irrigation and drainage service provision cannot be sustained without further investment in new or upgraded infrastructure and operation, maintenance, repair, and replacement of existing infrastructure;
(iii) The current Egyptian IWRM concept has to evolve into one that addresses the need to enhance access to traditional water resources; increases the supply of non-traditional resources, and further increase the already high productivity of water across the board;
(iv) Water Management decentralization through a transfer of water management at the mesqa level to WUA is a priority, mainly if it introduces integrated water management districts with unified budgeting flow.
(v) The role of planning should start at a local level and applying a bottom-up approach. A means of prioritizing financial expenditure is required and should be the regulatory authority's role (MWRI or another high-level authority with ruling power).

The results confirm the conclusions mentioned above regarding the relationship between system efficiency, water productivity, economic productivity, and Successful implementation of IWRM. Also, the clear, directly proportional relationship between the GWSI and TSI confirms the efficiency of the proposed procedure and system to analyse and assess the implementation of IWRM at both governorate and regional levels. Finally, with the application of IWRM GIS- DSS, the combination of Multi-Criteria Analysis (MCA), mathematical modelling, and GIS applications; provides an excellent, user-friendly tool for decision-makers to manage physical and monetary resources at a strategic level optimally.

## Nomenclature

| | |
|---|---|
| IWRM | Integrated Water Resources Management |
| GWP | Global Water Partnership |
| MCA | Multi Criteria Analysis |
| GIS | Geographic Information System |
| HDI | Human Development Index |
| NRW | Non-Revenue Water |
| ASME | Agricultural Sector Model of Egypt |
| GWSI | Governorate Water Security Index |
| WA | Water Accounting |
| UNDP | United Nations Development Programme |
| WQI | Water Quality Index |
| WSSI | Water Shortage Index |
| PWEI | Potable Water efficiency Index |
| WWCI | Wastewater Coverage Index |
| IWEI | Industrial Water Efficiency index |
| FWI | Fresh Water Index |
| IIEEF | Irrigation Efficiency Index |
| WCEI | Water Conveyance Efficiency Index |
| WAA | Water availability for Agriculture Index |
| WREI | Water reuse index |
| ERRA | Economic Rate of Return for water in agriculture |
| ERRM | Economic Rate of Return per cubic meter in the municipal sector |

## Ethical issue

Authors are aware of and comply with, best practices in publication ethics specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language. Also, all procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All procedures performed in this study involving animals were following the ethical standards of the institution or practice at which the studies were conducted.

## Competing interests

The authors declare that no conflict of interest would prejudice the impartiality of this scientific work.

## Authors' contribution

All authors of this study have a complete contribution for data collection, data analyses, and manuscript writing.

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