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Sensitivity Analysis for Multi-Criteria Decision Analysis Framework for Site Selection of Aquifer Recharge with Reclaimed Water

Heba Mohamed Hani *, Mohamed M. Nour El Din, Abdelkawi Khalifa and Ezzat Elalfy

Environmental Water Resources, Irrigation and Hydraulics Department, Faculty of Engineering, Ain Shams University, Cairo 11829, Egypt
* Correspondence: heba.alhariry33@gmail.com

Abstract: The pressure on Egypt's limited water resources has increased as a result of the country's growing industrial and agricultural sectors, coupled with climate change impacts and population growth. To overcome the current water stress situation, the utilization of new technologies such as managed aquifer recharge (MAR) is thought to be key for expanding the use of non-conventional water resources and providing necessary water supplies. Managed aquifer recharge can boost groundwater recharge and promote greater water accessibility. Suitability maps for MAR are widely offered as a tool to aid in decision-making in the context of balancing water demand and supply. Conducting a sensitivity analysis to validate suitability mapping can enhance the understanding of the results and pinpoint the influencing factors. The West Delta region was chosen as a case study given the existence of two MAR sites to examine the suitability of implementing MAR projects with reclaimed water. In this work, a spatially explicit sensitivity analysis is performed on a newly developed framework for MAR suitability maps that use multi-criteria decision analysis (MCDA) to determine suitable locations for MAR implementation, using spreading methods techniques. The performed sensitivity analysis uses spatial visualization to examine the effect of various weighted criteria on the final outputs and identifies criteria that are especially sensitive to weight changes. The results of the sensitivity analysis indicate that the applied MCDA framework for the suitability mapping in West Delta produced robust results in terms of the most suitable sites for MAR. The obtained results also indicate the possibility of the use of the suggested framework for arid environments with comparable data availability. Moreover, the results emphasize the possible use of suitability maps in sustainable groundwater management plans to support the actual implementation of MAR projects in the West Delta.

Keywords: Egypt; GIS; Western Nile Delta; multi-criteria decision analysis; aquifer recharge

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1. Introduction

The pressure on Egypt's limited water supplies has increased due to the country's growing industrial and agricultural sectors as well as its growing population. The supply of water is now almost at capacity. However, the Nile's water supply has not increased, and there are still very few alternatives for additional supplies [1]. The annual budget for renewable fresh water in Egypt (i.e., Nile River and rainfall) as estimated in 2017 was around 56.8 billion m^3. About 55.5 billion m^3 of this budget is provided by the river Nile and about 1.3 billion m^3 comes from rainfall. On the other hand, non-renewable groundwater systems are considered the second water source [2] and contribute about 10 billion m^3 of Egypt's total annual water budget [3]. Egypt uses more than 78 billion m^3 of water annually, leaving a shortfall of about 20 billion m^3 each year. The agricultural sector in Egypt uses 80% of the country's water budget, while the domestic and industrial sectors use no more than 20%. In the last three decades, the proportion of fresh renewable water per person has decreased dramatically, falling below the international critical limit of

1000 m^3/person/year. Thus, the country is transitioning from a situation of water stress to a state of water scarcity [1].

The climate is changing and, while uncertain, more extreme weather events are anticipated, with dry areas expected to get drier and wet areas expected to get wetter. At the same time, many developing countries such as Egypt share the common trait of rapid population growth which increases the risk of water scarcity for people as a result of rising water demand and stagnant or decreasing water supplies. Managed aquifer recharge (MAR) can be used as a sustainable solution to narrow the water supply and demand gap, especially in unconfined aquifers where 20 to 25% of the world's drinkable water supply is extracted [4].

MAR systems typically consist of several elements that affect where they are best suited to be implemented. The source of the recharged water [5], the characteristics of the receiving layer in the aquifer [6], potential recovery methods [7], and the location of the post-treatment systems are among these elements [8]. The majority of MAR implementation guidelines to date have emphasized the importance of careful planning to guarantee the effectiveness, accessibility, profitability, and sustainability of the systems. Therefore, choosing the appropriate recharge sites is seen as a crucial step that affects choosing the best MAR techniques, controls how they are implemented, and ensures their success [9].

Although MAR includes widely studied and applied techniques, MAR is not sufficiently comprehended with respect to the linkages between the selected MAR technique and the MAR suitability mapping procedures [10]. As a result, there is a lack of a globally consistent and understandable MAR framework that captures both elements for arid and semi-arid regions in the literature [10].

Around the world, MAR is currently playing a critical role in the utilization of non-conventional water resource [11], as it offers "Soil Aquifer Treatment" (SAT) "or "Geopurification" to the recharged effluent by allowing it to percolate through the soils and aquifers. Additionally, it gets rid of the undesirable "Tap to Tap" or "Toilet to Tap" connection between the sewage treatment plant and the water supply systems, which greatly increases public acceptance of the reuse of treated wastewater on an aesthetic level. The advantages of such a system in terms of improving water quality and availability, particularly in arid and semi-arid regions with rapid growth patterns in population such as Egypt, make it a crucial component of integrated water resources management (IWRM), especially in cases where excessive amounts of reclaimed water exist and where groundwater exploitation occurs at a faster rate than replenishment [12].

In 2021, wastewater production in Egypt was estimated to be around 4931 million m^3/year. Egypt has around 460 wastewater treatment plants. These plants are operating and treating around 5073.5 million m^3/year. This includes the Bahr Al-Baqar plant with a capacity of 5.6 million m^3/day—and the Hammam plant with a capacity of 7.5 million m^3/day [9]. Figure 1 shows the amount of annually treated wastewater between 2017–2018 in Egypt, per governorate [13].

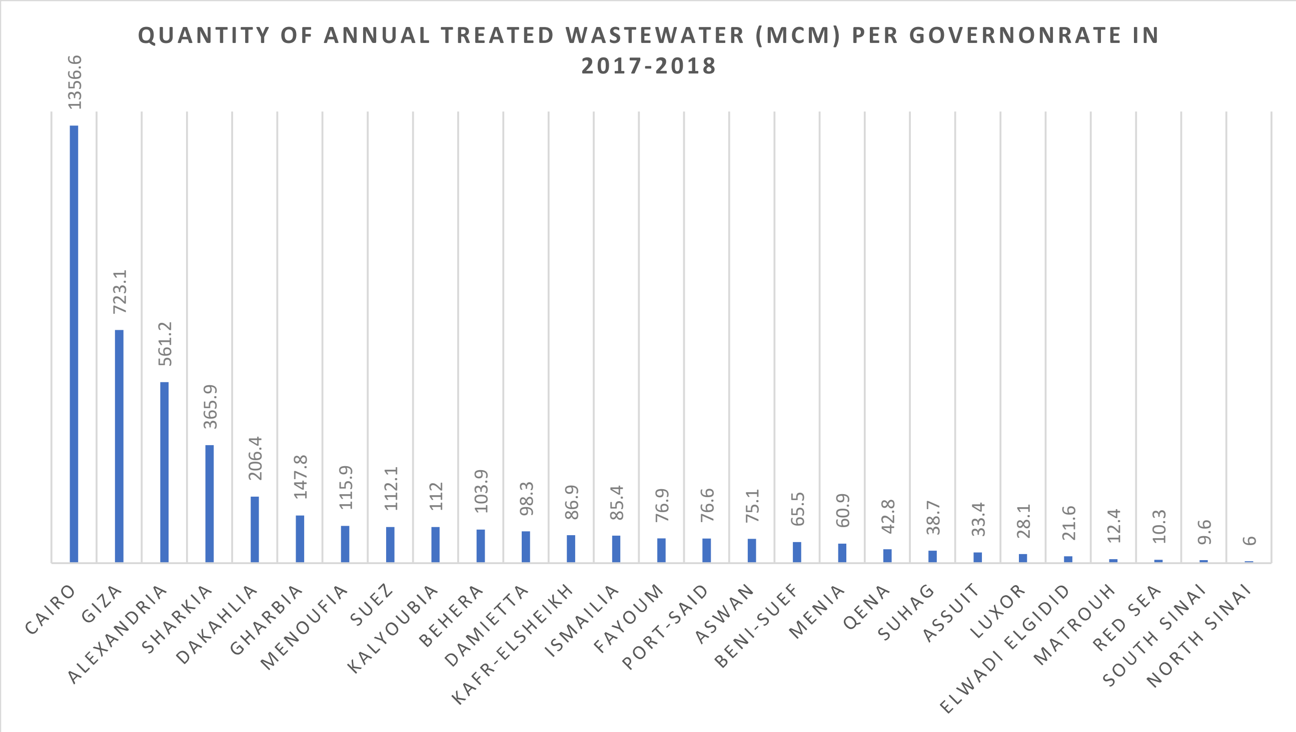

Figure 1. Quantity of annual treated wastewater in Egypt per governorate (CAPMASS 2017–2018) [13].

1.1. Suitability Mapping

Several studies, including Sallwey et al. [14] and Ahmadi et al. [15], have stressed the need for selecting an adequate site for MAR implementation. Environmental and social considerations should therefore be considered early in the site selection process. Due to the complexity and heterogeneity of the parameters, it is especially difficult to generalize distinctive landscape features that identify preferable MAR locations [10].

Suitability mapping is thought to be an important component of the MAR system's planning stage. The choice of recharge techniques, operational parameters, infiltration, and recovery efficiency are all significantly influenced by the site's location [9]. Suitability maps are considered a highly effective tool that can be used to inform strategic MAR site planning. They are thought to be the first step towards conducting extensive field applications to verify the main influencing parameters for MAR local implementation. Its benefits stem mainly from the ease of overlaying spatial analyses which are quick, dependable, and capable of making future predictions when used in conjunction with appropriate climatic scenarios, changes in land use, projected population growth rates, and new development plans [12].

While it is especially difficult to speculate distinctive landscape features that indicate ideal MAR locations due to the complexity and heterogeneity of hydrological and development conditions [16], currently, a multi-criteria decision analysis (MCDA) application is thought to be a great advance in mapping regional reservoir storage suitability [17]. MCDA can be defined as qualitative overlay methods that involve the weighting and ranking of different variables under particular thematic layers needed to achieve a specific objective, typically using a geospatial information system (GIS) [18]. Spatiotemporal data can be retrieved using remote sensing from large or physically inaccessible areas. Hence, integrated groundwater management for sustainable development can greatly benefit from (GIS- MCDA) to efficiently manage and analyze such spatiotemporal data [19].

Concerning MAR implementation, most cited publications consider soil and rock types, lineament and drainage density, slope, lithology, distance to water sources, geology, and geomorphology as factors influencing groundwater transport through aquifers, with resolutions ranging from meters to kilometers [20].

This study utilizes geospatial information systems and multi-criteria decision analysis (GIS-MCDA) to validate a newly developed framework for identifying appropriate implementation sites for MAR in the arid "Western Nile Delta" region. Under this work, a sensitivity analysis is performed to:

I. Examine the effect of various weighted criteria on the results of the suitability mapping development framework,
II. Identify the influencing criteria that are especially sensitive to weight changes,
III. Demonstrate the effect of modifying the weights of the criteria on the final outputs in a spatial dimension.

1.2. Case Study

Previously called the largest depocenter in the Mediterranean, the Nile Delta is now a man-altered coastal plain that has ceased to expand into the Mediterranean and is no longer an active natural Delta [21]. Less than two-thirds of its total area, which is about 22,000 km^2 and makes up the majority of Egypt's agricultural surface, is currently under cultivation [22]. The Nile Delta is mainly occupied by quaternary and tertiary deposits. The quaternary aquifers cover the greater part of the Nile Delta. The Nile Delta aquifer (NDA) (Figure 2), located in the Nile Delta, is thought to be a massive groundwater system which constitutes a sizable leaky quaternary aquifer from gravel and sand that is bordered by an upper semi-permeable layer (aquitard) from Holocene clay, and a lower impermeable rocky layer. The quaternary thickness of the aquifer varies from 200 m near Cairo in the south and reaches 1000 m towards the north [23]. The main method of recharging the NDA aquifer is thought to be infiltration from excess irrigation water, as very little rainfall percolates through the upper clay layer [23]. This clay layer thickness ranges from 5 to 25 m in the southern part of the Nile Delta, however, it reaches 50 m in several locations in the northern part [24].

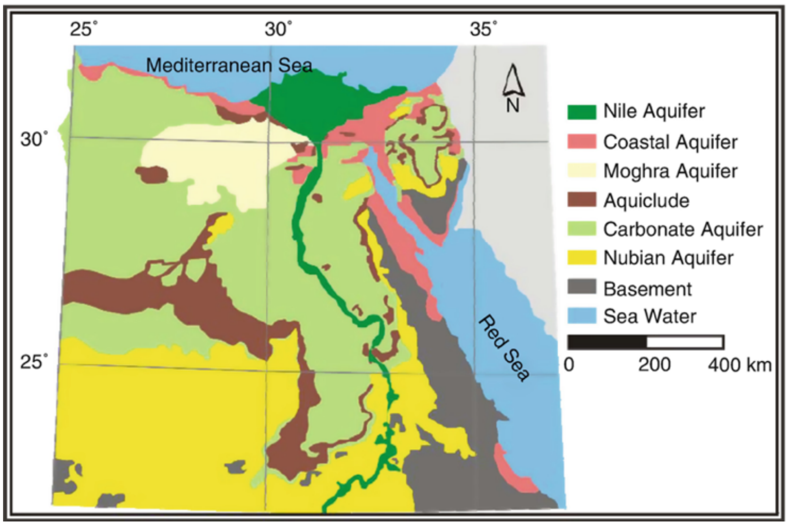

Figure 2. The Nile aquifer in Nile Delta [23].

Freshwater resources in the Nile Delta are under pressure due to the rapid growth of the population, and agricultural and industrial activities. As a result, groundwater aquifers are currently being over-extracted to meet the increase in water demand [21].

Figure 3 shows the quantities of various water resources and uses in Egypt during 2017. Data from the Ministry of Water Resources and Irrigation (MWRI) [3] indicate that agricultural drainage recycling produced 13.5 BCM in 2017, while the groundwater systems contributed with 9.6 BCM.

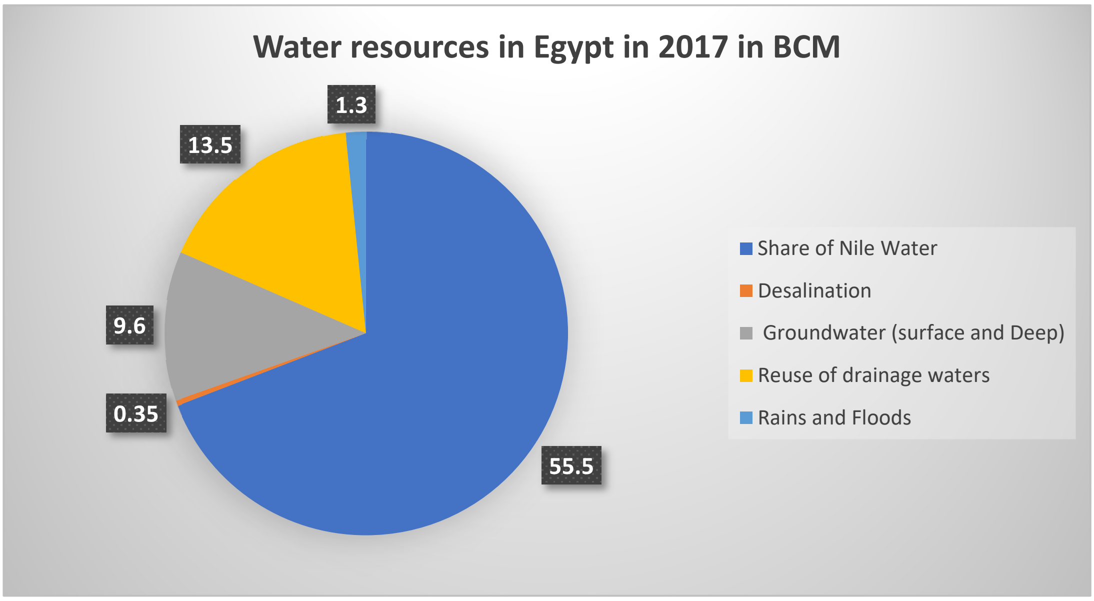

Figure 3. Quantities of various water resources in Egypt as reported in 2017 (MWRI 2022) [3].

Numerous studies, including Abdelaty et al. [25] and Abd-Elaty et al. [26], have shown and confirmed that the Nile Delta and particularly the coastal lands have experienced significant groundwater salinization (Figure 4) as a result of seawater intrusion and that this situation is only going to get worse [27]. Additionally, they emphasized the need for environmentally sound mitigation and adaptation strategies to stop the current decline in groundwater quality [27].

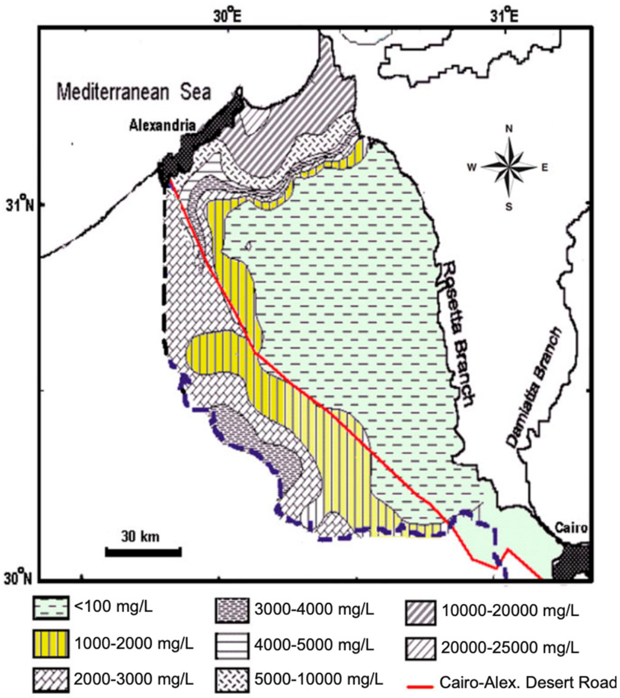

Figure 4. Groundwater salinity map of the groundwater in the Western Nile Delta [27].

The rehabilitation of the depleted aquifer through the application of artificial groundwater recharge and the implementation of MAR systems, where applicable, are considered part of the solution to enhance the aquifer quality, mitigate seawater intrusion, and reduce the water gap. Hence, the type of MAR technique that should be utilized should be tailored to the required objectives while the development of suitability mapping to optimize the location of potential MAR sites in the Nile delta can be used as a reference tool to prioritize the selection of various MAR operational sites.

In light of the above, Western Nile Delta was chosen as a case study (Figure 5) for a number of reasons. Existing operational MAR sites in the study area that ideally used the same recharge techniques (reclaimed water) were a crucial requirement. These operational sites were vital for evaluating the accuracy of the suitability map that had been created. In 1994, experiments on the artificial recharge of groundwater aquifers began in the Western Delta fringes [2]. With average infiltration rates varying between 0.1 and 0.4 m/day depending on the location of the basin and the mode of operation, these experiments looked at a variety of recharge techniques, including injection wells and spreading methods that showed promising results [2].

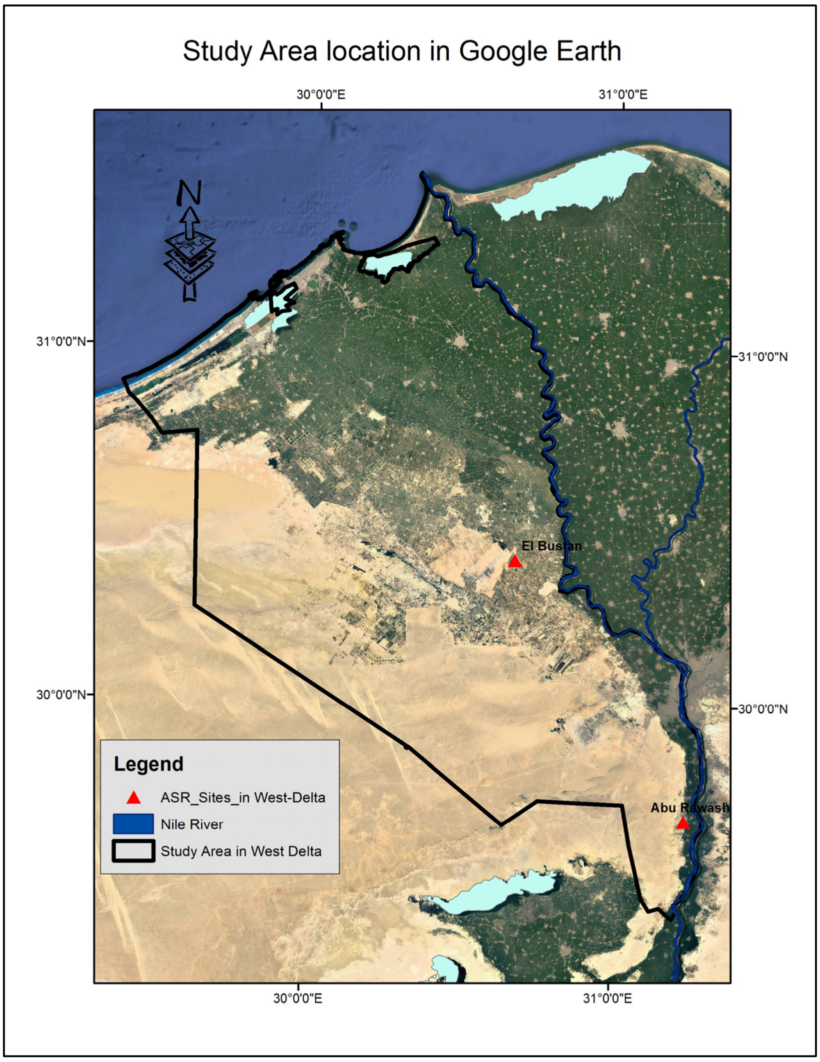

Figure 5. The study area and existing MAR sites.

The chosen location also considered the main recommendations that came out from the recently developed national strategy for water reuse "Towards Egypt 2030 Shared Strategy for Water Reuse" developed by IWMI Re-Water MENA Project [28]. This national strategy was developed in consultation with a national learning alliance during several national consultation dialogues organized during 2020–2021 [28]. The national learning alliance consists of more than 40 experts that include representatives from the national steering committees, technical representatives from uptakes ministries, local representatives from water users'/farmers' associations, a representative from a non-governmental organization, academia representatives, the private sector, and media [28]. The newly updated national strategy for wastewater reuse included a national target for 2030 to supplement depleted groundwater with 0.7 BCM/yr of treated wastewater for direct reuse for the priority areas in the West Delta. Moreover, the selection of the case study locations was also governed by data field and spatial availability (surface, subsurface, metrological, and socio-economic). Finally, the location was also selected considering projected water demands that are expected to rise in the future due to the possible expansion in agricultural development. These expansions are particularly related to the newly developed "West Delta Agricultural" project, with an area of 144,000 feddans, and the "New Delta National project" which falls within the study area. The New Delta project was launched by the Egyptian presidency in 2021 spanning over a million feddans and will be executed in two years to strengthen the state's strategy in agricultural and urban expansion, achieving food security, and establishing new agricultural, urban, and industrial societies [28]. This is considering that the Nile delta is occupied by the most populated governorates in Egypt where about 60% of Egypt's population lives and that it is also considered one of the most cultivated areas in Egypt; however, currently, less than two-thirds of its area is under cultivation [29].

2. Materials and Methods

2.1. Selection of the Best MAR Technique

MAR techniques comprise different types that vary according to their applicability, benefits, and drawbacks in implementation in various environments. The choice of an optimal MAR method for specific conditions (i.e., spreading methods, recharge wells, induced bank infiltrations, etc.) is frequently influenced by two major factors: a suitable aquifer and a readily available adequate water source. If these two criteria are provided, MAR can be used in most cases. Choosing the most appropriate approach for the particular local conditions is critical in developing, operating, and maintaining an efficient and cost-effective MAR project.

To determine the best type for the development of MAR projects in Delta, an assessment was conducted using a MAR data-driven selection tool developed by the Research Group INOWAS of the Department of Hydrosciences of the Faculty of Environmental Sciences at Technische Universität (TU) Dresden (INOWAS), Germany [30]. The selection tool aids the user in choosing a suitable MAR method for given characteristics defining the desired MAR site. The tool was created using a classification system based on the literature of hundreds of MAR case studies from around the world to assist in the identification of appropriate MAR methods based on various parameters that influence the purpose of the application [30]. In this case study, the selected parameters included the following parameters summarized in Table 1.

Table 1. Delta case study MAR type selection factors.

MAR Governing Parameters	West Delta Case Study
The Source of Water	Treated Wastewater (Industrial, Domestic, Desalination)
Soil Type	Sandy Loams, Silt Loams, and Deep Sands
Land Use	Agricultural Land
Purpose of the Application	Agricultural Uses/Irrigation and Restoration of Groundwater
Typical Scale	Large (Town)

By applying the above conditions to the data-driven selection tool, it reveals that infiltration basins or spreading methods seem to be the best options to recharge treated wastewater (Figure 6). The spreading methods technique tends to enhance the treated effluent in the soil using a natural technique known as soil aquifer treatment (SAT). The application of spreading methods techniques also tends to prevent and avoid potential clogging issues, which are common in recharge with injection wells and are also challenging to solve or redevelop [31].

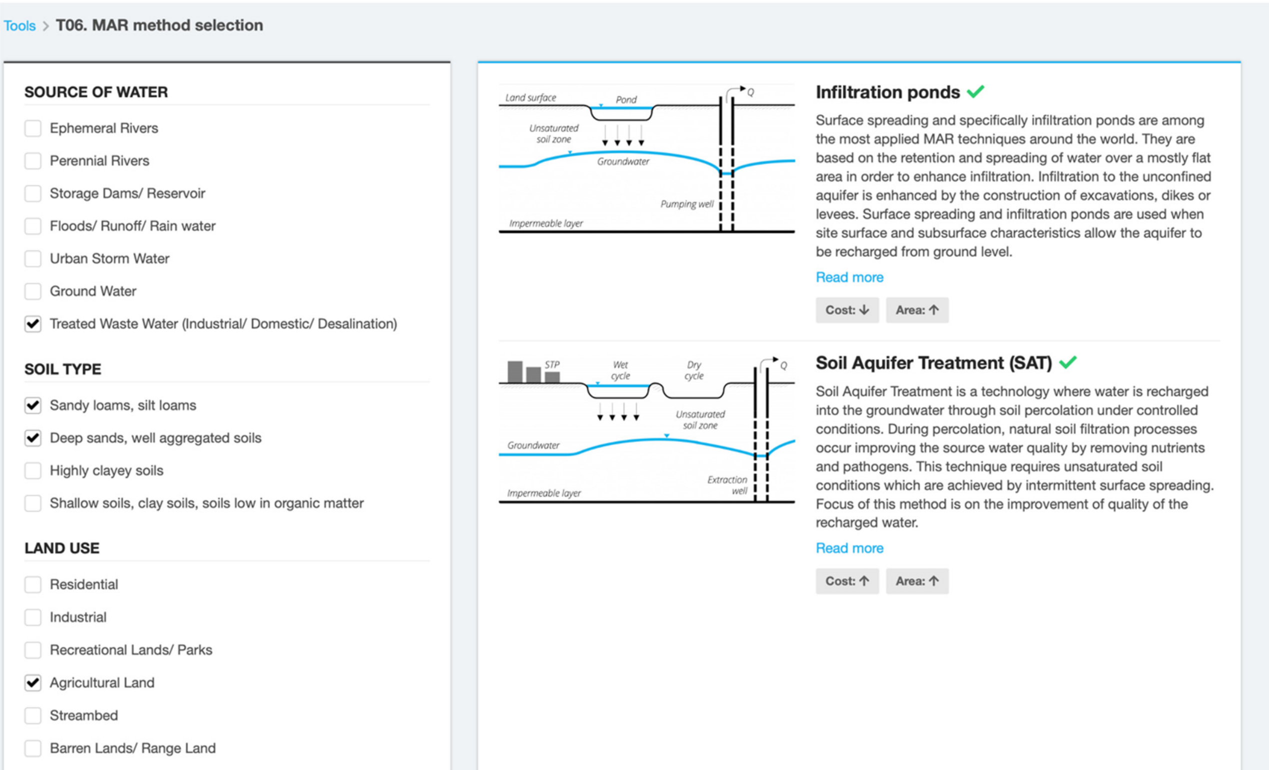

Figure 6. Results of data-driven selection tool confirming the suitability of spreading methods/infiltration ponds in MAR applications in West Delta conditions.

Based on the data analyzed for the selected case study using the INOWAS tool [30], the use of spreading methods or infiltration basins seems to result in low infrastructure demand and enables the infiltration and maintenance of large quantities of water at relatively low cost, which will result in a relatively simple anti-clogging procedure and will enable the removal of pollutants contained in the source water by the soil.

On the other hand, the data also reveals possible limitations in the operations including the requirements of large flat permeable areas, potential losses in water via evaporation, and potential surface water-related diseases. These limiting factors should later be taken into consideration while determining the main "site specific" considerations for the development of the suitability maps for MAR application at high potential sites.

2.2. Methodology

The development of the suitability map took place in numerous stages that form the main methodological framework in (Figure 7).

Following the data collection, constrain mapping techniques (stage 1) are utilized to screen restricted areas. Constrain mapping constitutes a very significant phase in the production of MAR suitability maps. It essentially allows for the exclusion of limited or unsuitable areas prior to performing the actual suitability process.

It starts by setting precise criteria that function as restriction factors and are believed to "prevent" the implementation of MAR projects under certain conditions. This stage is conducted utilizing Boolean logic algebra [18] in GIS. The operators "AND" and "OR" are used to generate reflections of suitable and unsuitable areas (cells) based on predefined criteria.

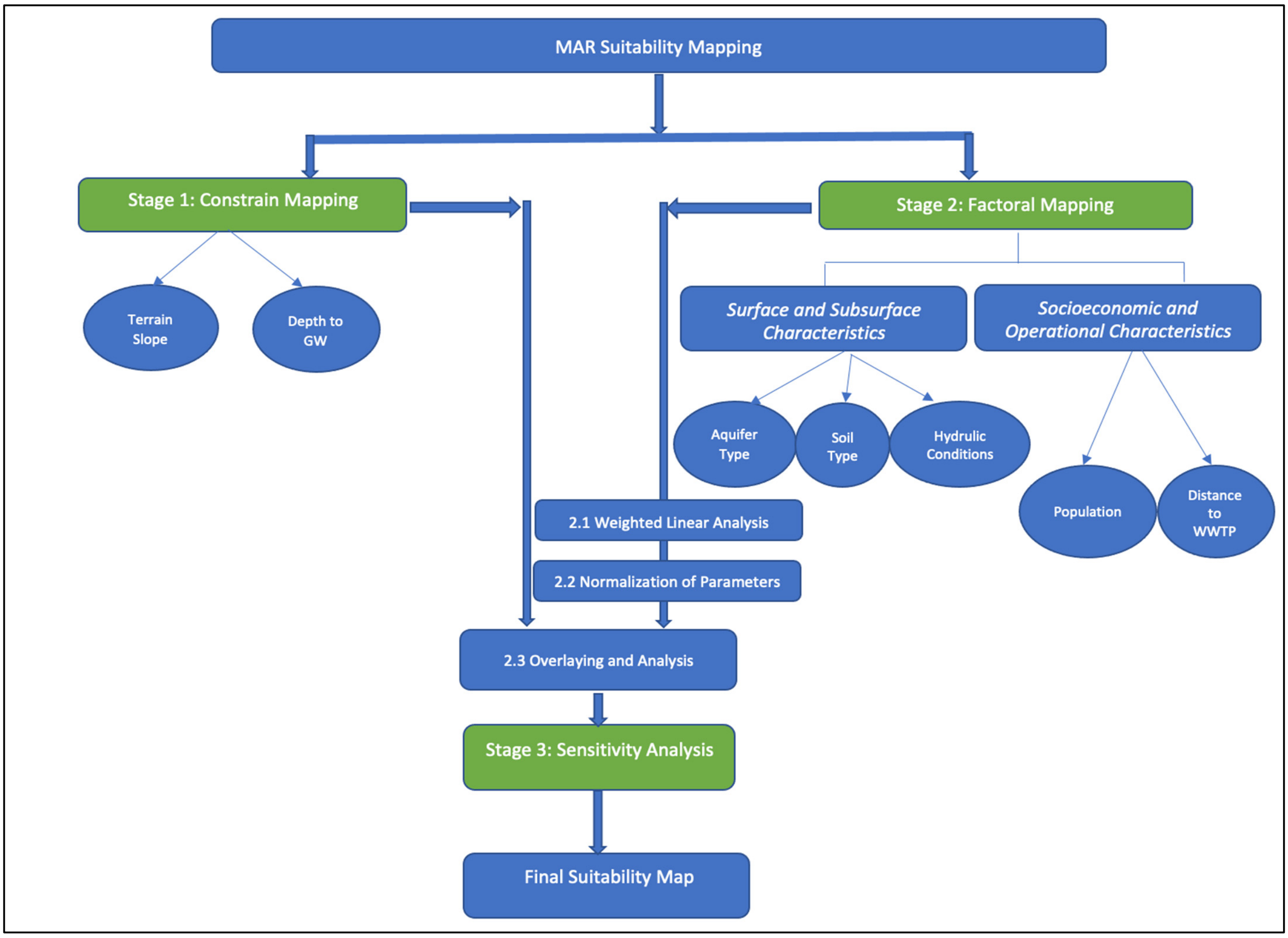

Figure 7. Flowchart of methodology.

Following constrain mapping methodologies, and to assure a successful installation of managed aquifer recovery (MAR) technology, numerous operational issues have to be examined. Thus, the second stage in the construction of the suitability mapping for the research region in West Delta encounters the factoral mapping, which contains the collection of numerous layers that reflect critical variables in the area's hydrological, hydrogeological, operational, and socioeconomic considerations. The second stage also includes assigning the different weights and the standardization of the criteria into a unified scale to facilitate the final integration of the suitability map.

The second stage is followed by a sensitivity analysis which represents the third stage in MAR suitability mapping development. The sensitivity analysis is carried out to determine how robust the results are. The selected criteria and defined weights are the primary sources of uncertainty in GIS-MCDA [19]. If the sensitivity analysis reveals highly sensitive criteria, the deterministic approach to MAR suitability mapping may be changed to a probabilistic approach. The following section discusses the specifics of each stage during the development of the suitability map, as well as the main outputs of each stage.

2.3. Development of Suitability Mapping

2.3.1. Criteria Selection

The determination of influencing criteria for MAR suitability mapping for the West Delta site using reclaimed water and utilizing infiltration basins was determined based on an intensive literature review conducted by INOWAS [30] for about 66 scientific case studies from more than 18 countries. This review resulted in a database query tool that was used in assessing the tendencies and preferences applied by the scientific community for MAR site selection using GIS-MCDA.

By applying the query tool to the site conditions (Figure 8), the findings of the query tool reveal the significant importance of the slope and depth to groundwater aquifers being the top influencing constrain factors for spreading methods techniques. This is considering that higher slopes increase construction costs, runoff, and soil erosion, therefore the best slope for developing recharge basins or percolation sites is between 0% and 5%. As a result, the first parameter in West Delta's MAR constrain mapping involved the elimination of sites and locations with slopes greater than 5% [15].

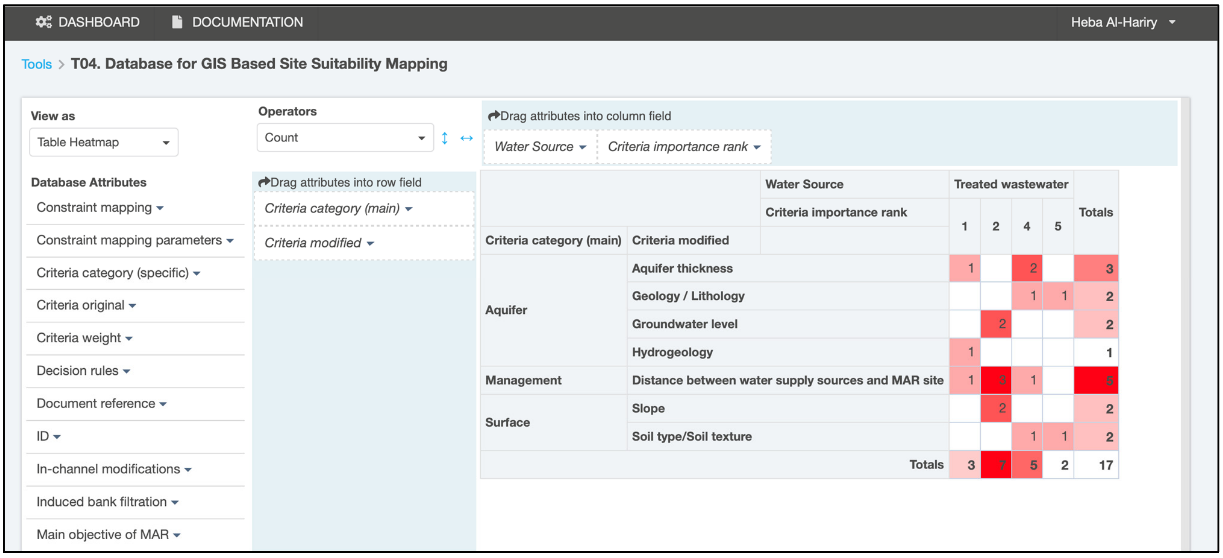

Figure 8. Results of Database Query Tool showing a heatmap table for MAR influencing parameters for spreading methods.

On the other side, the depth of the groundwater table is considered an important element for recharging the aquifer with reclaimed water, as the supplementary treatment of the recharged wastewater is dependent on the thickness of the vadose zone or unsaturated layer. The soil of the aquifer in the vadose zone improves sewage effluent treatment by eliminating the majority of biological loads and lowering chemical concentrations [2]. As a result, acceptable MAR sites should have a minimum of 5 m of unsaturated zone thickness. Another consideration in determining the adequacy of the aquifer depth was to avoid excessive elevations in the groundwater table due to recharging and to provide a suitable vadose zone for ultimate purification [32].

For the factoral parameters, the main parameters that are of high importance are related to the hydrological properties and operational and socioeconomic considerations, particularly concerning the aquifer type, soil texture, and hydraulic conditions. For the operational and socioeconomic parameters, the first criterion was related to the distance to the wastewater treatment plant (DWWT), where an assessment of the maximum acceptable distance was determined to reduce the transport costs. The second parameter mainly involves the population density projections in the study area which are used as an indicator for future water stress that should be taken into consideration in determining future hotspots.

Table 2 shows the data sources utilized to build the GIS/MCDA input maps. Data from the Shuttle Radar Topography Mission (SRTM) with a resolution of 1-arc second with a cell size of 30 m × 30 m were used to create a digital elevation model (DEM). The slope map was created in GIS using the DEM.

Table 2. The data sources utilized in building the GIS/MCDA input maps.

Thematic Layer	Source	Link	Resolution
Slope	The Shuttle Radar Topography Mission (SRTM)	"www.earthexplorer.usgs.gov (accessed on 20 November 2021)"	30 m
Depth to GW Table	Regwa company for Research & Ground Water	"http://www.regwa.net (accessed on 20 November 2021)"	30 m
Soil Texture	IGRAC-GGIS Global Portal	"https://ggis.un-igrac.org (accessed on 20 November 2021)"	250 m
Aquifer Type	IGRAC-GGIS Global Portal	"https://ggis.un-igrac.org (accessed on 20 November 2021)"	Shapefile
Hydraulic Conditions	IGRAC-GGIS Global Portal	"https://ggis.un-igrac.org (accessed on 20 November 2021)"	Shapefile
Population Projection	The Central Agency for Public Mobilization and Statistics (CAPMAS)	"https://www.capmas.gov.eg (accessed on 15 January 2022)"	Per Governorate
Distance to WWTPs	Holding Company for Water and Wastewater (HCWW)	"https://www.hcww.com.eg (accessed on 15 January 2021)"	Derived product

2.3.2. Weighted Linear Combination

According to the set of criteria, weights are assigned to each criterion based on their relative relevance. Usually, the most commonly used methods for determining weights are the pairwise comparison method (PCM), the rating method, the ranking method, and the multi-influence factor (MIF). In this paper, the pairwise comparison method is chosen for weight determination. PCM is described as a framework used as part of the analytical hierarchy process (AHP) to evaluate a specific problem where a matrix is developed by decision-makers to compare the importance of criteria to each other [33].

As part of this research paper, a survey was conducted that included national water experts and hydrogeologists who were requested to assign a scale of comparison for each criterion where each criterion was compared to others on a scale of 0 to 8, as shown below: 1: Equally important | 3: Slightly more important | 5: Much more important | 7: Far more important | 8: Extremely more important. Based on an experts' survey, the results of the survey are integrated in Table 3.

Table 3. Pairwise comparison matrix (PCM) for MCDA.

	Soil Texture	Aquifer Type	Type of Hydraulic Entity	Projected Population	Distance to WWTPs
Soil Texture (ST)	1	0.33	0.33	1.68	1.78
Aquifer Type (AT)	3	1	1	5.16	1.72
Type of Hydraulic Conditions (HC)	3	1	1	5.16	1.72
Projected Population (pp)	0.59	0.19	0.19	1	0.33
Distance to Wastewater Treatment Plants	0.56	0.58	0.58	3	1

The PCM approach produces weights as follows: aquifer type (AT) and the type of hydraulic conditions (HC) received the most weight (32.25%), showing the importance of the lithological characteristics that regulate recharging to the saturated zone [27] with hydraulic conductivity. Distance to wastewater plants (DWTT) had the second highest weight (18.75%) given its effect on the operational costs, followed by soil type (ST) (10.5%), and population projections as a reflection of future water demands (PP) (6.25%). Consequently, for MAR spreading methods, the "Suitability Layers Combined" (SLC) may be expressed using the following novelty formula reflecting the integrated criteria that are used to produce the final suitability map:

$$\text{SLC} = 0.32\ \mathbf{AT} + 0.10\ \mathbf{ST} + 0.\ 32\ \mathbf{HC} + 0.06\ \mathbf{PP} + 0.18\ \mathbf{DWTT} \quad (1)$$

in which **AT** is aquifer type, **ST** is soil type, **HC** is hydraulic conditions, **PP** is the population projection, and **DWTT** is the distance to wastewater treatment plant. These weights fall within ranges used in previous studies on MAR suitability in arid and semi-arid regions [34].

The weighted elements are integrated using new modeling platform created by the research unit of the Department of Hydrosciences of the Faculty of Environmental Sciences at Technische Universität Dresden (INOWAS). The INOWAS modeling platform is a Linux open-source empirical, analytical, and numerical web-based modeling tool created by INOWAS in 2019 to aid in the development, planning, management, and optimization of MAR applications [35].

2.3.3. Normalization of Parameters

The MCDA approaches require the evaluation criteria to be transformed into a uniform scale that can be compared. In this situation, a local form of a value scale is created to account for the numerous parameters. The factor criteria are normalized using an index ranging from 1 (unsuitable) to 5 (highly suitable), as shown in Table 4:

Table 4. Correspondence between the scale of standardization and the suitability class.

Suitability Class	Scale of Standardization
Highly Suitable	5
Suitable	4
Moderately Suitable	3
Low Suitability	2
Unsuitable	1

Given the type of MAR techniques used in this paper (i.e., spreading methods), the maximal suitability index is located in areas featured by unconfined aquifers, the moderate suitability ranking alternated between semiconfined and confined, and the minimal suitability ranking is assigned to fully confined or unknown areas.

For soil type, large soil particles are thought to be best for the recharge process because they facilitate surface infiltration, with the rate of infiltration increasing with particle size [36]. As a result, soils with no topsoil information and very fine soil textures are assigned the rank "unsuitable".

The cohort-component technique is used to generate the predicted population estimates in the Spectrum 5 model. The initial input data for this model is based on CAPMAS population estimations produced in 2013 [37]. Based on these forecasts, a standard suitability index is constructed to identify high-suitability recharge locations that accounted for the largest predicted population rates. The following figures (Figures 9 and 10) illustrate the standardization of the remaining parameters according to the determined scale for the West Delta case study.

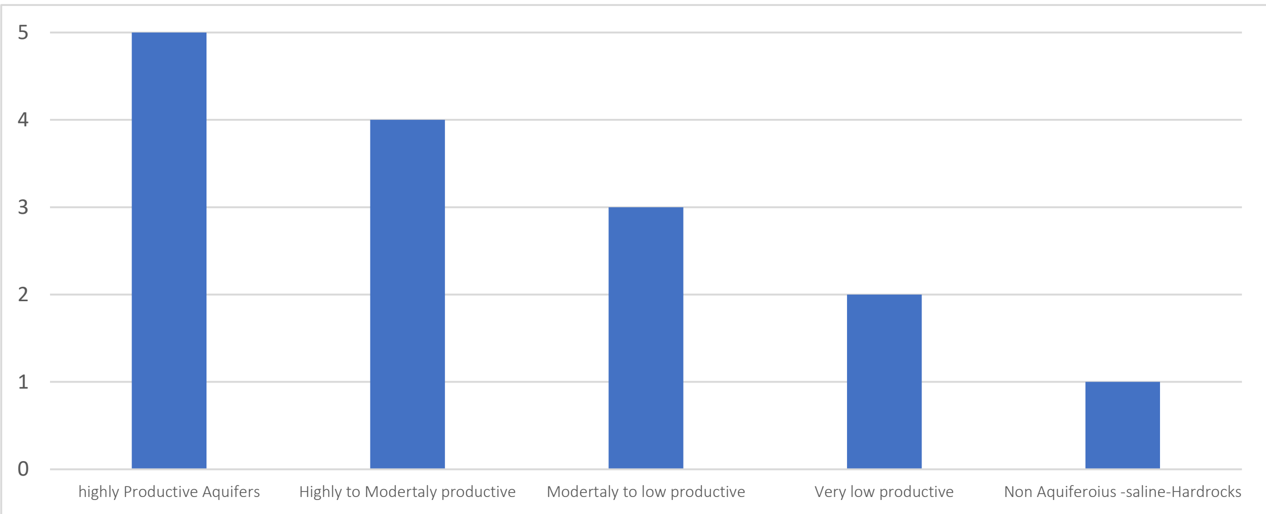

Figure 9. Applied functions for normalization (hydraulic conditions).

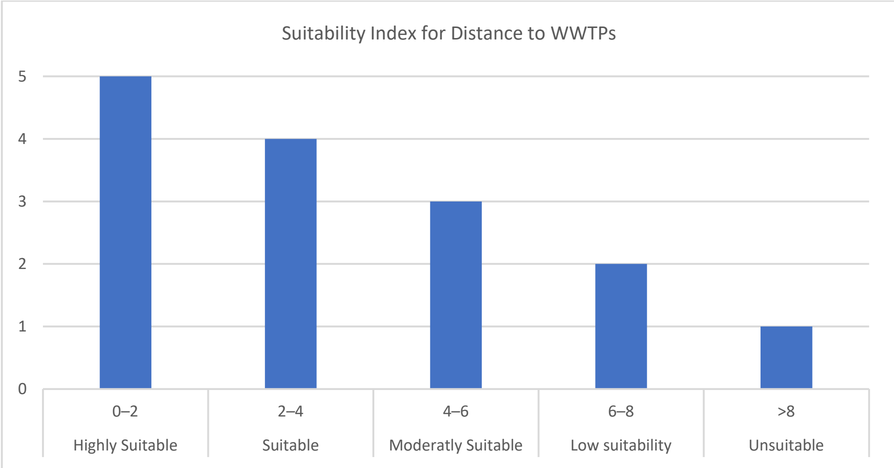

Figure 10. Applied functions for normalization (distance to WWTPs).

2.3.4. Overlaying and Analysis

The aggregation of the theme and constrain maps to produce the final suitability map for the West Delta area is the final stage of the suitability analysis. The map is produced using a multi-criteria analysis of six thematic maps. GIS tools are used to create the weighted overlay. The following GIS algebraic operations [38] are used to determine the computational approach used to overlap the limited areas and thematic maps:

$$\left(M^k_{ij}\right)_{mn} \times W = \sum_{k=1}^{tm} \left(\begin{pmatrix} M^k_{11} & M^k_{12} & \cdots & M^k_{1n} \\ M^k & M^k & \cdots & M^k_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ M^k & & \cdots & M^k_{mn} \end{pmatrix} \times W^k \right) \quad (2)$$

where M^k is the vector of cell values from each thematic map which is in line i in row j, m and n are the dimensions of the thematic grid map, k is the thematic map, tm is the number of thematic maps and W is the vector of values associated to each cell (0 for exclusion areas; 1 for inclusion areas).

3. Results and Discussion

3.1. Suitability Mapping Results

The map produced by screening suitable locations is shown in Figure 11 [38]. As can be observed, the separation between suitable and unsuitable locations is very well-identified and provides a good indication of places suited for spreading methods implementation.

According to the produced map, the best regions for the MAR spreading method in Western Delta are in the northeast, specifically near the left side of the Nile River valley. Low suitability locations are largely located closer to the northern Mediterranean shores and the southern half, reflecting the slope constrains for steep terrains and the existence of wadi deposits and volcanic formations. Areas of low suitability are also identified in the west-north, where the hydrological criterion appears to be impeding the implementation of MAR projects due to the low productivity of the hydrogeologic layer in this area.

The areas associated with each suitability class are calculated and indicate that no unsuitable areas for recharge are identified, while the percentage of low suitability areas is around 12% of the total areas, areas with moderate suitability are found to be around 65% suitable and highly suitable areas for recharge are around 23% [38].

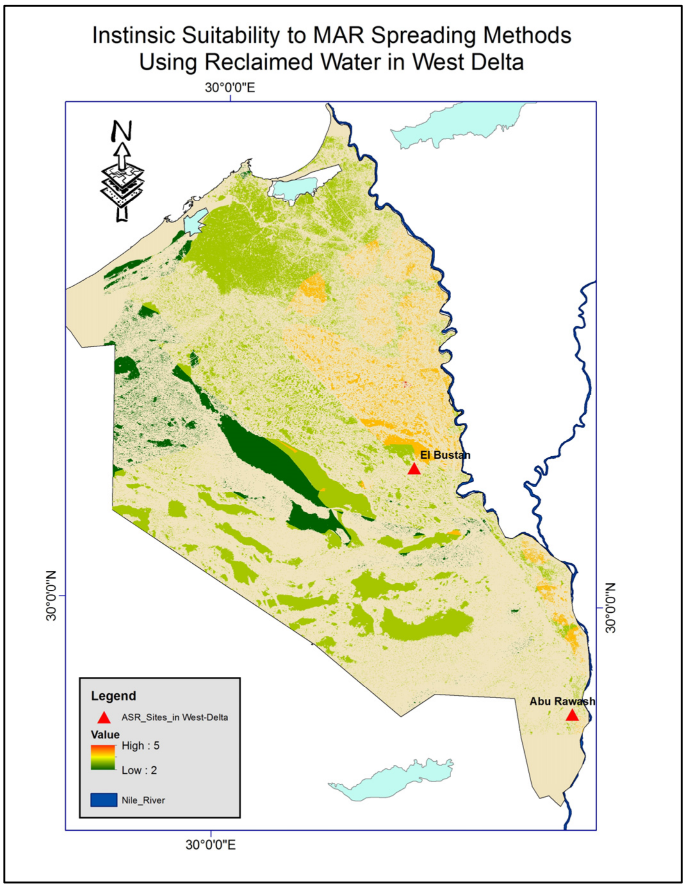

Figure 11. Suitability for MAR spreading method in West Delta [38].

3.2. Sensitivity Analysis Results

The literature describes a variety of approaches for sensitivity analysis in GIS-MCDA [18]. One method is to reassign criterion values. This approach is adopted in the current investigation where the weights of the criteria are systematically adjusted by increments (+10%, −10%), with impacts on dynamic interlinkages between the selected criteria assessed. To come up with the new suitability analysis equations, the weight of each parameter from the six criteria described in the methodology is increased once by 10%, then reduced once by −10% while maintaining the total sum of the weights in the equation equal to 100. For each trial, the model of the suitability analysis is recalculated to obtain the effect of each layer (criterion) on the modeling results. By modifying the weights of the criteria, the sensitivity analysis assumes that the weights are the primary source of uncertainty and hence concentrates on a one-dimensional sensitivity analysis.

The results of the sensitivity analysis are provided in Figure 12. The obtained maps, reveal that the most sensitive criteria/influencing parameters are the type of hydraulic conditions (HC) followed by the distance from the wastewater treatment plants (DWWT) which resulted in the presence of unsuitable areas of recharge, followed by the aquifer type (AT). The overall least sensitive criterion is the soil type (ST), while the population projection (PP) did not prove to be particularly sensitive. The investigation also showed that the suggested technique produced trustworthy, robust results in terms of the optimal MAR locations, which did not appear to be very sensitive to the changes in the weights. The outcomes of the spatial sensitivity mapping experiments support this interpretation by showing very small shifts in the final suitability map compared to the original map.

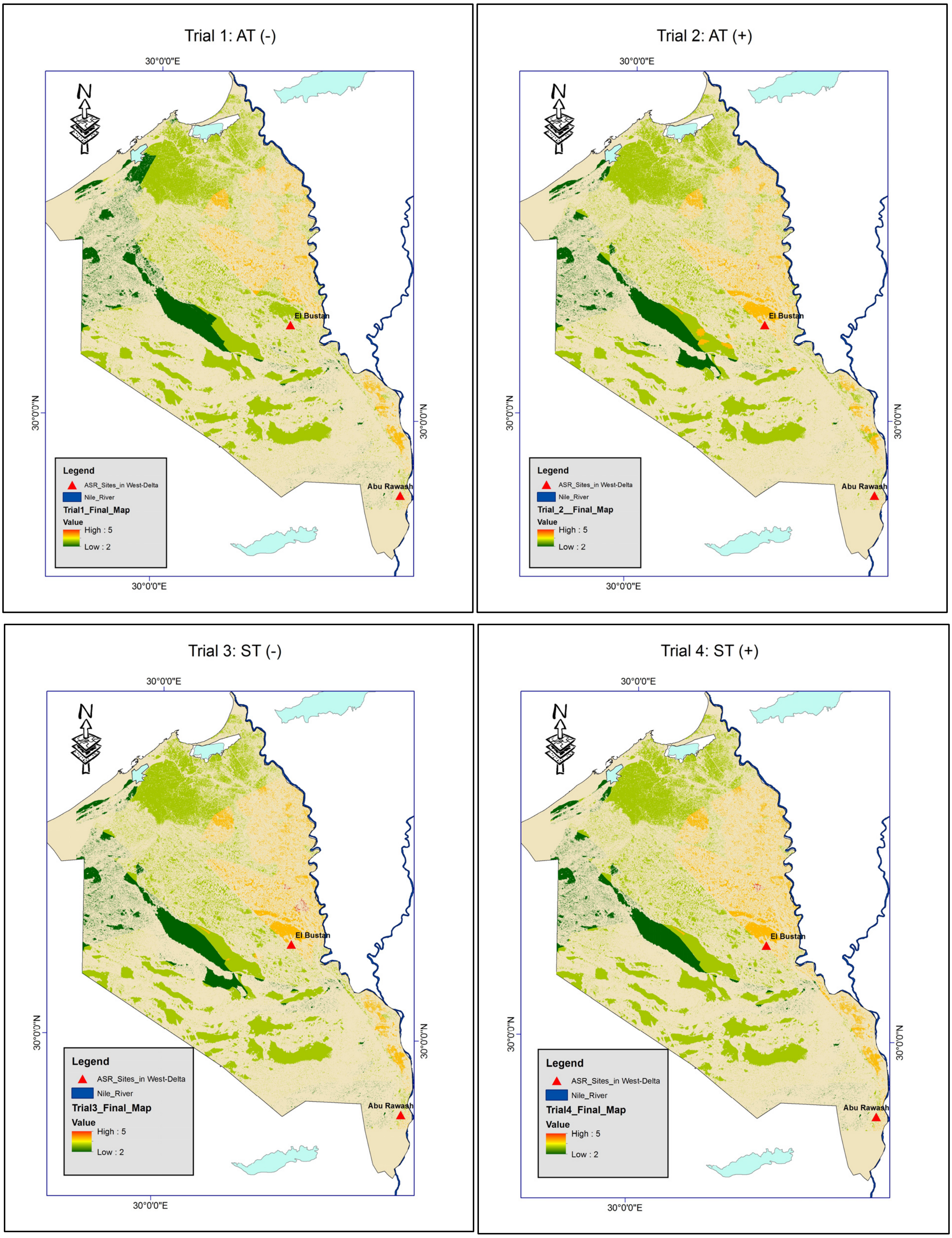

Figure 12. *Cont.*

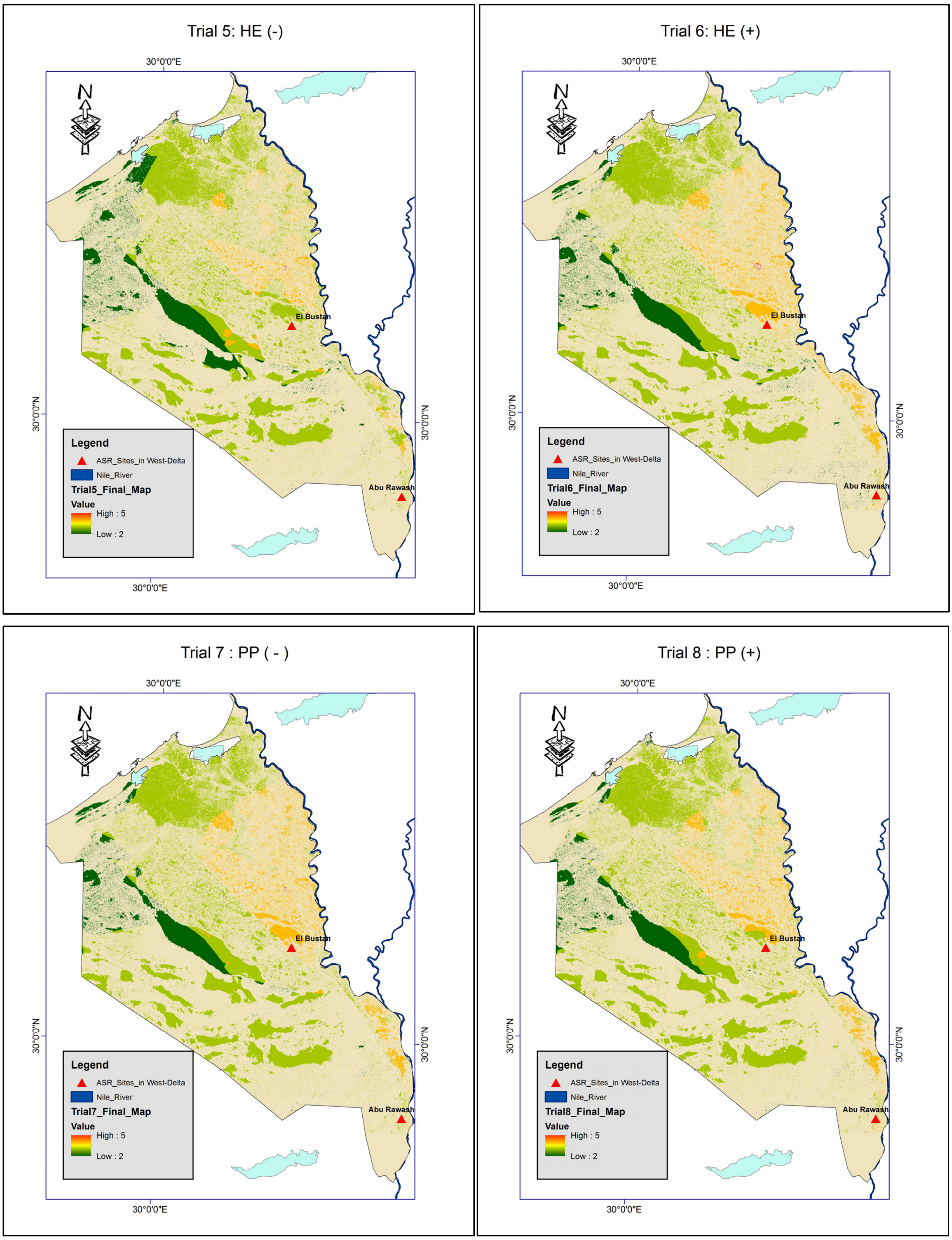

Figure 12. *Cont.*

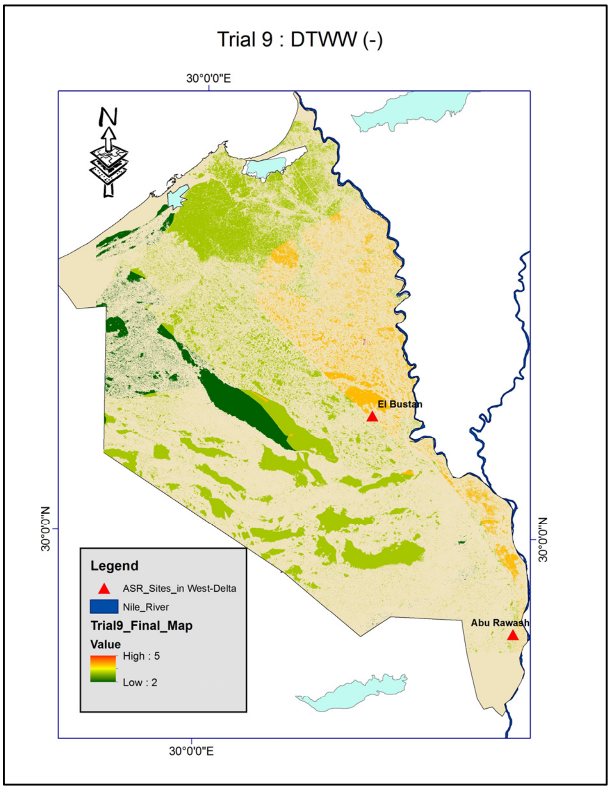

Figure 12. Results of the sensitivity analysis reflecting changes in weights by +10% and −10%.

In light of the above, the sensitivity analysis reveals that the spreading strategy produced robust results in terms of the most suitable sites for MAR. This highlights the possibility of using the suggested methodology for arid environments with comparable data availability. The maps can be utilized as a decision-making tool to support the actual planning and implementation of spreading methods in the West Delta. Furthermore, with the implementation of MAR, such maps can be used in a participatory manner to obtain public approval prior to implementation.

4. Conclusions

In this paper, the West Nile Delta region was chosen as a case study given the existence of two MAR sites in the study location. A spatially explicit sensitivity analysis was conducted on a newly developed framework for MAR suitability maps that use multi-criteria decision analysis (MCDA) to determine suitable locations for MAR implementation, using spreading methods techniques. The examined MAR method focused on the replenishment of reclaimed water via spreading ways approaches, with numerous technical and socioeconomic parameters used to establish the optimal suitable locations for MAR project implementation. The feasibility of implementing MAR-suitable sites with reclaimed water was investigated, using multi-criteria decision analysis integrated with GIS tools where six themed maps were created using environmental, socioeconomic, and hydrological parameters. A digital elevation model with a cell size of 30 m × 30 m was created for the research region and was used to determine the constrain conditions for the slope, which were then integrated into each thematic map. The constrain mapping's exclusion areas were coded as 0 and the inclusion areas as 1. By combining the constrain mapping and factorial mapping techniques for socioeconomic and hydrological criteria, a suitability map for MAR implementation in the West Delta was produced.

The sensitivity analysis assumed that the weights were the main source of uncertainty and therefore focused on a one-dimensional sensitivity analysis by changing the weights of the criteria. The results of the analysis illustrated that the proposed methodology yielded reliable robust findings in terms of the best MAR locations that seemed to be not too sensitive to the changes in the weights. This was made further evident by the spatial sensitivity mapping results, which revealed relatively modest changes in the final suitability map during a series of trials.

The results also confirmed that the developed MCDA framework which addressed the linkages between the MAR selected technique and the suitability mapping procedure can effectively identify influencing parameters based on various sensitivity parameters. Moreover, the results demonstrated the applicability of applying the proposed technique in dry regions with comparable data availability. The produced suitability map framework therefore can be used as a decision-making tool to help real spreading technique design and execution in the West Delta. Furthermore, with the adoption of MAR, such maps can be utilized to discover unanticipated societal concerns and obtain public approvals prior to implementation.

Although the methodology cannot be generalized for arid regions based on a single case study, it can be utilized to obtain a better understanding of more arid-specific aspects for determining the potential for MAR in different regions via spreading methods, as more case studies are considered. Based on the findings, a more environmentally friendly and productive use of reclaimed water can be obtained in West Delta to narrow the present supply-demand gap. By utilizing the investigated approach, better scientifically grounded decisions can be taken to improve groundwater and agricultural planning in the Delta region. Furthermore, it can also help in reducing the over-exploitation of current groundwater resources by introducing an alternative water source through the utilization of non-conventional water resources.

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