Al Bardawil Lagoon Hydrological Characteristics

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Abstract: Al Bardawil Lagoon is a very saline lagoon located in North Sinai, Egypt. It is subjected to environmental changes due to the implementation of a mega agricultural project close to its southern border. Accordingly, defining the hydrological characteristics of the lagoon was the objective of the current work to set the hydrological baseline for future changes expected due to ongoing human activities and agricultural developments planned in the lagoon’s vicinity. Historical meteorological data were collected and statistically analyzed to achieve the study objective. In addition, tide action, the lagoon’s bathymetry, and water table fluctuation were studied. Furthermore, groundwater aquifer interaction with the lagoon’s hydrologic system was considered. The study defined the water resources and water losses of the hydrological system of the lagoon. In addition, tide investigations revealed that the tide range is small. Furthermore, the study defined the water budget of the lagoon. Results indicated that the lagoon’s water resources are rainfall with an annual volume of 61.95 million cubic meters (4.4%); the groundwater aquifer contributes about 8.64 million cubic meters (0.6%). Annual evaporation losses are 1155 million cubic meters (82.2%). Salt production requirements represent about 17.8% of the outflow from the lagoon. Results of wind speed and direction data revealed that the dominant regional wind direction is NW and is characterized by magnitudes of about 4.5 m/s Results analysis demonstrated that the inflow of the lagoon is always less than the outflow with an annual volume of 1335 million cubic meter supplemented by the Mediterranean Sea water. This difference maintained water levels in the lagoon below mean sea level throughout the year, with values ranging between 11 and 22 cm. This process maintained a continuous movement of the seawater toward the lagoon. Water table fluctuation results indicated that the average water table in the lagoon is lower than the seawater level, with an average value of 22 cm for the observation period. Furthermore, the difference between the maximum and the minimum water table is in the tide range of the eastern region of the Mediterranean Sea. Similar hydrological studies are recommended for other coastal lagoons in Egypt. In addition, a hydrological observation system is recommended for the Al Bardawil Lagoon.

Keywords: hydrological characteristics; Al Bardawil Lagoon; water balance; water table; water resources

1. Introduction

Coastal lakes within the coastal zone of Egypt act as multi-functions for the surrounding environment and local people. These lakes are sensitive to a group of stressors which include reclamation for alternative uses, hydrological modifications, pollution, and erosion [1]. In Egypt, as a country characterized by water scarcity, increasing water demands, and different development activities, such as agriculture, have affected many ecosystems across the coastal zones of Egypt during the last century [2]. As populations grow and economic development proceeds through the twenty-first century, human-induced pressures on aquatic resources in the already heavily populated coastal zone will increase [3]. Furthermore, climate change will have negative impacts on water resources and sea level rise [4,5].
In fact, monitoring and modeling ecosystem functions is an important prerequisite for developing management policies for coastal lagoons in Egypt. In fact, hydrology is the principal driving factor of the environmental role of wetland ecosystems. In this context, the importance of initiating a hydrological database represents the core role for hydrological and environmental studies for all wetlands, including coastal lagoons and shallow lakes [6,7].

Hydrological processes depend on meteorological circumstances. These include the water resources of direct precipitation and water loss by evaporation. Any changes in the balance between precipitation and evaporation influence seasonal changes in lagoons’ hydrological environment.

At the lateral boundaries of coastal lagoons in Egypt, hydrological conditions are controlled by freshwater discharged into the lagoon and water exchange between the lagoons and the sea. Water exchange is influenced by two factors. The first is the difference between water levels in both the sea and the lagoon. The second is the type of the connection between the sea and the lagoon.

Regarding the lagoons’ catchment area, freshwater resources represent a major factor in the inflow term of the water budget of the lagoon. In many cases, as in Egypt, coastal lagoons receive freshwater from groundwater aquifers. In fact, freshwater inflows into the lagoon impact lagoons’ water quality, in particular, water salinity [8,9]. In addition, freshwater inflows provide coastal lagoons with nutrients and sediment. In fact, hydrological processes are the main source of nutrient supply within coastal lagoons [10]. The continuous freshwater inflows, coupled with seasonal the difference between precipitation and evaporation magnitudes, result in spatial and temporal variability in lagoons’ water levels, salinity, and nutrient status [11].

Both quantities and qualities of freshwater inflows into the lagoons and lakes are largely influenced by the catchment area size, its geology, and its climate [12]. Human activities within the coastal lagoons’ catchment areas have a direct impact on the magnitude and the quality of freshwater inflows [13]. Human activities that influence lagoons’ water quality are the direct result of water resources management within the catchment area [14].

Like other coastal lagoons, Al Bardawil Lagoon is subjected to different anthropogenic activities, such as the mega land reclamation project in Northern Sinai and El-Salam canal. Seepage from both irrigation and drainage waters through the soil of loose sand will affect the water quality of the lake and eventually end up in the aquifer beneath the lake and its catchment area. Domestic wastes of the new settlements in the vicinity of the project will be added to agricultural wastes and pollutants and will undoubtedly alter the environmental picture of the region. In addition, the limited amount of rainfall in the region and shoreline changes can have a profound effect on the geomorphology of the lagoon. These circumstances enhanced the need to assess Al Bardawil Lagoon hydrological characteristics to set the hydrological baseline for future changes expected due to ongoing human activities and agricultural developments planned in the lagoon’s vicinity.

The meteorological factors were investigated to assess the hydrological characteristics of the lagoon. Historical rainfall records, evaporation loss measurements, water level fluctuation data were collected and analyzed. Meteorological data were statistically analyzed, and the water resources of the lagoon were estimated. Water losses and outflows were assessed. The lagoon bathymetry and wind action were investigated. Furthermore, the water balance of the lagoon’s hydrology system was defined by implementing the water budget procedure. In addition, a field program was implemented to record the water table for a period of three months in the year 2004.

2. Study Area

Al Bardawil Lagoon is located on the northern coast of the Sinai, Egypt. It extends from 32°41′00″ to 33°30′00″ E longitude and from 31°03′00″ to 31°14′00″ N latitude. It has a surface area of 650 square kilometer with a total length of 80 km and a maximum width of 14 km. The lagoon is a shallow water body with an average depth of 1 m, Figure 1. The
Mediterranean Sea borders the lagoon from the north. The lagoon is bordered by a sand dune belt from the south while the Al-Arish-Rafah sector presents its eastern border, and the Al Tinah plain represents its western border. The bottom of the lagoon is composed of sand and silt.

Figure 1. Study area.

A long sand bar separates the lagoon and the Mediterranean Sea. The lagoon contains the Al Zaranik protectorate area in the eastern section. Al Zaranik area represents the most east section of Al Bardawil Lagoon with a length of about 30 km. It hosts the Al Nasr salt production company. On the other hand, the western part of the Al Bardawil Lagoon has a length of about 80 km [15].

The Al Bardawil Lagoon has six habitats, including open water, wet salt marshes, saline sand flats and hummock (nebkas), stabilized sand dunes, inter-dune depressions, and mobile sand dunes [16]. It receives the migrating birds as well as the Al Zaranik area. Fishing and salt production are the main economic activities in the lagoon. It contains many ecosystems of habitat. It is the least polluted lagoon within the Mediterranean coastal lagoons. The lagoon is connected to the sea by three inlets.

Al Bardawil Lagoon has Mediterranean weather with low water temperature in the winter season and high temperature in the summer season. Many development projects are carried out within the lagoon vicinity. The North Sinai agriculture development project is the largest project under execution in the area, Figure 2. It is expected that the seepage of agriculture water used in the project will deteriorate the lagoon’s water quality and will alter the salinity of the lake water from hypersaline to a brackish environment.

The site provides an important spawning area for fish, supports commercially important fish populations, and is an important wintering and staging area for about 500,000 birds. Considerable ecological changes have occurred due to the extension of salt extraction and the constant formation of sand bars (siltation), which close the channels connecting the lagoon to the sea.

Like all coastal lagoons in Egypt, the Al Bardawil Lagoon has many challenges which might result in environmental retreating. The most effective challenge is the changes that takes place in its inlets due to sedimentation processes and sediment transport along its coastline. This process results in decreases the fishing activities as the fishing boots face transportation problems between the sea and the lagoon. Additionally, the expected water quality deterioration would result in changing the lagoon ecosystems.
3. Materials and Methodology

3.1. Al Bardawil Lagoon Climate

The climate of the Al Bardawil Lagoon is described as an arid Mediterranean climate. Climate parameters were estimated by the Egyptian Meteorological Organization through long-term historical records. The mean annual rainfall over the area is less than 100 mm. Air temperature does not exceed 35 °C in the summer months. Air pressure has no huge differences during the different seasons of the year. Wind direction takes mainly the directions of north and northwest.

3.1.1. Rainfall

Rainfall data measured at two adjacent meteorological stations at the Al Arish airport and Port Said harbor were collected and treated. A statistical analysis process was implemented to define the mean monthly values of rainfall over the study area. The data set of rainfall included rainfall data recorded over the last 40 years (1970–2010) in Al Arish and rainfall data recorded in Port Said for the last 30 years (1980–2010). According to the World Meteorological Organization recommendations, data measured at these two stations were considered as a representative for the whole lake as the area of Al Bardawil Lagoon is less than 1200 km². Mean monthly rainfall depths are defined and presented in Table 1, and illustrated in Figure 3.

Table 1. Mean monthly rainfall depth over the Al Bardawil Lagoon.

| Month    | January | February | March | April | May | June | July | August | September | October | November | December | Mean Annual |
|----------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|-----------|-----------|-------------|
| Port Said (mm) | 18  | 12  | 10  | 5  | 4  | 0   | 0   | 0     | 3        | 8      | 7         | 16        | 83          |
| Al Arish (mm)  | 28  | 16  | 13  | 11 | 1  | 0   | 0   | 0     | 0        | 6      | 9         | 22        | 106         |
| Al Bardawil    | 23  | 14  | 11.5 | 8  | 2.5 | 0   | 0   | 0     | 1.5      | 7      | 8         | 19        | 94.5        |
3.1.2. Temperature

Air temperature is affected by the geographic location of the lagoon. According to the Egyptian Meteorological Organization’s historical records for the last 30 years, the mean air temperature usually attains its minimum value of about 14.4 °C during the winter season. It increases gradually through spring, reaching its average maximum values of 28 °C in the summer, Table 2 and Figure 4.

Table 2. Mean monthly air temperature at the Al Bardawil Lagoon.

| Month | January | February | March | April | May | June | July | August | September | October | November | December |
|-------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Mean (°C) | 14 | 15 | 17 | 19 | 21 | 25 | 28 | 27 | 26 | 23 | 19 | 16 |

Figure 4. Mean air temperature (°C) at the Al Bardawil Lagoon.

3.1.3. Relative Humidity

The mean monthly relative humidity ranges between 60 and 78% throughout the year, as indicated in Table 3. The maximum value of relative humidity was recorded in the month of August in the summer season. The lowest value was measured in the spring season, and the variation is little from one month to another, Figure 5.

Table 3. Mean monthly relative humidity at the Al Bardawil Lagoon.

| Month | January | February | March | April | May | June | July | August | September | October | November | December |
|-------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| R.H. | 69 | 70 | 68 | 65 | 65 | 65 | 70 | 73 | 70 | 70 | 68 | 67 |
3.1.4. Air Pressure

Air pressure in the area varies from one month to another, as presented in Table 4. It varies from 1008 to 1016 Hecto-pascal. Figure 6 illustrates the mean air pressure in the study area.

Table 4. Mean monthly air pressure at the Al Bardawil Lagoon (Hecto-pascal).

| Month   | January | February | March | April | May | June | July | August | September | October | November | December |
|---------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Press. (hps) | 1018    | 1016     | 1016  | 1014  | 1010| 1008 | 1008 | 1012   | 1014      | 1014   | 1018     | 1016     |

hps means hector-pascal.

3.1.5. Wind Speed and Direction

The wind speed and direction were measured in the study area by the Al Nasr Company for Salt Production, as presented in Table 5. The data set covered wind speed values and wind direction measured at a 10 m height. More data were obtained from the Port Said station, 40 km to the west of the Al Bardawil Lagoon. This set of wind data covered daily averaged wind speed and direction measured at 10 m height in the period 1985–2014.

Table 5. Mean monthly wind speed (m/s) and direction.

| Month   | January | February | March | April | May | June | July | August | September | October | November | December |
|---------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| Direction | SW      | SW       | NW    | NW    | NW  | NW   | NW   | NW     | NW        | NW      | N-NW     | SW       |
| Speed (m/s) | 4.5     | 4.6      | 4.9   | 4.8   | 4.5 | 4.3  | 3.8  | 3.7    | 4.1       | 4.6     | 4.5      | 4.7      |

S = south, N = north, and W = west.
Wind direction was illustrated from the Climate Atlas prepared by the Egyptian Meteorological Organization. Mean monthly wind speed is illustrated in Figure 7 for the Al Zaranik protectorate area in the far east section of the Al Bardawil Lagoon.

3.1.6. Sunshine Ratio

The sunshine ratio for each month was reported by the Climate Atlas of Egypt prepared by the Egyptian Meteorological Authority as presented in Table 6, Figure 8. The sunshine ratio contributes to the evaporation process. It increases the process of evaporation and increases the magnitude of the evaporation losses from the lagoon.

| Month | January | February | March | April | May | June | July | August | September | October | November | December |
|-------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| % Sun-shine | 70 | 73 | 70 | 72 | 78 | 85 | 85 | 82 | 87 | 80 | 73 | 78 |

Figure 8. Mean monthly sunshine at the study area.

3.2. Tidal Effect

The tidal characteristics of the eastern Mediterranean dominate the tidal action in the Al Bardawil Lagoon. Field measurements indicated that the tide in the Mediterranean Sea ranges between 25 and 35 cm [17]. The author concluded that an average value of 30 cm was considered as a mean annual range. Another tidal range was concluded by [18]. They considered an average tide range of 25 cm. They estimated this value as the ranges between 40 cm (during neap) and 15 cm (during spring), Figure 9. This value was considered as a small tidal range, and it has an implicit effect on the interaction processes between the Mediterranean Sea and the lagoon waters.
3.3. Evaporation Losses

Daily evaporation losses were measured by the Al Nasr Salt Production Company in the Al Zaranik protectorate area (the eastern part of the lagoon). American Evaporation Pan Class A was used to measure daily evaporation losses. Evaporation measurements were collected, treated, and subjected to statistical analysis. An average value for daily evaporation losses was defined as demonstrated in Table 7. The mean annual evaporation at the lagoon was 1777 mm. Mean monthly evaporation losses are illustrated in Figure 10.

| Month     | January | February | March | April | May    | June   | July   | August  | September | October | November | December | Tot. |
|-----------|---------|----------|-------|-------|--------|--------|--------|---------|-----------|---------|----------|----------|------|
| Daily     | 3.52    | 3.04     | 4.35  | 4.9   | 5.2    | 5.67   | 5.77   | 1.68    | 5.5       | 5.06    | 4.6      | 4.1      |      |
| Month (mm)| 109     | 113      | 138   | 147   | 161    | 167    | 179    | 176     | 165       | 157     | 138      | 127      | 1777 |

Figure 9. Tidal elevation values measured at Port Said- Egypt (1999).

Figure 10. Mean monthly evaporation.

3.4. Groundwater

The thickness of the quaternary aquifer in the North Sinai coastal zone (Holocene and Pleistocene) varies from 150 m to 330 m and rests directly on the Pliocene. According to [19], the groundwater in the southern Al Bardawil Lagoon is tapped from different water-bearing formations, which are Holocene and Pleistocene. The Holocene sand aquifer in the studied area is developed along the coastal plain with an average width of 20 km in the form of elongated sand dunes (coastal) or sand sheet (inland), or saline sand (sabkhas).

Water levels of the quaternary aquifer (sand dunes system) in North Sinai, Egypt, have been measured since 1954 in a small number of wells. Since 1982 more studies have been carried out, and a continuous monitoring program was carried out on a monthly basis by the Water Resources Research Institute (WRRI), National Water Research Center (NWRC), Egypt.

Water level measurements for the quaternary aquifer revealed that the water level in the phreatic aquifer (sand dunes system) fluctuates and changes seasonally. Measurements indicated that the highest levels take place after the rainfall season. The highest level recorded was 13.9 above mean sea level (amsl), and the lowest level was −1.5 m at areas
around the sabkhas to the west of the Al Bardawil Lagoon. Studies carried out by WRRI revealed that groundwater flows from the south toward the north and northwest. The average level of groundwater table in the study area ranges from +3 m to +0.5 m amsl. This means that the quaternary aquifer contributes to the Al Bardawil Lagoon.

The investigations and hydrogeological studies of the groundwater aquifer of the sand dune system assessed the daily contribution of the aquifer to the Al Bardawil Lagoon. Assuming that the ground slope is 2.5 m/km, the connection length between the dune system and the lagoon is 80 km, and implementing Darcy’s Law, [20] estimated the groundwater aquifer contribution to the lagoon to be about 24,000 m$^3$/d.

3.5. Investigating Water Table of the Al Bardawil Lagoon

A water table monitoring program was carried out by a group of staff gages (stage boards) in the year 2004 (21 August until 20 November). Five stage boards were installed within the eastern sector of the Al Bardawil Lagoon (Al Zaranik protectorate area). This area was chosen as the movement of fishing boots is minimum in the protectorate area, and it has permanent employees for daily measurements. The locations’ information for stage boards is presented in Table 8.

| Site No. | Site Name              | Latitude (N)     | Longitude (E)     | Starting Date    | First Reading |
|----------|-----------------------|------------------|-------------------|-----------------|---------------|
| 1        | Coasts Police Guards  | 31°12'19.40"    | 33°16'15.52"     | 21 August 2004  | 122           |
| 2        | Salt Company Pump S   | 31°07'48.31"    | 33°28'15.66"     | 21 August 2004  | 70            |
| 3        | Salah Eddin           | 31°11'38.44"    | 33°20'01.35"     | 21 August 2004  | 54            |
| 4        | In front of Flustat Island | 31°08'06.17" | 33°23'21.00"     | 21 August 2004  | 49            |
| 5        | West of Flustat Island | 31°08'11.36"   | 33°22'09.13"     | 21 August 2004  | 62            |

The stage boards were scaled timber with a 4 m length and 15 × 2.5 cm cross-section. Each stage board was fixed on a timber stick of 6 m length of 20 × 20 cm in a sheltered area. In fact, the inhabited islands scattered within the area inhabited by fishermen enabled the installation of the stage boards in the lagoon.

Daily observations measurements were made two times a day in the investigation period (August and November 2004). Stage boards were a relatively inexpensive tool to perform water table monitoring. Figure 11 shows the installation processes of the stage boards in the lagoon. The first reading was assumed to be the zero level of water surface in each site. Accordingly, any increase in the readings means water level has raised above mean sea level by this increase and vice versa.

![Figure 11. Installation of stage boards in the Al Bardawil Lagoon by the first author.](image)

3.6. Al Bardawil Lagoon Bathymetric Map

Al Bardawil is a shallow lagoon with water depths varying from 0.3 m to 6.0 m with an average water depth of 1.0 m. Its bed topography is irregular and composed of silt and sand, Figure 12 [21].
4. Results and Analysis

4.1. Wind Speed and Direction

Results of wind speed and direction data revealed that the dominant wind direction is NW with values around 4.5 m/s. The area experienced a few strong storms that had speed values greater than 10 m/s associated with W and SW winds. Previous studies concluded that NW winds that blow in the afternoon have strong magnitudes that vary between 6 and 7 m/s, and those that blow in the evening have low values of about 2 m/s [22]. Fortunately, these winds do not contribute to wave action as they blow offshore on the Mediterranean coast, Figure 13.

The seasonal variation in the wind shows stronger winds blow in March in the winter season with a maximum monthly mean value of 4.9 m/s and weaker winds with a minimum monthly mean magnitude of 3.7 m/s blow in August during the summer season.
4.2. Water Resources of the Lagoon (Inflow)

Study results revealed that water resources are rainfall, groundwater, and water inflows from the Mediterranean Sea through the lagoon openings.

4.2.1. Rainfall

Rainfall analysis revealed that water resources are rainfall, groundwater, and water inflows from the Mediterranean Sea through the lagoon openings. The rainfall analysis showed that the study area received 94.5 mm per year. This amount of rainfall contributed about 61.95 million cubic meters to the lagoon’s hydrologic balance, Table 9. Furthermore, the analysis revealed that most rainfall takes place in the winter season while the summer season has no rainfall. In this respect, rainfall analysis proved that 70% of the rainfall takes place in four months (December through March).

Table 9. Monthly rainfall depth and volume over the lagoon.

| Month    | January | February | March | April | May | June | July | August | September | October | November | December | Total |
|----------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|-------|
| Depth (mm) | 23      | 14       | 11.5  | 8.0   | 2.5 | 0.0  | 0.0  | 0.0    | 1.5       | 7.0     | 8.0      | 19.0     | 94.5  |
| Volume($10^6$ m$^3$) | 14.95   | 9.1      | 7.475 | 5.2   | 1.625 | 0.0  | 0.0  | 0.0    | 0.975     | 4.55    | 5.2      | 12.35    | 61.95 |

4.2.2. Groundwater Inflow/Outflow

Hydrological studies analysis manifested that groundwater in the sand dune aquifer system moves toward the north. This means that the dune system supplies the lagoon with a fraction of its water resources. The analysis demonstrated that the dune system provides the hydrological balance of the lagoon with a daily volume of 24,000 m$^3$. This rate contributes as much as 0.72 million m$^3$/month and about 8.64 million cubic meter per year.

4.3. Outflows from the Lagoon

4.3.1. Salt Production Requirements

The Al Nasr Company for Salt Production discharges about 250 million cubic meters of water from the lagoon to its salting basins. This volume was divided over the year according to the monthly evaporation rate. Accordingly, that volume was divided as presented in Table 10.

Table 10. Monthly outflow for salt production from the lagoon.

| Month    | January | February | March | April | May | June | July | August | September | October | November | December | Total |
|----------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|-------|
| Outflow for Salt Product. ($10^6$ m$^3$) | 15.33   | 15.8     | 19.41 | 20.68 | 22.65 | 23.49 | 25.18 | 24.76   | 23.21     | 22.1    | 19.41    | 17.87    | 250   |

4.3.2. Evaporation Losses

Evaporation losses from the lagoon were estimated for each month. The average monthly losses depth was transformed to monthly losses volume by considering the lagoon surface area (650 km$^2$), Table 11. Analysis revealed that the lagoon experiences annual evaporation losses of about 1155.05 million cubic meters. Figure 14 illustrates the monthly rainfall volumes, salt production requirements, and evaporation losses from the lagoon.

Table 11. Average daily, monthly, and volume of evaporation.

| Month | January | February | March | April | May | June | July | August | September | October | November | December | Evap. (mm) | E Losses ($10^6$ m$^3$) |
|-------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|------------|------------------------|
|       | 109     | 113      | 138   | 147   | 161 | 167  | 179  | 176    | 165       | 157     | 138      | 127      | 70.85      | 73.45      | 89.7 | 95.55 | 104.65 | 108.55 | 116.35 | 114.4 | 107.25 | 102.05 | 89.7 | 82.55 |
4.3.3. Al Bardawil Lagoon Water Balance

The water balance procedure was implemented to assess the interaction between the Al Bardawil Lagoon and the sea. The water balance is a systematic method for quantifying the hydrologic components within a specified hydrologic system. It includes all the major inflows and outflows of water within the hydrologic boundaries of the lagoon system. This procedure was applied to assess the values of unknown elements of the hydrologic system, such as the changes in the lagoon storage and the rate of outflow from the lagoon.

The water budget was defined through the continuity equation as follows:

$$\frac{ds}{dt} = \text{Inflow} - \text{Outflow}$$

In which $ds/dt$ is the storage change rate within a specified time interval. Inflow is the water discharged into the lagoon. Outflow includes the water losses from the hydrologic system and water interaction between the lagoon and the sea.

The Inflow term in the equation includes monthly rainfall and groundwater quantities. On the other hand, the Outflow term includes monthly evaporation losses and water required for salt production. Water balance results are shown in Table 12, Figure 15. Results of the water balance of the Al Bardawil Lagoon indicated the following:

- Annual rainfall provides the lagoon with 4.4% of its annual inflow.
- Groundwater provides the lagoon with 0.6% of its annual inflow.
- Annual inflow volume is about 70.59 million cubic meters.
- Annual evaporation losses account for 82.2% of its total annual outflow.
- Annual water discharged from the lagoon for salt production represents about 17.8% of the water outflow from the system.
- The outflow term from the lagoon is 1405.05 million cubic meters annually.
- The difference between inflow and outflow is 1334.46 million cubic meters annually. This volume is replenished by Mediterranean Sea water.
- Results presented in the table showed that the monthly outflow (evaporation + salt production requirements) is always greater than the monthly inflow (rainfall and groundwater). Accordingly, water moves from the sea to the lake every month to replenish the monthly difference. This is the reason for the negative sign in the $ds/dt$ column in the Table. This process resulted in a continuous movement of seawater into the lagoon, with discharges varying from 27.2 to 54.3 m$^3$/s. In addition, this process keeps water level in the lagoon below mean sea level with values range between 11 and 21 cm.
Table 12. Water balance of the Al Bardawil Lagoon.

| Month   | Inflow From the Sea to the Lagoon (10^6 m^3) | Inflow from the Rainfall (10^6 m^3) | Groundwater (10^6 m^3) | Salt Production Requirements (10^6 m^3) | Evaporation (10^6 m^3) | Inflow–Outflow (10^6 m^3) | Storage Change (ds/dt) Water Level (cm) | Inflow from the Sea to the Lagoon (m^3/a) |
|---------|-----------------------------------------------|-----------------------------------|------------------------|------------------------------------------|------------------------|--------------------------|----------------------------------------|------------------------------------------|
| January | 14.95                                         | 0.72                              | 15.33                  | 70.85                                    | −70.51                 | −70.85                   | −11                                     | 27.2029                                  |
| February| 9.1                                           | 0.72                              | 15.9                   | 73.45                                    | −79.53                 | −79.32                   | −12                                     | 30.6829                                  |
| March   | 7.475                                         | 0.72                              | 19.415                 | 89.7                                     | −100.92                | −103.31                   | −16                                     | 38.9352                                  |
| April   | 5.2                                           | 0.72                              | 20.68                  | 95.55                                    | −110.31                | −110.31                   | −17                                     | 42.5579                                  |
| May     | 1.625                                         | 0.72                              | 22.65                  | 104.65                                   | −124.95                | −124.95                   | −19                                     | 48.2079                                  |
| June    | 0                                             | 0.72                              | 23.49                  | 108.55                                   | −131.32                | −131.32                   | −20                                     | 50.6636                                  |
| July    | 0                                             | 0.72                              | 25.18                  | 116.35                                   | −140.81                | −140.81                   | −22                                     | 54.3248                                  |
| August  | 0                                             | 0.72                              | 24.76                  | 114.4                                    | −138.44                | −138.44                   | −21                                     | 53.4105                                  |
| September | 1.5                                           | 0.72                             | 23.22                  | 107.25                                   | −128.24                | −128.24                   | −20                                     | 49.4753                                  |
| October | 4.55                                          | 0.72                              | 22.09                  | 102.05                                   | −118.87                | −118.87                   | −18                                     | 45.8603                                  |
| November | 5.2                                           | 0.72                             | 19.415                 | 89.7                                     | −103.195               | −103.195                  | −16                                     | 39.8129                                  |
| December | 12.35                                         | 0.72                             | 17.87                  | 82.35                                    | −87.35                 | −87.35                    | −13                                     | 33.6998                                  |
| Total   | 61.95                                         | 0.6%                             | 250                    | 1155.05                                  | −1334.46               | −1334.46                  | % 4.4% 17.8% 82.2% 95% | % 4.4% 17.8% 82.2% 95% |

Figure 15. Water Balance of the Al Bardawil Lagoon.

4.4. Water Table Fluctuation

The water table was recorded on a daily basis at 6 am and 6 pm for the period (21 August until 21 November 2004). Assuming that the water table in the lagoon has the same level as seawater at the beginning of the observation program, the first reading at each site was considered as zero sea water level.

Although the observation period was insufficient to draw concrete conclusions about water table fluctuation, the difference between the average maximum and the average minimum values of the water table for the observation period agreed to some extent with water balance results, Table 13. Comparing water table in Tables 12 and 13 demonstrated that the water table fluctuation resulted from the water balance procedure for the months August through November ranged from 18 to 21 cm below sea level with a mean value of 19.5 cm, while the average value of water fluctuation for the five observation sites varying between 19.5 and 24.5 with an average value of 22 cm.

Table 13. Average fluctuation range at the observation sites.

| Site Number | Site (1) | Site (2) | Site (3) | Site (4) | Site (5) |
|-------------|----------|----------|----------|----------|----------|
| Average Maximum (cm) | 124      | 67.5     | 60       | 57.5     | 71       |
| Average Minimum (cm)  | 104      | 48       | 35.5     | 35       | 46.5     |
| Difference (cm)       | 20       | 19.5     | 24.5     | 22.5     | 24.5     |

Although the difference between the results of observed data and water balance was small, the difference is attributed to the short observation period while the water
balance results were drawn from long-term records of historical data. In addition, wave action-induced windstorms and fishing boat activities have a direct influence on water surface fluctuation.

Daily readings analysis indicated that water fluctuated in the morning and the evening without any clear trend, Figures 16–20.

**Figure 16.** Water Table Fluctuation at Borders Guards (Site # 1).

**Figure 17.** Water Table Fluctuation at Pumping Station of the Salt Production Company (Site # 2).

**Figure 18.** Water Table Fluctuation at Salah Eddin Opening (Site # 3).
Figure 19. Water Table Fluctuation at the East of Al Flustat Island (Site # 4).

Figure 20. Water Table Fluctuation at the West of Al Flustat Island (Site # 5).

For more analysis, Table 14 demonstrates the maximum difference between the first reading at each site (assumed as zero water level) and water table fluctuation. From the results illustrated in the Table, the following could be concluded.

Table 14. Maximum and minimum readings of the water table at observation sites.

| Site Number | Site (1) | Site (2) | Site (3) | Site (4) | Site (5) |
|-------------|----------|----------|----------|----------|----------|
| Time        | Mor.     | Eve.     | Mor.     | Eve.     | Mor.     | Eve.     | Mor.     | Eve.     | Mor.     | Eve.     |
| Maximum     | 125      | 128      | 70       | 70       | 63       | 70       | 65       | 70       | 70       | 75       |
| Minimum     | 100      | 100      | 40       | 45       | 30       | 30       | 30       | 30       | 40       | 45       |
| First Reading (Zero Level) | 122 | 70 | 54 | 49 | 62 |
| Difference from Maximum (cm) | 3 | 8 | 0 | 0 | 9 | 16 | 16 | 21 | 8 | 13 |
| Maximum Water Table Above Sea Level (cm) | 5.5 | 0.0 | 12.5 | 18.5 | 10.5 |
| Difference from Minimum (cm) | -12 | -12 | -30 | -25 | -24 | -24 | -19 | -19 | -22 | -17 |
| Maximum Water Table Below Sea Level (cm) | -12 | -27.5 | -24 | -19 | -19 | -19.5 |

Maximum water table fluctuation changed from one site to another. During the observation period, the maximum water table was raised above mean sea level with
magnitudes reaching up to 18.5 cm. On the other hand, the minimum water table had levels less than the mean sea level, with values ranging from 12 to 27.5 cm.

The fluctuation ranges were within the tide range (30 cm). The fluctuation of the water table included all factors that affect this process, such as wind action, boat movements, tide action, and storage change due to the net evaporation and salt production requirements. The maximum water table above sea level is due to wind and tide actions, while the maximum fluctuation below sea level is mainly attributed according to storage change which is the difference between monthly inflow and outflow.

Study results defined the main components of the lagoon hydrological system. It presents the baseline for the hydrological status of the lagoon. This baseline could be used by the local and governmental authorities to monitor and assess any changes in the hydrological status of the lagoon due to human and tourism activities as well as the agricultural development projects in the vicinity of the lagoon. Accordingly, a hydrological monitoring system is recommended to assess any changes in the water table, groundwater quality as well as any other hydrological parameters.

5. Summary and Conclusions

Al Bardawil Lagoon is a shallow hypersaline lagoon located in the North Sinai, Egypt. The hydrological characteristics of the lagoon were investigated in the current study. The study investigated the meteorological parameters of the study area, groundwater, wing field, tide action, and the bathymetry of the lagoon. The study defined the water resources (rainfall and groundwater) and water losses (evaporation and salt production water requirements) of the hydrological system of the lagoon. Furthermore, the study defined the water budget of the lagoon and water table fluctuation through a field measurements program. The study concluded the following:

- The lagoon receives about 95 mm of rainfall annually. This depth contributes about 61.95 million cubic meters of rainwater to the lagoon, which accounts for 4.4% of its water resources.
- Groundwater aquifer of the sand dunes system contributes about 8.64 million cubic meters to the lagoon, which accounts for 0.6% of its annual water resources.
- As an arid zone, the evaporation losses are 1155 million cubic meters per year which represents about 82.2% of the outflow of the lagoon system.
- Salt production requirements are of the magnitude 250 million cubic meters which represent about 17.8% of the outflow from the lagoon.
- Water balance results indicated that the inflow is always less than the outflow. The difference between inflow and outflow is about 1335 million cubic meters per year.
- This annual volume of water is replenished by seawater.
- This difference maintains the water level in the lagoon below the mean Mediterranean Sea level with values ranging between 11 and 22 cm according to the monthly inflow–outflow rate.
- This process maintained a continuous movement of the seawater toward the lagoon.
- Wind analysis results indicated that the prevailing direction is the NW with values around 4.5 m/s.
- Although the water table fluctuation period is insufficient to draw concrete conclusions, results indicated that the average water table in the lagoon is lower than the sea water level with values ranging between 19.5 and 24.5 with an average value of 22 cm for the observation period.
- Water fluctuation results indicated that the maximum water table was raised above mean sea level with magnitudes reaching up to 18.5 cm. On the other hand, the minimum water table had levels less than the mean sea level, with values ranging from 12 to 27.5 cm. These values are within the tide range of the eastern region of the Mediterranean Sea.
• A hydrological monitoring system is recommended to assess any changes in the water table, lagoon water quality, groundwater quality as well as any other hydrological parameters.
• Similar studies are recommended for the coastal lagoons in Egypt.

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