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# Groundwater Resources in Moroccan Coastal Aquifers: Insights of Salinization Impact on Agriculture †

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**Abstract:** Across several coastal areas in Morocco, groundwater is the strategic source of irrigation. In this work, a database of thirteen Moroccan coastal aquifers was used to assess groundwater for agriculture purposes, as well as to highlight the process responsible of the degradation of groundwater resource quality in Moroccan coastal areas. According to electrical conductivity parameter, the results show that 92% of the collected samples were not suitable for irrigation uses. This situation is due to seawater intrusion and water–rock interaction processes, in addition to intensive agriculture activities and the introduction of domestic and industrial wastewater without any treatment. In order to control the impact of groundwater salinity on agriculture, management plans are proposed.

**Keywords:** salinity; aquifer; water–rock interaction; seawater intrusion; agriculture; pollution



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## 1. Introduction

Being a precious water resource in coastal areas, coastal aquifers are undergoing significant degradation due to overexploitation, climate change, and the implementation of several socio-economic projects in different sectors, such as tourism, industry, and agriculture [1]. Agriculture represents the main factor that requires water resources in terms of quantity and quality. Salinity risk is the main problem that threatens most of the coastal aquifers in Morocco [2]. The chemical composition of irrigation water has a direct impact on plants and agricultural soil, potentially resulting in lower productivity [3]. To ensure good agriculture performance, monitoring and assessment of water quality is needed. The main focus of this study is to assess the groundwater suitability of Moroccan coastal aquifers for irrigation purposes. Moreover, in this study, some alternative solutions are suggested in order to preserve groundwater resources against pollution and to ensure the sustainability of soil and water.

## 2. Materials and Methods

Chemical analyses of groundwater samples were performed in order to determine the suitability for agricultural use. A series of irrigation water indices were used: electrical conductivity (EC), sodium absorption ratio (SAR), sodium percentage (Na%), magnesium ratio

(MR), total hardness (TH), permeability index (PI), residual sodium bicarbonate (RSBC), and Kelly's ratio (KR). A database (Table 1) of 542 samples collected from thirteen Moroccan coastal aquifers [2] (Figure 1) was used. The following equations (Equations (1)–(7)) (Table 2) were used to calculate the indices. All of the ion concentrations used were converted to meq/L. TH was expressed as ppm.

**Table 1.** Summary of groundwater physico-chemical parameters of Moroccan coastal aquifers (*SD*: standard deviation).

| **Parameters** | **EC** | **$Ca^{2+}$** | **$Mg^{2+}$** | **$Na^{+}$** | **$K^{+}$** | **$HCO_3^{-}$** | **$Cl^{-}$** | **$SO_4^{2-}$** | **$NO_3^{-}$** |
|---|---|---|---|---|---|---|---|---|---|
| | **(μS/cm)** | **(mg/L)** | | | | | | | |
| Max | 21,000 | 37.1 | 65.6 | 200.0 | 6.4 | 21.0 | 220.0 | 46.3 | 521.1 |
| Min | 190 | 0.4 | 0.2 | 0.5 | 0.0 | 0.1 | 0.4 | 0.0 | 0.0 |
| Mean | 3243 | 7.7 | 8.4 | 17.8 | 0.3 | 5.0 | 21.3 | 7.4 | 64.8 |
| *SD* | 2600 | 5.8 | 7.6 | 20.9 | 0.6 | 2.6 | 26.1 | 7.6 | 66.2 |

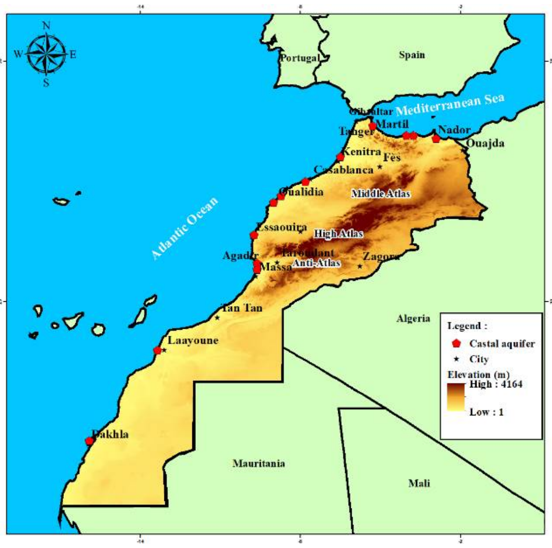


**Figure 1.** Location of Moroccan coastal aquifers.

**Table 2.** List of irrigation water indices and their equations used in this study.

| **Index** | **Index Formula** | **Equation Number** | **Source** |
|---|---|---|---|
| Sodium Absorption Ratio | $SAR = Na^{+}/\sqrt{((Ca^{2+} + Mg^{2+})/2)}$ | (1) | [4] |
| Sodium Percentage | $Na^{+}\% = ((Na^{+} + K^{+}) * 100/(Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}))$ | (2) | [5] |
| Magnesium Ratio | $MR = (Mg^{2+} * 100/(Ca^{2+} + Mg^{2+}))$ | (3) | [6] |
| Total Hardness | $TH = (2.497\ Ca^{2+} + 4.11\ Mg^{2+})$ | (4) | [7] |
| Permeability Index | $PI = (Na^{+} + \sqrt{}HCO_3^{-}) * 100/Ca^{2+} + Mg^{2+} + Na^{+}$ | (5) | [8] |
| Residual Sodium Bicarbonate | $RSBC = (HCO_3^{-} - Ca^{2+})$ | (6) | [9] |
| Kelly's Ratio | $KR = (Na^{+}/(Ca^{2+} + Mg^{2+}))$ | (7) | [10] |

## 3. Results and Discussion

Results of all indices are summarized in Table 3.

**Table 3.** Statistical summary of irrigation water indices used in this study.

| Index | Min | Max | Mean | *SD* |
|---|---|---|---|---|
| SAR | 0.2 | 45.2 | 6.1 | 6.3 |
| Na% | 5.5 | 94.9 | 45.8 | 17.9 |
| MR | 4.2 | 93.3 | 49.3 | 13.7 |
| TH | 74.1 | 4316.4 | 808.2 | 637.6 |
| RSBC | −33.2 | 15.9 | −2.7 | 6.1 |
| KR | 0.1 | 18.1 | 1.2 | 1.6 |
| PI | 10.8 | 101.8 | 57.0 | 15.8 |

The results show high values of EC reaching 21000 µS/cm (Table 1). Comparing all values with the classification adopted by [4], the results show that 8% of samples fall in the excellent class to good class. However, 92% samples fall into other classes not suitable for irrigation (permissible, doubtful, and unsuitable). This situation is explained by high concentrations of major elements in the groundwater. The SAR index shows values ranging from 0.2 to 45.2, with an average 6.1 (Table 3). According to the classification of [4], 95% of samples fall in the excellent and good classes. However, 3% and 2% of samples fall into the doubtful and unsuitable class, respectively. Concerning Na%, the results illustrate that 223 samples are within the excellent to good classes. However, 195, 101, and 23 samples fall within the permissible, doubtful, and unsuitable classes, respectively (Supplemental Table S1). Thus, 41% of the groundwater samples are suitable and 59% are unsuitable according to classification scheme of [5]. This situation reflects the abundance of $Na^+$ in coastal aquifers due to seawater intrusion and water–rock interaction processes (dissolution of halite rock) [2]. The MR values are between 4.2 to 93.3, with an average value of 49.3 (Table 3). Comparing these results with the classification adopted by [6], 48% of the samples have MR values <50, falling into the suitable class. However, 52% of the samples have MR values >50, falling into the unsuitable class. The TH index of groundwater samples ranged from 74.1 to 4316.4 mg/L, with an average of 808.2 mg/L (Table 3). Most of the water samples are classified as not suitable (hard and very hard). Both classes account for 97% of the samples of the study area. The results for PI show that values range from 10.8 to 101.8, with an average of 57.0 (Table 3). Nearly 14% of the samples fall into the class I category, which is considered to be the best for irrigation water. However, 85% of the samples fall into the class II category (acceptable for irrigation water), while the remaining 1% fall into the class III category, which is considered to be unacceptable for irrigation water. The RSBC index ranges from −33.2 to 15.9, with an average of −2.7 (Table 3). Moreover, 95% of the samples fall into the safe category, 4.6% of the samples fall into the marginal category, and 0.4% are in the unsatisfactory category. Results in Table 3 show that the values of KR range from 0.1 to 18.1, with an average of 1.2 (Table 3). The samples with values >1 indicate high values of sodium, and others with values < 1 are characterized by low concentrations of sodium [10]. In this study, 66% of the groundwater samples are suitable for irrigation. Nonetheless, 34% of the samples are unsuitable for irrigation purposes. These results show that the groundwater is considerably polluted and is under continued degradation. This situation is explained by over pumping in coastal areas and the occurrence of some hydrogeochemical processes that are dominant in coastal aquifers, such as evaporation, seawater intrusion, human activities (wastewater, agriculture), and water–rock interactions [2]. These processes increase the concentration of chemical elements within the water table, may result in the salinization of water, and can impact farmer activities. In addition, the return of irrigation water towards the water table and nitrate pollution represent another threat to groundwater in Morocco coastal aquifers [11,12]. In this study, the nitrate values are very high, exceeding 521.1 mg/L (Table 1). This situation is mainly due to agricultural activities (e.g., fertilizers) and anthropogenic activities (e.g., manure and septic effluents) in the coastal area. However, solutions are needed to preserve coastal aquifers against salinity risk. Pumping control, monitoring of seawater intrusion, desalination projects, bio-saline agriculture adoption, treated wastewater reuse, artificial recharge, and sustainable drip

irrigation and subsurface drip irrigation can implemented as sustainable management plans to preserve groundwater resources, to ensure good water for irrigation purposes, and to increase agriculture production. The promotion of scientific research projects that bring innovative solutions for the treatment of high salinity of irrigation water is also strongly required.

## 4. Conclusions

The assessment of groundwater samples for irrigation uses in coastal aquifers showed that some samples were within the permissible limit and can be used with caution, for example 8% and 41% for EC and Na%, respectively. However, several water samples were observed to be inadequate for irrigation purposes. This situation is due to salinity risk (e.g., seawater), which can degrade groundwater resources in coastal environments. Some management plans have been presented in order to reduce the salinity impact on groundwater and soil resources. These proposals will serve as a reference for future water- and agriculture-related initiatives.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environsciproc2022016048/s1, Table S1: Classification of groundwater samples of Moroccan coastal aquifers for suitability in irrigation.

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