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# Effect of Climate Change on the Quality of Soil, Groundwater, and Pomegranate Fruit Production in Al-Baha Region, Saudi Arabia: A Modeling Study Using SALTMED

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**Abstract:** Groundwater depletion coupled with climate change, increasing temperature, and decreasing precipitation, has led to groundwater quality deterioration and diminishing groundwater quantity, subsequently affecting agricultural productivity in arid environments. The groundwater of the Al-Baha region, Saudi Arabia is located in unconfined shallow aquifers and responds quickly to climate change. The Al-Baha region is facing an increase in temperature and a substantial decrease in precipitation. Over the 24-year period from 1995 to 2019, average temperatures increased by 1.1 °C–1.6 °C, while rainfall decreased by 24–41%. Consequently, this study aimed at investigating the influence of climate change on soil salinity and pomegranate productivity. To achieve this goal, a hundred and fifteen samples of soil and groundwater were collected from different locations in the Al-Baha region. Furthermore, the SALTMED model was calibrated using the salinities of 50 groundwater samples, which are used as irrigation water, and climatic data from the year 2020. The model was then validated using 65 irrigation water salinities and climatic data from the year 2020. Pomegranate fruit yield was used as the main variable for calibration and validation. After successful calibration and validation, the SALTMED model was run using 'what if' scenarios for the years 2044, 2068, and 2092. It is assumed that the temperature will increase, while the annual rainfall will decrease in upcoming decades. Consequently, the groundwater salinities will reach 1.44, 2.59, and 4.67 dS $m^{-1}$ for the years 2044, 2068, and 2092, respectively. The results revealed that the soil salinities will increase by 113%, 300%, and 675%, respectively, compared with the average soil salinity of the year 2020 (2.22 dS $m^{-1}$). Furthermore, the pomegranate tree productivity in the Al-Baha region will decrease significantly (24.0%, 36.6%, and 41.6%) in the predicted three years due to deterioration of groundwater quality and increasing temperatures. Interventions by the regional authorities to minimize the impact of climate change on crop and fruit productivity and groundwater deterioration in the Al-Baha region should be planned and carried out as soon as possible. The method used in this investigation can be utilized in similar ecosystems worldwide.

**Keywords:** climate change; modeling; projection; water quality; salinity; arid environment; pomegranate yield

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## 1. Introduction

Increased temperature and decreased precipitation, particularly in arid regions, undoubtedly has led to diminished recharge rates and degraded groundwater quality [1,2]. Low recharge rates and degraded groundwater quality pose a serious threat to ecosystem services, particularly in periods of water scarcity [1–3]. Due to lower precipitation and harsh climatic conditions, the groundwater deterioration rates are higher in the Kingdom of Saudi Arabia (KSA) [4–6]. Climate change affects groundwater quality and quantity in many direct and indirect ways [6–8]. Xiaolong and Boufadel [9] and Ludwig and Moench [10]

reported that climate change affected not only recharge rates and the depth of groundwater but also the consumption of water for irrigation and human activity. Indeed, the temperature fluctuations are not merely due to climate change but are also due to seasonal variations (spring, summer, autumn, and winter). Many studies confirm the impact of seasonality on groundwater and water-supply quality [11–14]. Jil et al. [12] reported that seasonal variation influenced groundwater contamination in the city of Guanzhong Plain, China. Furthermore, Zhang et al. [13] mention that the bacterial community structure varied significantly among seasons, and the diversity and richness of the community were much higher in spring. Treidel et al. [1] and Aly [14] reported that arid regions of the world exhibit lower recharge rates which subsequently results in the depletion and deterioration of groundwater, especially in dry season. Groundwater resources are regarded as the primary source of water for drinking and irrigation in KSA [5]. Al-Barakah et al. [15] reported that Saudi's water resources change rapidly due to climate change. An increase of groundwater depletion and deterioration in KSA occurred over the past two decades due to increased temperatures [4,16]. In arid climates experiencing climate change, temporal monitoring of groundwater quality is important to prevent hazardous influences on human health and agronomic production. It is well established that precipitation, land cover, and evapotranspiration are responsible for affecting the groundwater-recharging rates. Moreover, higher temperature leads to higher evaporation, which in turn, results in lower groundwater [17]. Unconfined shallow aquifers respond quickly to raised temperature; on the other hand, confined aquifers react slowly [18]. Consequently, confined and deep aquifers are less exposed to the direct influence of temperature [19].

The Al-Baha region, located in southwestern KSA, is now suffering from salinity increase in the groundwater [20]. The groundwater is shallow and considered a valuable natural resource vulnerable to climate change. Over the past decades, the Al-Baha region has confronted a constant increase in temperature and a substantial decrease in precipitation [4,6,8]. The twenty-five years of climatic data (1995–2019), which is divided into five cycles (1995–1999, 2000–2004, 2005–2009, 2010–2014, and 2015–2019), shows a clear trend of increasing temperatures and decreasing rainfall with time. Therefore, the first cycle period, (1995–1999) was taken as the baseline period to assess further changes in temperature and rainfall over time. Consequently, it was found that the average temperature values in the Al-Baha region increased by 1.1–1.6 °C, while rainfall decreased by 24–41% based on the average values presented in the first cycle [20]. Limited studies have been conducted to investigate groundwater quality change and agricultural productivity under rapidly changing climatic conditions [15,20]. The region of Al-Baha is famous for the cultivation of fruits, such as pomegranates, which are known to be one of the finest types of pomegranates in the Arab world [20]. Agriculture in the Al-Baha region is not limited only to pomegranate; other agricultural crops are grown there, such as grapes, peaches, and apricots, as well as grains, such as wheat, corn, barley, sesame, and lentils [8]. The number of pomegranate fruit farms in the Al-Baha region exceeds 1000. These farms contain approximately 200,000 pomegranate trees and produce about 30,000 tons of pomegranates annually (according to the approximate statistics of the Pomegranate Cooperative Society in the Al-Baha region). The farms are spread out in valleys; the most famous are Wadi Beida, Wadi Turbah Zahran, Wadi Marawa, Bani Harir, Bani Adwan, Berrahh, and Bani Kabir [20] (Figure 1). Pomegranate trees in the Al-Baha region begin to bear fruit early as they can give a crop in the third year of planting in the orchard. The trees have their highest yield when they reach the age of 10–12 years [21]. Trees may live up to 50 years. The yield of one tree ranges from 25–30 kg of fruit annually. The fruits usually ripen in the summer in the month of August, and ripening continues until the end of September, depending on the region and according to the varieties [21]. The productivity of pomegranate trees is projected to decrease in the future due to climate change. Modeling studies are a useful tool to predict the effect of climate change on crop production.



**Figure 1.** Pomegranate trees in the Al-Baha region.

Modeling studies are a labor-saving tool, inexpensive, and quick to simulate changes in crop yield, soil salinities, water and solute dynamics, irrigation water salinities, and irrigation techniques under different climatic conditions [22,23]. Indeed, many mathematical models can describe and simulate different crop growth, soil, water, and irrigation management practices. The SALTMED model has been widely used for these generic purposes [24]. The SALTMED model can be used for the modeling of a variety of soil types, crop and tree growth, application of irrigation water, and others.

The model works to establish solute and water transport, plant water uptake, evapotranspiration equations, and the effect of climate change on yield production [25,26].

The initial SALTMED model version was used during 2000–2002 for data on tomato fields in Syria and Egypt. The results presented reasonable agreement between the observed and simulated data [27–29]. Furthermore, the model was run using an experiment with sugar cane in Iran [30] and on several crops in Brazil [31]. The 2009 version of SALTMED was run, and its results were compared with the data acquired from fields of potatoes and tomatoes in Italy, Serbia, and Crete using drip (sub-surface), sprinkler, and furrow irrigation systems as full and deficit irrigation. The model displayed good ability to predict soil salinity, soil moisture, and final yield of crops [32]. In addition, the 2011 model version accurately simulated the water table, salinity, and yield of olive in the Siwa Oasis, Egypt [33]. Aly et al. [34] successfully employed the SALTMED model for irrigation water management in KSA. The model was run using deficit irrigation data ranging from 30% to 100% of the irrigation water requirements. The calibration and validation of the model showed that it satisfactorily could simulate soil salinity, soil water, and final yield of cucumber. The SALTMED model can also be used to investigate the impact of climate change on yield production. The model was used by Hirich et al. [26] to assess the change in corn yields in the Souss area in the south of Morocco with climate change, where by 2090, the temperature will increase by 3 °C, while the total quantity of rainfall will decrease by 63%.

The SALTMED model has been applied under different climatic conditions to determine the quantity of irrigation water and yield in many places all over the world. It is, therefore, suitable for predicting the effect of climate change on crop yield under arid conditions, such as in KSA. The SALTMED model could efficiently estimate crop water and irrigation water requirements, water conservation, and soil salinization, and it could predict crop production under different climatic conditions. Consequently, the main objective of this research was to study the effect of climate change on soil and groundwater salinization and pomegranate yields in the Al-Baha region using the SALTMED model.

## 2. Materials and Methods

### *2.1. Study Area*

The Al-Baha region is in the southwest of KSA (latitudes 19°27′17″ and 20°49′75″ N and longitudes 40°46′30″ and 42°10′10″ E), (Figure 2). Al-Baha consists of a total 11,221 km$^2$ area. It has six governmental areas (Al-Mkhwah, Al-Aqiq, Al-Mandq, Belgrashi, Qolwah, and Al-Qora) along with the city of Al-Baha. The Al-Baha area set on the Arabian Shield has soils containing a crystalline basement that consists of the Precambrian continental crust [35]. The weather is warm to cold in winter and reasonable to hot in summer with mean annual temperatures between 12 °C and 23 °C. Average precipitation ranges between 150 and 200 mm/year, with humidity between 50% and 70% [15].

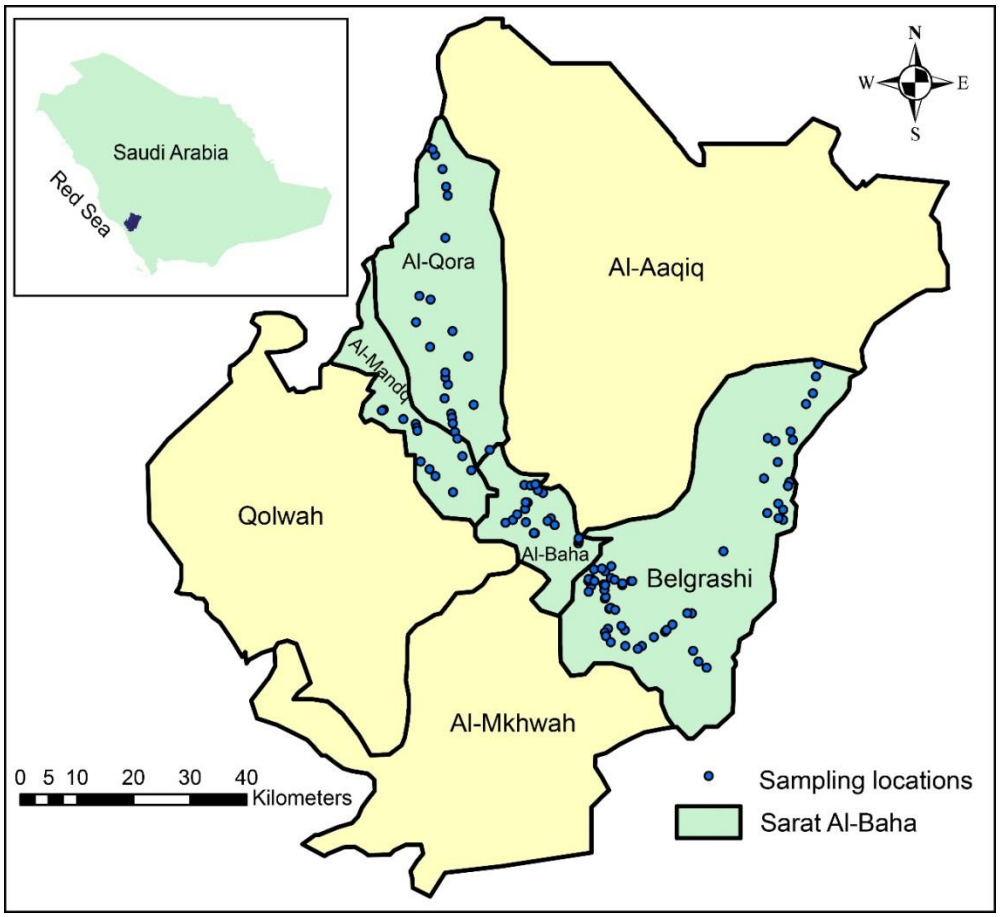



**Figure 2.** Location of the study area representing Sarat Al-Baha (Al-Qora, Al-Mandq, Al-Baha, and Belgrashi governorates) as part of the Al-Baha region.

In the modeling study, we concentrated on the central region (Sarat Al-Baha) that covers about 26.7% of the area of Al-Baha (Figure 2). However, it has the biggest population and the largest cultivated area in the region of Al-Baha. Consequently, the sustainable and economic development of Sarat Al-Baha is highly important. Protecting groundwater resources and the assessment of the impact of climatic change on the quality of groundwater is very significant for sustainable crop productivity in the region because ground water is the major source of water for irrigation and drinking purposes. The historical daily climatological reports (1995–2019), including temperature and precipitation, of Al-Baha were obtained from the General Authority for Meteorology and Environmental Protection (GAMEP, KSA) [36].

### 2.2. Soil and Groundwater Sampling and Analysis

Groundwater Analysis

Sarat Al-Baha was visited during August 2020, and a total of 115 samples consisting of groundwater and surface soil (0–30 cm) were collected from different locations (Figure 2). Four samples were gathered from the 115 locations. The groundwater samples were collected in 400 mL airtight plastic bottles. Thereafter, the collected samples were closed and carried to the laboratory for further analyses. A small portion of the groundwater samples was taken, and the pH was adjusted to <2 with concentrated $HNO_3$ for precise measurement of trace elements [37].

Groundwater and soil samples were analyzed in the laboratory for various chemical properties. The electrical conductivity (EC) and pH of the soil and water samples were determined by a pH meter (pH meter–CG 817) EC meter, respectively (Test Kit Model 1500_20 Cole- Parmer). The titration method was used to analyze soluble ions of Ca and Mg using versenate solution (Sparks, 1996), whereas the soluble K and Na were analyzed through a flame photometer (Corning 400) [38]. Acid titration was used to measure soluble ions of carbonates and bicarbonates (Sparks, 1996). Titration with silver nitrate was used to measure chloride ions [38]. The turbidity method was used to determine soluble sulfate [39]. Nitrate was determined by the phenoldisulfonic acid method [39] (Table 1). Concentrations of Fe, Cu, Mn, and Zn were measured using inductively coupled plasma (ICP) spectroscopy (Perkin Elmer Model 4300DV). Average concentrations of Fe, Cu, Mn, and Zn were 0.31, 0.02, 0.00, and 0.04 mg $L^{-1}$, respectively, for the year 2020. Assurance of measurement quality was carried out by regularly running blanks and standard solutions to test for possible inaccuracies in analysis.

**Table 1.** Average chemical properties of groundwater samples used for irrigation ($n$ = 115).

| Sampling Date | pH | $EC_W$ (dS $m^{-1}$) | Cations (meq $L^{-1}$) | | | | Anions (meq $L^{-1}$) | | | | $NO_3^-$ (mg $L^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $Ca^{++}$ | $Mg^{++}$ | $Na^+$ | $K^+$ | $CO_3^-$ | $HCO_3^-$ | $Cl^-$ | $SO_4^-$ | |
| August 2016 * | 8.01 | 0.8 | 1.8 | 4.3 | 1.9 | 0.2 | 0.0 | 2.9 | 4.7 | 0.7 | 5.7 |
| August 2020 | 7.70 | 1.1 | 3.1 | 6.2 | 2.1 | 0.3 | 0.0 | 1.0 | 8.5 | 1.7 | 4.1 |

* Data of year 2016 published by Al-Barakah et al. [15].

### 2.3. Soil Analysis

One surface soil sample was collected from each site with a total of 115 sites representing the soil depth of 0 to 30 cm. Soil salinity was determined for all soil samples. The 115 randomized surface soil samples (0–30 cm) were collected from different sites that covered the Sarat Al-Baha ecosystem, and then, they were transferred to the laboratories at KSU, Riyadh for analyses. Soil paste extracts were prepared for soil salinity measurements (ECe), and the physical and chemical characteristics were determined as described by Sparks [40] (Table 2). Fifty soil salinities collected from fifty sites were used for model calibration, and sixty-five soil salinities collected from sixty-five sites were used for model validation. The soil water content at field capacity (FC) and permanent wilting point (WP) were measured by the pressure membrane extractor (Soilmoisture Equipment Corp., Santa Barbara, CA USA) at −100 and −15,000 hPa matric potential, respectively [41]. Soil texture was determined by the hydrometer method [42]. The pH and calcium carbonate ($CaCO_3$) were determined according to Sparks [40] (Table 2).

### 2.4. The Description SALTMED Model

The SALTMED model is available and free for downloading from the following link: (http://www.icid.org/res_tools.html, accessed on 25 May 2022). The SALTMED model was subjected to calibrations and validations by numerous studies. For example, Aly [33] successfully used the SALTMED to simulate the water table, salinity, and yield of olive in the Siwa Oasis, Egypt. Aly et al. [34] successfully calibrated and validated the SALTMED model using greenhouse data of cucumber in Saudi Arabia. Hirich et al. [26] successfully

investigated changes in corn yields in the Souss area in Morocco with climate change using the SALTMED. Hirich et al. [43] successfully calibrated and validated the SALTMED model using field data of quinoa (Chenopodium quinoa Willd.) for three consecutive growing seasons.

**Table 2.** Selected soil properties (average values of 115 samples) used for the SALTMED model.

| Parameter | Unit | Surface Layer (0–30 cm) |
|---|---|---|
| EC | dS $m^{-1}$ | 2.22 |
| pH | - | 7.69 |
| $CaCO_3$ | % | 1.11 |
| Soil texture | - | Loamy sand |
| Sand | % | 78.45 |
| Silt | % | 19.96 |
| Clay | % | 1.59 |
| Bulk density | g $cm^{-3}$ | 1.31 |
| Saturated hydraulic conductivity | mm $d^{-1}$ | 1614 |
| Salinity | dS $m^{-1}$ | 2.07 |
| Water content at saturation (porosity) | $m^3m^{-3}$ | 0.420 |
| Water content at field capacity | $m^3m^{-3}$ | 0.196 |
| Water content at wilting point | $m^3m^{-3}$ | 0.043 |
| Residual water content | $m^3m^{-3}$ | 0.035 |
| Bubbling pressure | cm | 14.2 |
| Root width factor | - | 1 |
| Max depth for evaporation | mm | 140 |
| Lambda pore size distribution index | - | 1.25 |
| Longitudinal dispersivity | cm | 1.5 |
| Transverse dispersivty | cm | 0.1 |

### *2.5. Model Data Requirements*

1. Plant characteristics included basal crop coefficients, Kcb, and crop coefficient, Kc [44], crop height, root depth, root lateral development, and potential and maximum final yield recorded in the region under optimal conditions [33].
2. Soil properties included hydraulic conductivity, soil horizon depth, saturated soil water content, saturated salt diffusion coefficient, longitudinal and transversal dispersion coefficient, initial soil moisture and salinity profiles, soil moisture versus hydraulic conductivity, and tabulated data of soil moisture versus soil water potential. Laboratory measurements were used to obtain the parameters of the soil water retention curves, whereas initial soil water content, shallow groundwater depth and salinity, and soil salinity were based on measurements either made in the laboratory or in the field.
3. Meteorological data were provided by the meteorological station of Saudi Arabia, and TU TIEMPO.NET (online at: https://en.tutiempo.net/climate/01-2021/ws-410550.html, accessed on 1 May 2022). The meteorological data consisted of the daily maximum and minimum temperatures along with the relative humidity, wind speed, precipitation data, and the radiation.

### *2.6. SALTMED Calibration and Validation*

The SALTMED model was calibrated using fifty groundwater samples with different salinities (EC, dS $m^{-1}$) as irrigation water and climatic data from the year 2020. In addition, fifty soil samples were collected from groundwater at the same sites and were used to compare the observed and simulated soil salinity. The model was then validated using 65 soil salinities with pomegranate fruit yield as the main variable for calibration and validation.

Calibration of SALTMED was carried out to adjust the irrigation data, which contained soil parameters, such as the saturated and unsaturated hydraulic conductivity, and the plant data, such as plant height, rooting depth, and leaf area index, until a minimal difference

between observed and modeled salinity was achieved. The calibrated SALTMED input of the control treatment was used in the validation of the other treatments. The process of calibration was performed by altering the originally estimated or measured values of the irrigation and soil parameters one at a time until the differences between the calibrated and observed soil salinities are equal to or less than a specific threshold value. Fine tuning of few soil and crop parameters was performed to get a good calibration.

The validation process of soil salinity was based on the use of the irrigation data, flow rate, duration of irrigation, and climatic data from the year 2020. Parameters of the saturated and unsaturated soil hydraulic conductivity of the control treatment were also used.

After the successful completion of the calibration and validation processes, the SALTMED model was run using 'what if' scenarios for the years 2044, 2068, and 2092 using projected climatic data and irrigation water salinities. Because the groundwater salinity in the Al-Baha region is predicted to increase due to a decrease in precipitation, increasing temperatures, dissociation of halite minerals, and locations in unconfined shallow aquifers which respond quickly to climate change [20], the model was run with new irrigation input files for the years 2044, 2068, and 2092. It was assumed that the groundwater salinities would be 1.44, 2.59, and 4.67 dS $m^{-1}$ for these years, respectively. This assumption is based on the finding of Alghamdi et al. [20] who monitored the groundwater of the Al-Baha region over a period of four years, 2016–2020, and found that the average groundwater salinity increased by 27.3%.

The climatic input file included maximum and minimum temperatures that increased by 1.35, 2.7, and 4.05 °C for the years 2044, 2068, and 2092, respectively.

### *2.7. Statistical Analyses*

Three statistical indicators were used to determine the goodness of fit between the observed and simulated model values:

(1) The root mean square error (RMSE) is calculated as Equation (1):

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n} (Oi - Si)^2 / n} \quad (1)$$

where $Oi$ and $Si$ are the $i^{\text{th}}$ values of the observed and simulated values, respectively, and $n$ is the total number of values.

(2) The coefficient of residual mass (CRM) [45] is defined by:

$$\text{CRM} = \frac{\sum_{i=1}^{n} Oi - \sum_{i=1}^{n} Si}{\sum_{i=1}^{n} Oi} \quad (2)$$

The CRM assesses the tendency of the model to overestimate or underestimate simulation values in comparison to the observed values. Positive CRM values are an indication that the model is underestimating measurement values, whereas negative CRM values indicate overestimation of measurement values.

(3) The coefficient of determination ($R^2$) was measured by the Equation (3):

$$R^2 = \frac{\left[\sum_{i=1}^{n} \left(Oi - O_{avg}\right)\left(Si - S_{avg}\right)\right]^2}{\sum_{i=1}^{n} \left(Oi - O_{avg}\right)^2 \sum_{i=1}^{n} \left(Si - S_{avg}\right)^2} \quad (3)$$

where $O_{avg}$ and $S_{avg}$ are the averages of experiential and simulated values, respectively. The $R^2$ value ranges between 0 and 1. An $R^2$ close to one is an indication of a more perfect correlation between the simulated and experimental values. In general, the perfect fit between the observed and simulated results occurs when values of RMSE, CRM, and $R^2$ approach or are equal to 0, 0, and 1, respectively.

## 3. Results and Discussion

### *3.1. Sarat Al-Baha Climatic History*

Analysis of the climatic data in the Al-Baha region for the past 24 years (1995–2019) revealed average temperature periodic cycles of every two to three years. Yearly rainfall presented slightly longer periodic cycles of four to five years (Figure 3). Between 1995 and 2019, the average temperature in the region increased by 1.1–1.6 °C. Rainfall decreased between 24% and 41% during the same period (Figure 3).

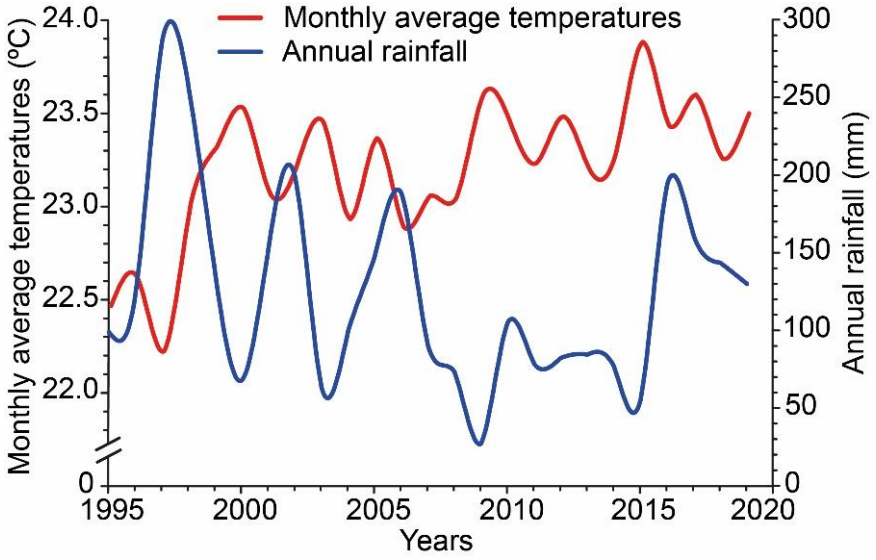



**Figure 3.** Average monthly temperatures (°C) and annual rainfall (mm) during the period of 1995–2019 in the Al-Baha region.

### *3.2. Change Detection of Al-Baha Groundwater Quality*

Al-Baha is a highly vulnerable area due to the fragile ecosystem. Thus, the impacts of climate change are prominent on water resource degradation. Moreover, the improper management of groundwater has resulted in the deterioration of water resources and groundwater quality in the region.

The quality of groundwater of Al-Baha was classified according to the salinity diagram (U.S. Salinity Laboratory) by Al-Barakah et al. [15,46]. It was concluded that 60% of the groundwater in Al-Baha was within class C3-S1 (high salinity and low sodium hazards). In this study, we found this class of salinity (C3-S1) to represent 80.7% of collected groundwater samples. These findings indicate a clear trend of groundwater salinity increase during the period of 2016–2020. Previous research have indicated that around 10% of the tested samples of groundwater contained a higher salinity level (i.e., class C4-S1). Such findings suggest rapid deterioration in the quality of groundwater in Al-Baha [14,16]. The excessive amount of salts in groundwater found in some of the sampling locations indicates that groundwater in these locations cannot be used for irrigation of most crops [47]. Alghamdi et al. [20] calculated the saturation index of Al-Baha groundwater samples and reported that almost all the groundwater samples analyzed showed under-saturated conditions with halite (NaCl) minerals, which indicate a possible increase in the concentration of sodium and chloride ions in groundwater due to the dissolution of this mineral [48,49].

### *3.3. Groundwater Salinity Impact on Soil Salinity*

Because groundwater in Al-Baha is in unconfined shallow aquifers (5–10 m in depth), it responds quickly to climate change, low rainfall, and an increase in temperature and therefore, increase salinity [20]. In response to the increase of irrigation groundwater salinity, 41.7% of the irrigated soils had an ECe of less than 1 dS $m^{-1}$, 38.3% of the soils had an ECe that ranged between 1 and 2 dS $m^{-1}$, and 20% of the soils had an ECe more than

2 dS $m^{-1}$. However, 52.5% of the groundwater used for irrigation had ECw (groundwater electrical conductivity) less than 1 dS $m^{-1}$, 33.9% of the groundwater had ECw that ranged between 1 and 2 dS $m^{-1}$, and 13.9% of the groundwater had ECw with more than 2 dS $m^{-1}$ (Figure 4).

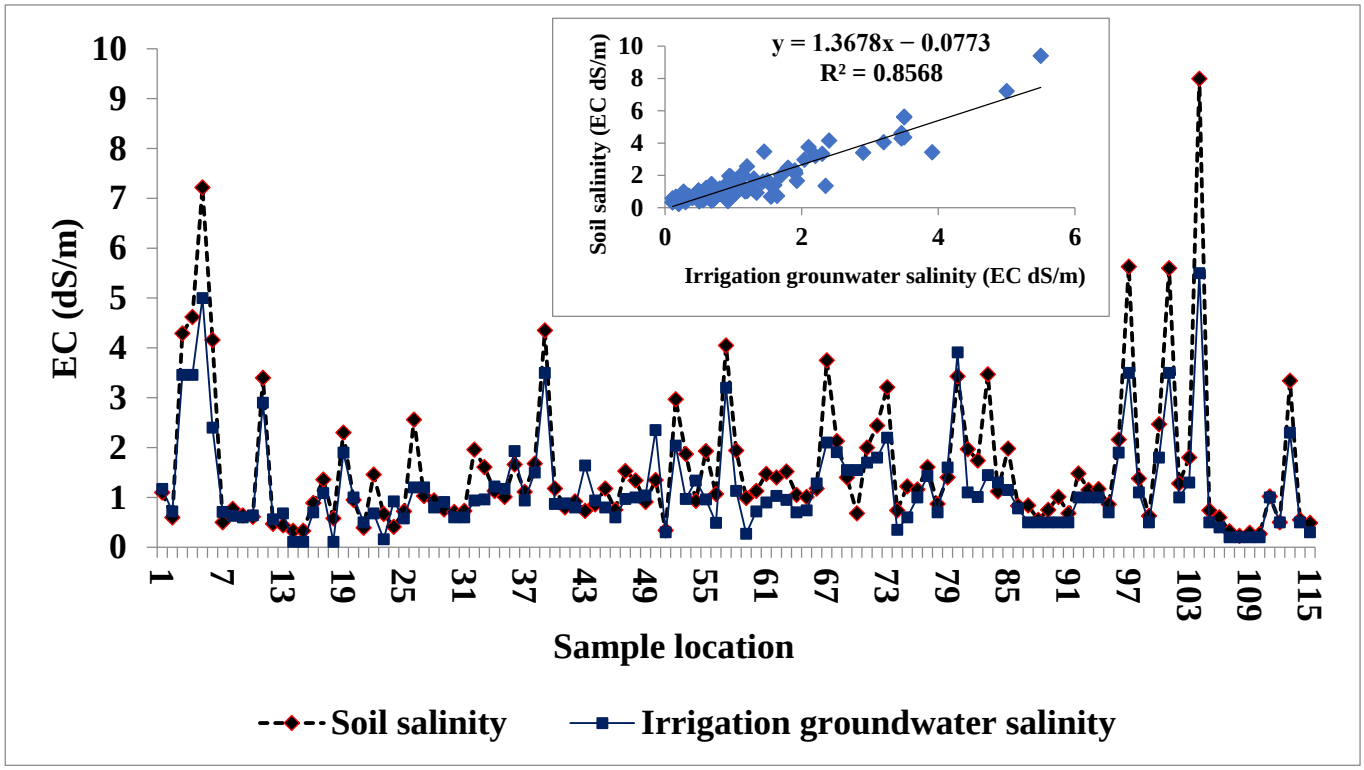



**Figure 4.** The relation between irrigation groundwater salinity and soil salinity.

The Al-Baha ecosystem was shown to be more vulnerable to soil salinization when irrigated with saline water in the absence of proper irrigation water management. Irrigating the soil with saline water led to a soil salinity increase (Figure 4). Consequently, there was a decrease in the productivity of crops. This finding agrees with those of Flowers et al. [50], Aly [33], Aly et al. [16], and Aly [14].

### *3.4. SALTMED Model Calibration and Validation*

The values of the soil parameter based on laboratory measurement and academic research were employed in the first calibration stage. It is essential to fine-tune the calibration parameters, particularly for those directly related to the yield of pomegranates and soil salinity [33]. The analyzed soil parameters were used as is, while the soil parameters from the previous research were adjusted during the calibration process.

To obtain a good relationship between simulated and experimental soil salinity values, all soil parameters were adjusted (Figure 5). A large variation in the salinity of the topsoil layer (0–30 cm) was observed due to the large variation in irrigation groundwater salinities. The upper soil layer receives irrigation water and is subject to the largest evaporation rates [33]. In addition, root development is usually more concentrated in the surface soil layer, consequently, higher soil moisture depletion occurs and soil salinity increases. These findings are consistent with Aly et al. [34] and Silva [51].

Figure 5A,B demonstrate the relationship among the simulated and observed soil salinity values, showing good agreement. The coefficient of determination ($R^2$) and RMSE were 98.6% and 0.11, respectively, during the salinity calibration process (Figure 5A and Table 3) and 98.2% and 0.17, respectively, during the salinity validation process (Figure 5B and

Table 3). These finding are consistent with those obtained by Silva et al. [51], Aly et al. [34], and Hirich et al. [26].

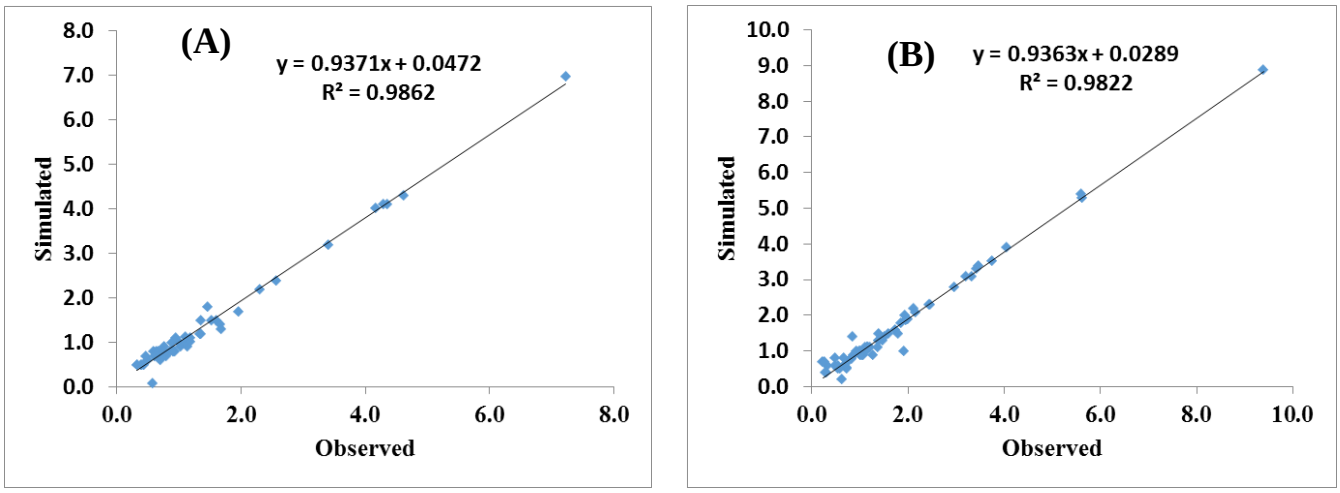



**Figure 5.** Observed vs. simulated and the correlation of soil salinity at the 0 to 30 cm depth (**A**) calibration and (**B**) validation using 50 and 65 sites for calibration and validation, respectively (sampling date August 2020).

**Table 3.** Root mean square error (RMSE) and coefficient of residual mass (CRM) between simulated and observed soil salinities for the calibration and validation process.

| | Calibration Process | Validation Process |
|---|---|---|
| RMSE | 0.11 | 0.17 |
| CRM | 0.02 | 0.05 |

Tables 3, A1 and A2 show that soil salinities (EC dS $m^{-1}$) were slightly underestimated. Overall, there was a minor underestimation predicted through the SALTMED model in both the calibration (CRM = 0.02) and validation (CRM = 0.05) processes.

### *3.5. Projection of Soil Salinity in the Al-Baha Region*

Because groundwater salinity in the Al-Baha region is predicted to increase due to a decrease in precipitation, increasing temperatures, and a dissociation of halite minerals [20], the model was run for the years 2044, 2068, and 2092. It had a new irrigation input file assuming that the groundwater salinities will be 1.44, 2.59, and 4.67 dS $m^{-1}$ for these years, respectively, and a new climatic input file assuming temperatures will increase by 1.35, 2.7, and 4.05 °C, respectively, for these three years. The model projected that the soil salinities for the years 2044, 2068, and 2092 will increase by 113%, 300%, and 675% (4.73, 8.89, and 17.21 dS $m^{-1}$), respectively, compared with the average soil salinity of the year 2020 (2.22 dS $m^{-1}$) (Figure 6) [14,33]. Results show the need for urgent governmental actions to take place to mitigate the impact of climate change on the groundwater resources in the Al-Baha region.

### *3.6. Projection of Pomegranate Fruit Yields in the Al-Baha Region*

Pomegranate fruit is one of the most prominent and most widespread fruits in the Al-Baha region. The average pomegranate productions in Al-Baha were 9.25 and 9.13 ton $ha^{-1}$ in the years 2016 and 2020, respectively. Pomegranates yields calculated by SALTMED were 9.17 and 9.08 ton $ha^{-1}$ for years 2016 and 2020, respectively. In general, good agreement between simulated and observed pomegranate yields was observed for the years 2016 and 2020 (Figure 7). However, the SALTMED model slightly underestimated pomegranate yield as evident by CRM values (CRM = 0.01). Similar results were found by Hirich et al. [26]

and Aly et al. [34]. Furthermore, the model predicts that pomegranate yields will decrease by 24.0%, 36.6%, and 41.6% (∽6.9, 5.76, and 5.3 ton $ha^{-1}$) in the years 2044, 2068, and 2092, respectively, compared to the yield of the year 2020 if the same amount of irrigation water is used but with increased temperatures and irrigation water salinity (Figure 7). However, when we assume that the amount of irrigation water will decrease in the years 2068 and 2092 by 32.5% and 65%, respectively, due to precipitation decrease, the yield is then projected to decrease by 38.3% and 53.7% (5.6 and 4.2 ton $ha^{-1}$), respectively [26,34].

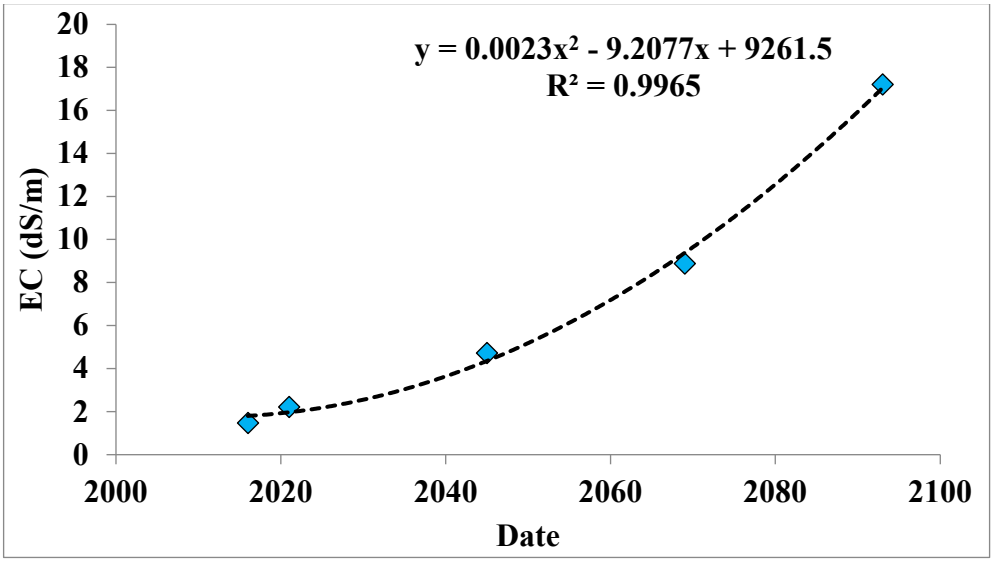



**Figure 6.** Projected salinity of Al-Baha soils using SALTMED.

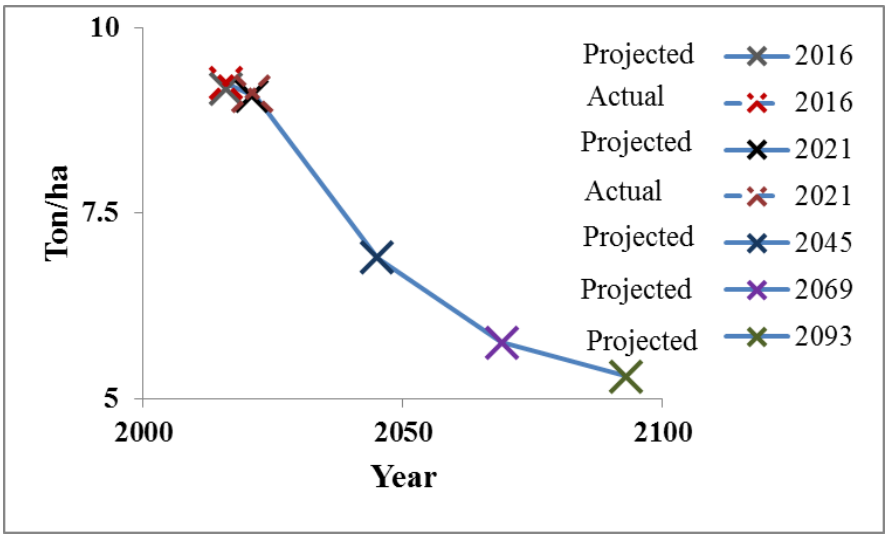



**Figure 7.** Actual and projected pomegranate yields in the Al-Baha region using the SALTMED model.

Research methodologies and approaches used in this study can be applied in other locations with similar ecosystem conditions worldwide. This approach can help to predict and understand the impact of climate change on soil salinity and crop productivity, hence, contributing to the achievement of sustainable development goals.

## 4. Conclusions

The main objective of this study was to investigate the effect of climate change on soil and groundwater quality in the Al-Baha region located in Saudi Arabia using the SALTMED model. A hundred and fifteen sites in the Sarat area in the Al-Baha region

were selected to collect groundwater and soil samples. The study found that groundwater salinity will increase due to the increase in temperatures and the decrease in rainfall. The results showed that 41.7% of the soils irrigated with groundwater had an ECe that was less than 1 dS $m^{-1}$, 38.3% of the soils had an ECe that ranged between 1 and 2 dS $m^{-1}$, and 20% of the soils had an ECe that was more than 2 dS $m^{-1}$. Furthermore, it was observed that there was a large variation in salinity in the topsoil layers (0–30 cm) due to large variations in salinity of the groundwater that was used for irrigation. The SALTMED model was used to predict over a long time the impact of climate change on soil salinization and yield of pomegranate in the Al-Baha region. The results revealed that there was good agreement between the simulated and observed soil salinities and pomegranate yield values. Soil salinities (EC dS $m^{-1}$) were slightly underestimated (CRM = 0.02 and 0.05 during calibration and validation, respectively). Furthermore, the model projected that for 2044, 2068, and 2092, the soil salinities will increase by 113%, 300%, and 675%, respectively, compared with the average soil salinity of the year 2020 (2.22 dS $m^{-1}$). Pomegranate yields will decrease by 24.0%, 36.6%, and 41.6% (6.9, 5.76, and 5.3 ton $ha^{-1}$), respectively, compared to the yield of the year 2020. This study confirms a general trend of increase of groundwater and soil salinization in the Al-Baha region. Therefore, the decision makers should take actions to decrease the influences of projected changes in climate, which may reduce the yield of crops. Consequently, it is necessary to stop drilling for more wells; furthermore, there is a need for more research to monitor groundwater quality and quantity seasonally and for a long period in the region. In addition, it is important to select suitable crops that can tolerate increasing salinities and to implement proper water management practices to minimize reduction of crop productivity, improve water productivity, and protect groundwater resources in Sarat Al-Baha region.

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## Appendix A

**Table A1.** Variation between observed and simulated soil salinities of 50 sites for the calibration process (sampling date August 2020).

| Location | Calibration Process | | Location | Calibration Process | |
|---|---|---|---|---|---|
| | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) | | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) |
| 1 | 1.10 | 1.13 | 33 | 1.61 | 1.50 |
| 2 | 0.60 | 0.80 | 34 | 1.13 | 0.90 |
| 3 | 4.29 | 4.10 | 35 | 1.01 | 1.00 |
| 4 | 4.62 | 4.30 | 36 | 1.66 | 1.40 |
| 5 | 7.22 | 6.99 | 37 | 1.11 | 1.00 |
| 6 | 4.16 | 4.02 | 38 | 1.68 | 1.30 |

**Table A1.** *Cont.*

| Location | Calibration Process | | Location | Calibration Process | |
|---|---|---|---|---|---|
| | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) | | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) |
| 7 | 0.50 | 0.60 | 39 | 4.35 | 4.10 |
| 8 | 0.77 | 0.90 | 40 | 1.18 | 1.01 |
| 9 | 0.64 | 0.80 | 41 | 0.80 | 0.70 |
| 10 | 0.61 | 0.70 | 42 | 0.92 | 0.80 |
| 11 | 3.40 | 3.20 | 43 | 0.73 | 0.70 |
| 12 | 0.47 | 0.70 | 44 | 0.86 | 0.80 |
| 13 | 0.44 | 0.50 | 45 | 1.18 | 1.10 |
| 14 | 0.33 | 0.50 | 46 | 0.75 | 0.80 |
| 15 | 0.33 | 0.50 | 47 | 1.53 | 1.50 |
| 16 | 0.89 | 1.00 | 48 | 1.34 | 1.20 |
| 17 | 1.36 | 1.20 | 49 | 0.91 | 0.80 |
| 18 | 0.58 | 0.80 | 50 | 1.35 | 1.50 |
| 19 | 2.30 | 2.20 | RMSE | | 0.11 |
| 20 | 0.95 | 1.10 | CRM | | 0.02 |
| 21 | 0.39 | 0.50 | | | |
| 22 | 1.46 | 1.80 | | | |
| 23 | 0.67 | 0.80 | | | |
| 24 | 0.41 | 0.50 | | | |
| 25 | 0.72 | 0.80 | | | |
| 26 | 2.56 | 2.40 | | | |
| 27 | 1.03 | 0.90 | | | |
| 28 | 0.94 | 0.80 | | | |
| 29 | 0.76 | 0.80 | | | |
| 30 | 0.71 | 0.60 | | | |
| 31 | 0.73 | 0.80 | | | |
| 32 | 1.96 | 1.70 | | | |

Notes: RMSE = root mean square error. CRM = coefficient of residual mass

**Table A2.** Variation between observed and simulated soil salinity of 65 sites for the validation process (sampling date August 2020).

| Location | Validation Process | | Location | Validation Process | |
|---|---|---|---|---|---|
| | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) | | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) |
| 51 | 0.34 | 0.60 | 84 | 1.12 | 1.10 |
| 52 | 2.97 | 2.80 | 85 | 1.98 | 1.89 |
| 53 | 1.87 | 1.80 | 86 | 0.83 | 0.80 |
| 54 | 0.93 | 1.00 | 87 | 0.84 | 0.79 |
| 55 | 1.93 | 1.01 | 88 | 0.55 | 0.50 |
| 56 | 1.07 | 0.90 | 89 | 0.75 | 0.70 |
| 57 | 4.05 | 3.91 | 90 | 1.01 | 1.00 |
| 58 | 1.94 | 2.00 | 91 | 0.68 | 0.60 |
| 59 | 0.99 | 1.00 | 92 | 1.48 | 1.29 |
| 60 | 1.13 | 0.99 | 93 | 1.15 | 1.10 |
| 61 | 1.47 | 1.35 | 94 | 1.17 | 1.12 |
| 62 | 1.40 | 1.30 | 95 | 0.86 | 1.40 |
| 63 | 1.52 | 1.40 | 96 | 2.16 | 2.10 |
| 64 | 1.05 | 0.90 | 97 | 5.63 | 5.31 |
| 65 | 1.01 | 0.90 | 98 | 1.38 | 1.10 |
| 66 | 1.18 | 1.10 | 99 | 0.63 | 0.20 |
| 67 | 3.75 | 3.53 | 100 | 2.47 | 2.30 |
| 68 | 2.13 | 2.20 | 101 | 5.60 | 5.41 |
| 69 | 1.40 | 1.50 | 102 | 1.28 | 0.90 |
| 70 | 0.68 | 0.80 | 103 | 1.80 | 1.50 |

**Table A2.** *Cont.*

| Location | Validation Process | | Location | Validation Process | |
|---|---|---|---|---|---|
| | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) | | Observed (EC dS $m^{-1}$) | Simulated (EC dS $m^{-1}$) |
| 71 | 2.00 | 1.90 | 104 | 9.40 | 8.90 |
| 72 | 2.44 | 2.30 | 105 | 0.74 | 0.55 |
| 73 | 3.21 | 3.10 | 106 | 0.60 | 0.50 |
| 74 | 0.74 | 0.50 | 107 | 0.32 | 0.40 |
| 75 | 1.22 | 1.10 | 108 | 0.23 | 0.70 |
| 76 | 1.16 | 1.10 | 109 | 0.29 | 0.40 |
| 77 | 1.61 | 1.50 | 110 | 0.27 | 0.70 |
| 78 | 0.87 | 0.90 | 111 | 1.02 | 0.90 |
| 79 | 1.40 | 1.30 | 112 | 0.50 | 0.60 |
| 80 | 3.43 | 3.30 | 113 | 3.34 | 3.10 |
| 81 | 1.97 | 1.87 | 114 | 0.55 | 0.60 |
| 82 | 1.74 | 1.60 | 115 | 0.49 | 0.80 |
| 83 | 3.47 | 3.40 | RMSE | | 0.17 |
| | | | CRM | | 0.05 |

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