



Statistical modeling of spatial and temporal vulnerability of groundwater level in the Gaza Strip (Palestine)

Hassan Al-Najjar ^{a,*}, Gokmen Ceribasi^b, Emrah Dogan^c, Khalid Qahman^d, Mazen Abualtayef^e and Ahmet Iyad Ceyhunlu ^b

^a Department of Civil Engineering, Institute of Natural Sciences, Sakarya University, 54187 Sakarya, Turkey

^b Department of Civil Engineering, Technology Faculty, Sakarya University of Applied Sciences, 54187 Sakarya, Turkey

^c Department of Civil Engineering, Faculty of Engineering, Sakarya University, 54187 Sakarya, Turkey

^d Environment Quality Authority, Gaza, Palestine

^e Department of Civil and Environmental Engineering, Islamic University of Gaza, Gaza, Palestine

*Corresponding author. E-mail: hassan.al-najjar@ogr.sakarya.edu.tr

 HA, 0000-0003-2192-4301; AIC, 0000-0003-3192-6132

ABSTRACT

The water supply in the Gaza Strip substantially depends on the groundwater resource of the Gaza coastal aquifer. The climate changes and the over-exploiting processes negatively impact the recovery of the groundwater balance. The climate variability is characterized by the decline in the precipitation of -5.2% and an increase in temperature of $+1\text{ }^{\circ}\text{C}$ in the timeframe of 2020–2040. The potential evaporation and the sunshine period are expected to increase by about 111 mm and 5 hours, respectively, during the next 20 years. However, the atmosphere is predicted to be drier where the relative humidity will fall by a trend of -8% in 20 years. The groundwater abstraction is predicted to increase by 55% by 2040. The response of the groundwater level to climate change and groundwater pumping was evaluated using a model of a 20-neuron ANN with a performance of the correlation coefficient (r)= $0.95\text{--}0.99$ and the root mean square error ($RMSE$)= $0.09\text{--}0.21$. Nowadays, the model reveals that the groundwater level ranges between -0.38 and -18.5 m and by 2040 it is expected to reach -1.13 and -28 m below MSL at the northern and southern governorates of the Gaza Strip, respectively.

Key words: climate change, coastal aquifer, Gaza Strip, groundwater, Palestine

HIGHLIGHTS

- Groundwater in the Gaza Strip faces serious decline of about -18 m below mean sea level.
- The climate change affects the future groundwater balance by a decline of about -10 m over 2020–2040.
- Nontraditional water resources should be introduced to cope with the water scarcity in the Gaza Strip.

1. INTRODUCTION

Groundwater is the dominant water resource for more than half of the domestic and agricultural needs on Earth (Anderson 2017). The Mediterranean arid and semi-arid regions are experiencing serious water supply threats due to the impacts of extreme climate changes which affect the natural recovery of the limited groundwater resources (Gopalakrishnan *et al.* 2019; Hussain *et al.* 2019). Moreover, the abuse of the groundwater through high over-pumping processes causes severe and subnational depression in the groundwater table to levels below the mean sea level (MSL) and this, in turn, causes prolonged salinization, irreversible economic losses, and a serious threat to food security (Zekri *et al.* 2017). In this scope, groundwater modeling-based management becomes crucial to evaluate the groundwater level variability to develop effective mitigation strategies and efficient management policies in order to preserve the groundwater resources sustainably (Gladden & Park 2016; Karimi *et al.* 2019). The data-driven statistical models are common types of climate and groundwater models that are widely developed to simulate the long-term time series data of groundwater level for future forecasting and decision-making (Yan & Ma 2016; Zhou *et al.* 2017). In addition, artificial intelligence (AI) techniques are intelligent data-driven methods that can capture efficiently the nonlinear relationships between the groundwater level and other related climatic parameters (Emamgholizadeh *et al.* 2014). In applicability, the artificial neural networks (ANNs) are the most promising and competitive algorithms among the AI algorithms which

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are widely utilized in the applications of groundwater modeling (Chang *et al.* 2016; Ebrahimi & Rajaei 2017). The power of ANN models in groundwater studies refers to their advantages as groundwater management tools for studying the impact of water policies and intervention plans on the sustainability and the recovery of groundwater resources (Krishna *et al.* 2008; Trichakis *et al.* 2009; Mohanty *et al.* 2010). The statistical data-driven methods have been exploited by many researchers to simulate the climate and hydrology of water (Kumbuyo *et al.* 2014; Al-Najjar *et al.* 2020). The stochastic ARIMA models are widely used in water resources management applications, especially for modeling hydrological stream flows, groundwater level fluctuations, and drought patterns (Myronidis *et al.* 2018; Takafuji *et al.* 2018; Sakizadeh *et al.* 2019; Al-Najjar *et al.* 2020). Moreover, the ability of AI in hydrology and water resources management and for groundwater level modeling has been examined by many studies (Rakhshandehroo *et al.* 2012; Ghose *et al.* 2018; Kouziokas *et al.* 2018; Guzman *et al.* 2019; Lee *et al.* 2019; Tang *et al.* 2019). In particular, this study aims to simulate the fluctuations in the groundwater level of the Gaza coastal aquifer in light of the climate change consequences.

2. SCOPE OF THE STUDY AREA

The Gaza Strip (Figure 1) is a littoral strip of land that comprises an area of 365 km² on the southeast coast of the Mediterranean Sea with a stretch of 42 km and a width that ranges between 6 and 12 km. The Gaza Strip is categorized as one of the world's highly populated areas with a population of about two million inhabitants (PCBS 2020).

Several agencies identify the current situation in the Gaza Strip as a severe humanitarian crisis where the coastal aquifer that is the only accessible resource for water supply is heavily contaminated and suffers from chronic degradation conditions (UN 2012; PWA 2014). Quantitatively, the total water extracted from the Gaza coastal aquifer is reported by about four times the amount, i.e., 55 million cubic meters per year, that the aquifer can sustainably produce each year (PWA 2013, 2014, 2015). The groundwater of the Gaza coastal aquifer is, in general, neutral with a slight trend to the alkalinity condition, with a pH value that ranges from 6.7 to 8.3, due to the existence of the carbonate mineral dissolution in the form of bicarbonate (HCO_3^-). The electrical conductivity (EC) ranges between 597 and 30,400 $\mu S/cm$ and demonstrates recorded values ranging between 370 and 18,848 mg/L for total dissolved

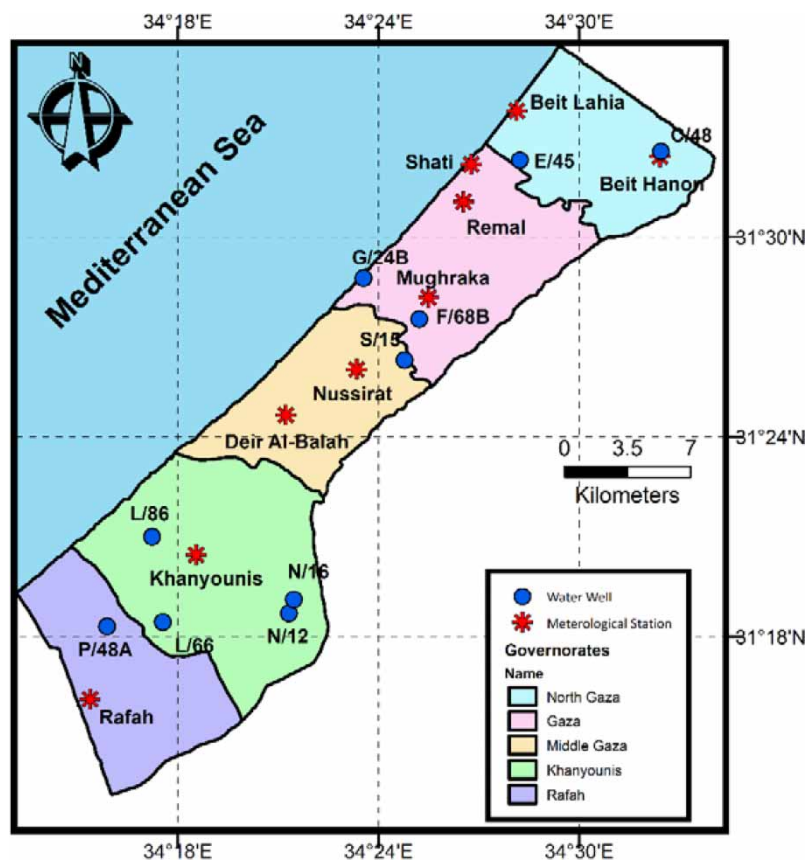


Figure 1 | The geographical location of the Gaza Strip.

solids (TDS). The concentrations of the detected ions in the groundwater for chloride (Cl^-), sodium (Na^+), magnesium (Mg^{+2}), calcium (Ca^{+2}), potassium (K^+), (SO_4^{2-}), (HCO_3^-), and (NO_3^-) were 78–10,318, 41–5,400, 23–665, 25–657, 1.4–155, 8–1,604, 101–1,280, and 18–496 mg/L, respectively (Abu-alnaeem *et al.* 2018). Climatic drought is a significant occurrence in the Gaza Strip owing to climate change consequences which adversely influence the vulnerability of the coastal aquifer and the sustainability of agricultural activities. Drought investigation studies reveal that the incidence of drought occurrence has increased from about 20% in the 1970s to more than 80% in the last ten years (Al-Najjar *et al.* 2020). The increase in drought events can be imputed to the decrease in precipitation and the spike of evaporation related to temperature rises. Generally, the total average annual rainfall in the Gaza Strip is typically estimated to be about 370 mm. Climate models indicate that the amount of precipitation is diminishing, and the local downscaling of the drought demonstrates that the southern Gaza Strip governorates are in prolonged drought, while the northern areas are experiencing drought every 9–12 years (Al-Najjar *et al.* 2020).

3. MATERIAL AND METHODS

The study aims at investigating the climate change traces and modeling the groundwater level of the Gaza coastal aquifer according to the approaches described in Figure 2. The methodology relies on the merit of coupling the stochastic time series models and the artificial neural networks (ANNs) to construct an integrated groundwater management model capable of describing the groundwater dynamic of the Gaza coastal aquifer in terms of the change in climate conditions over the next 20 years to 2040.

The available data for climate and water supply in the Gaza Strip were collected through a field survey of the meteorological stations and the monitoring groundwater wells; however, the lack of possibility and the operational phase of these monitoring stations led to a lack of available data to a period extending only to 2016 for climate parameters and 2018 for groundwater level. The available historical records for the climate parameters of the monthly precipitation (P), minimum temperature (T_{min}), average temperature (T_{avg}), maximum temperature (T_{max}), evaporation (E_o), sunshine (S_o), and humidity (H_o) for the period of 1974–2016 were collected, screened, and statistically analyzed for the meteorological stations distributed over the Gaza Strip. The groundwater table level due to the excessive pumping and the low recharge rate shows significant depression; therefore, the historical water-table level records from ten groundwater wells, shown in Figure 1, which exhibit an influential change in the water level and over-abstraction activity from the Gaza coastal aquifer were collected throughout 1974–2018. In generating the models, 90% of the observed data were utilized for calibration while the other 10% of the data were used for validation and testing the performance of the model in forecasting the future. In terms of models, the stochastic autoregressive integrated moving average (ARIMA) models, mathematically described in Equation (1), were used in this study to forecast the future trend of the time series (Box & Jenkins 1976; Kottogoda 1990; Tong 1990; Polyak 1996; Sharma *et al.* 2019).

$$\left[1 - \sum_{i=1}^p \phi_i B^i\right] \cdot \left[1 - \sum_{i=1}^P \phi_{is} B^{i \times s}\right] \cdot (1 - B)^d \cdot (1 - B^s)^D x_t = \left[1 + \sum_{i=1}^q \theta_i B^i\right] \cdot \left[1 + \sum_{i=1}^Q \theta_{is} B^{i \times s}\right] \cdot \varepsilon_t \quad (1)$$

where, ϕ_i is the i^{th} autoregressive (AR) parameters, ϕ_{is} is the i^{th} seasonal autoregressive (AR) parameters, θ_i is the i^{th} moving average (MA) parameters, θ_{is} is the i^{th} seasonal moving average (MA) parameters, B is the backshift

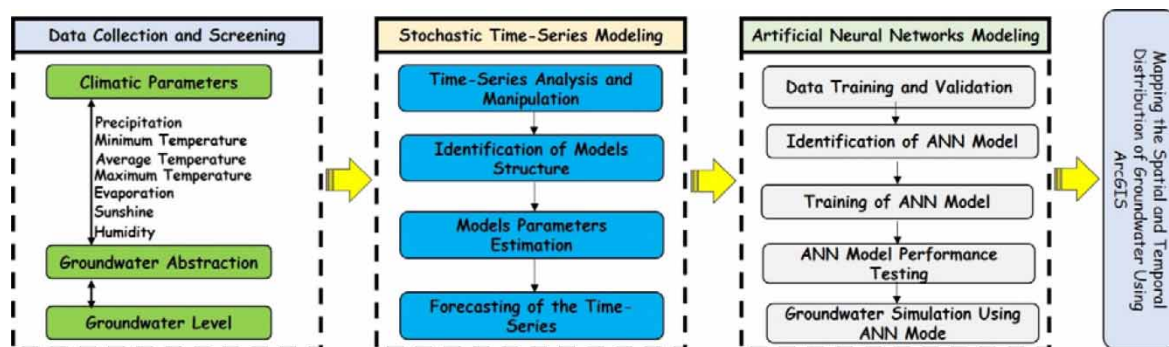


Figure 2 | The methodology of the study.

Table 1 | The model non-seasonal autoregressive (ar) and moving average (ma) parameters for the climate parameters

Parameter	Model	Φ_1	Φ_2	Φ_3	Φ_4	Φ_5	θ_1	θ_2	θ_3	θ_4	θ_5
Minimum temperature	(3,1,2) (2,1,1) ₁₂	0.8972	-0.273	0.0476	-	-	-1.5116	0.5117	-	-	-
Average temperature	(3,1,2) (2,1,1) ₁₂	0.9692	-0.2214	0.0184	-	-	-1.6557	0.6560	-	-	-
Maximum temperature	(3,1,2) (2,1,1) ₁₂	0.9377	-0.1725	0.0154	-	-	-1.6136	0.6203	-	-	-
Evaporation	(2,1,5) (2,1,1) ₁₂	-0.1266	0.6175	-	-	-	-0.5577	-0.7155	0.4327	-0.1447	-0.0148
Sunshine	(5,1,3) (2,1,3) ₁₂	-1.0384	-0.8514	0.0600	-0.0779	-0.0676	0.2856	-0.0353	-0.8846	-	-
Humidity	(4,1,2) (5,1,2) ₁₂	-0.8294	0.0325	0.008	0.0839	-	-0.0415	-0.8815	-	-	-

operator, d is the differencing, D is the seasonal differencing, S is the seasonality period, and ε_t is a noise random component.

Moreover, the logistic sigmoid ANN of multi-layer feed-forward perceptron (MLP), shown in Equations (2) and (3), with a single hidden layer was exploited to obtain the relationships between the climate factors and ground-water level (Bishop 1995; Haykin 2009; Sahoo & Jha 2013).

$$y_k = \sum_{j=1}^l w_{jk}z_j + b_j \tag{2}$$

$$\varphi \left(\sum_{j=1}^l w_{jk}z_j + b_j \right) = \frac{1}{1 + e^{-\left(\sum_{j=1}^l w_{jk}z_j + b_j \right)}} \tag{3}$$

where, w_{jk} is the connection weight between j^{th} node of hidden layer and output node k , z_j is the output of the j^{th} hidden neuron resulting from the input data, and b_j is the connection weight for bias term.

For quality control and quality assurance, both R -statistical analysis language and the Statistical Package for Social Sciences (SPSS) were used in this research to evaluate the nature of the rainfall time series. The R -statistical analysis language is highly recommended for climatic studies because of the vast availability of case studies. The SPSS is a familiar and established tool to confirm the consistency of results. The MATLAB software was used to establish the ANN where the MATLAB has a high and fast ability to manipulate the long and complex networks better than R . In addition, the use of MATLAB gives some indication about the quality control of the data integrity and the model workability.

4. RESULTS AND DISCUSSION

4.1. Forecasting of climate parameters

The forecasted rainfall time series data up to 2040 was obtained from Al-Najjar *et al.* (2020). The rainfall model reveals that the rainfall declines by a yearly average trend of about -0.26% , hence the average yearly rainfall for the Gaza Strip over the next 20 years is predicted as 370 mm. The stochastic time series model (Tables 1 and 2) of the structure (3,1,2) (2,1,1)₁₂ was recommended to simulate the manner of minimum temperature, average temperature, and maximum temperature. Moreover, the stochastic models of (2,1,5) (2,1,1)₁₂, (5,1,3) (2,1,3)₁₂, (4,1,2) (5,1,2)₁₂ were structured to demonstrate the time series of evaporation, sunshine and humidity, respectively. In terms of climate change tracking, as shown in Figure 3, the effect of climate change is tangible in the Gaza Strip where, according to expectations of the stochastic models, there is a significant increasing trend in the temperature of approximately $+0.03$ to $+0.09$ °C each year, which is averagely compatible with the IPCC assessment scenarios of climate change where the worst climate scenario of RCP 8.5 indicates that the temperature will increase by 1.5 °C above the normal by 2040. However, in the most optimistic scenario of RCP 2.8 the increase

Table 2 | The model seasonal autoregressive (ar) and moving average (ma) parameters for the climate parameters

Parameter	Model	Φ_{1s}	Φ_{2s}	Φ_{3s}	Φ_{4s}	Φ_{5s}	θ_{1s}	θ_{2s}	θ_{3s}
Minimum temperature	(3,1,2) (2,1,1) ₁₂	-0.0482	0.0605	-	-	-	-1.0000	-	-
Average temperature	(3,1,2) (2,1,1) ₁₂	-0.0707	0.0927	-	-	-	-0.9723	-	--
Maximum temperature	(3,1,2) (2,1,1) ₁₂	-0.0961	0.0244	-	-	-	-0.9992	-	-
Evaporation	(2,1,5) (2,1,1) ₁₂	0.1487	-0.1042	-	-	-	-0.9210	-	-
Sunshine	(5,1,3) (2,1,3) ₁₂	-0.576	-0.8670	-	-	-	-0.4308	0.5696	-0.9059
Humidity	(4,1,2) (5,1,2) ₁₂	-1.0158	-0.3057	-0.1495	-0.1191	-0.1211	0.0613	-0.6850	-

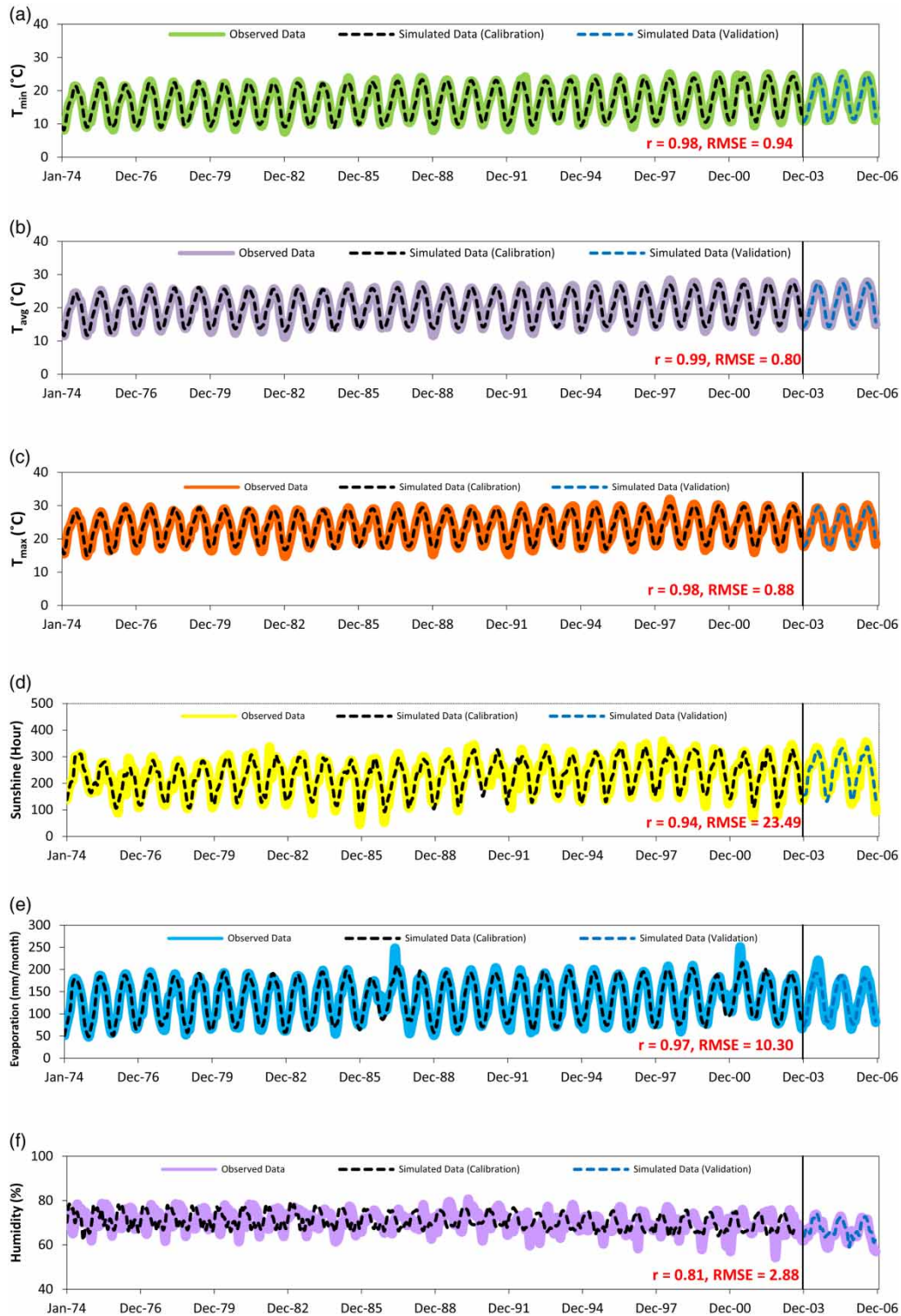


Figure 3 | Time series modeling for: (a) minimum temperature, (b) average temperature, (c) maximum temperature, (d) sunshine, (e) evaporation, and (f) humidity.

in temperature will be about 1 °C by 2040. Therefore, it is expected that the average temperature in the Gaza Strip be between 21 °C in the winter seasons and 25 °C in the summer seasons with an overall average temperature of about 23 °C by the year 2040.

The climatic parameters of evaporation, sunshine, and humidity also reflect tangible traces regarding the tendency of climate changes in the Gaza Strip. The annual period of sunshine shows a rising behavior by +1 hour where the simulation manner indicates that the sunshine is expected to reach 2,891 hours by the year 2040. In

response, the evaporation reveals an increasing trend of about 7 mm per year. However, the humidity demonstrates a declining yearly trend of -0.3%.

The performance testing of the models that were examined using the correlation coefficient (*r*) and the root mean square error (*RMSE*) shows that the stochastic models introduce proper simulations for the climate data and gives a good indication in forecasting the future. The data fitted for temperature by the suggested stochastic models indicate a robust simulation manner where the models give a correlation coefficient of *r*=98–99% and an *RMSE* of 0.69–0.94. The performance of the sunshine and evaporation models reveal high simulating quality with a correlation coefficient of *r*=0.94–0.96, *RMSE*=21.68–23.49 and *r*=0.97, *RMSE*=10.30–11.03 for the sunshine and evaporation, respectively. However, the stochastic model of humidity shows less performance in fitting the data and in forecasting the future, where the correlation coefficient was *r*=0.74–0.81, *RMSE*=3.07–2.88.

4.2. Modeling and forecasting of groundwater

The groundwater table was evaluated and simulated through a 20-neuron ANN which demonstrates the linkage processes for the relationship between the inputs and the output within a reasonable period. The monthly data of the $P(t)$, $T_{min}(t)$, $T_{avg}(t)$, $T_{max}(t)$, $E_o(t)$, $S_o(t)$, and $H_o(t)$ were chosen as a combination of inputs to represent the comprehensive influence of the climatic and hydrological factors on the aquifer water level. The combination of the input parameters within the ANN enhances the interpretation of the groundwater time series and it shows better presentations for the outlier points of the observed data. The network was developed using MATLAB by training the network on 540 combinations of the data for each time series of the ten groundwater wells. In terms of performance testing, the generated stochastic-ANN model shows a valid presentation of the observed groundwater level. Overall, as shown in Figure 4, the stochastic models describe the relationship between the observed and the simulated data by a correlation coefficient (*r*) of 94–99% and *RMSE* of 0.1–0.22.

The fluctuation of groundwater levels was represented by an ANN of 20 neurons, and the model was generalized (Table 3) to simulate the groundwater level at all of the ten water wells. Generally, the groundwater levels

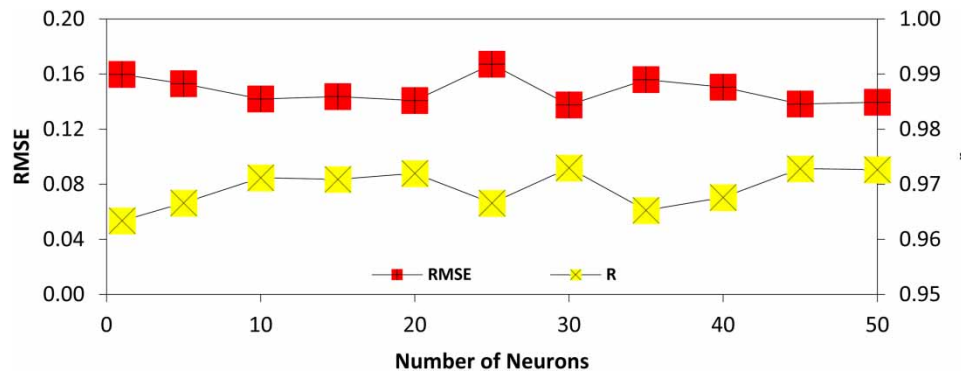


Figure 4 | Performance testing of ANN.

Table 3 | ANN parameters for groundwater

Water well	ANN parameters						
	$P(t)$	$T_{min}(t)$	$T_{avg}(t)$	$T_{max}(t)$	$E_o(t)$	$S_o(t)$	$H_o(t)$
C/48	0.3144	0.2179	-0.2246	-0.2746	0.0283	-0.0411	-0.1023
E/45	0.4368	0.207	-0.2662	-0.4434	-0.0791	0.0106	-0.0032
G/24B	-0.9390	-0.3240	0.7909	0.0644	-0.1924	-0.1409	0.0095
F/68B	0.1147	0.4551	0.1237	-0.544	-0.2337	-0.0305	-0.0105
S/15	-0.0248	0.2567	0.1335	-0.3582	-0.1767	-0.0672	-0.0879
L/86	0.4634	0.2497	-0.5946	-0.2145	-0.1113	0.0214	0.1273
L/66	-0.1522	0.1769	0.3225	-0.4422	-0.3210	0.0373	-0.1208
N/12	-0.0313	0.4298	0.1935	-0.5718	-0.3219	-0.1102	0.0795
N/16	-0.3282	0.6212	0.4375	-0.8122	-0.3422	0.0127	0.1050
P/48A	0.0778	-0.8018	0.1100	0.7464	-0.0357	-0.1446	-0.1755

demonstrate a declining trend over time due to the groundwater over-pumping activities and the negative effects of climate changes.

The data of the groundwater level and the findings of the model, shown in Figure 5, reveal that the groundwater resource faces real threats in terms of water balance. Historically, the groundwater level was in an abundant state in the 1970s. However, the groundwater is declining and it is significantly overexploited where the groundwater level shows a drop to less than -15 m below the MSL.

The general indication of the groundwater model reveals that the level is decreasing continuously except for some parts in the eastern region of the study area that form semi-separated small basins. The groundwater simulation findings, shown in Figure 6, illustrate that the groundwater level drop is between -0.38 and -18.49 m below MSL in 2020 and between -1.13 and -27.77 m below MSL in 2040. Geographically, the southern governorates of the Gaza Strip, especially in Rafah, show more deficit in the groundwater balance than other locations where the decline in the groundwater will reach -27.77 m below MSL in 2040.

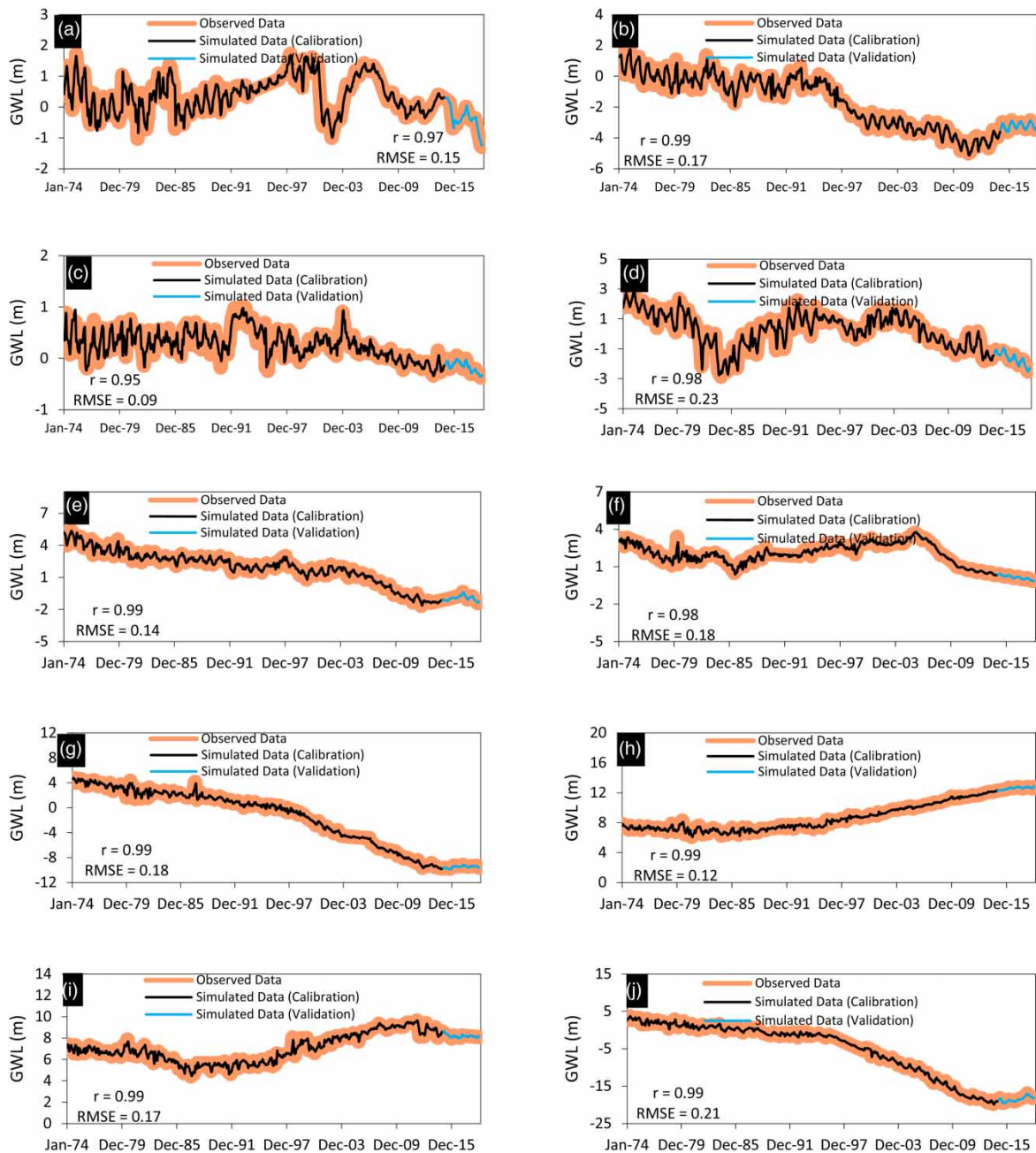


Figure 5 | Groundwater simulation for: (a) C/48, (b) E/45, (c) G/24B, (d) F/68B, (e) S/15, (f) L/86, (g) L/66, (h) N/12, (i) N/16, and (j) P/48H.

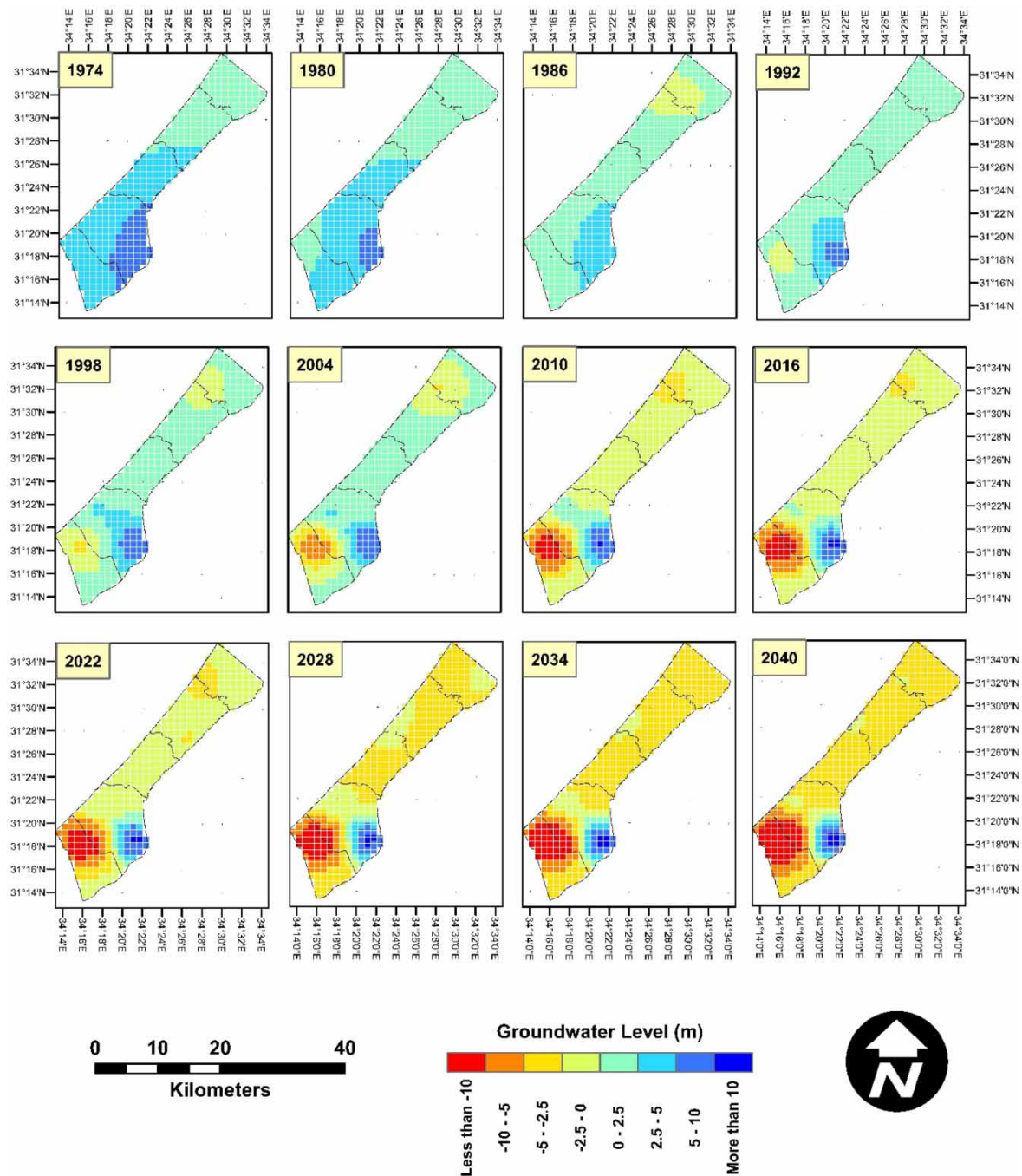


Figure 6 | Groundwater level of the Gaza coastal aquifer.

The southern part of the Gaza Strip is the most populated area. The municipal wells pump the groundwater at an extensive rate of more than 100 m³ per hour which adversely affects the quality and quantity of the Gaza coastal aquifer in this part of the area. Regionally, the groundwater depression cone started to form in 1992 and followed an expansion pattern towards the north of the Gaza Strip. The diameter of the cone was less than 1 km in 1992 and it is expected to reach 4–5 km in 2040. In consequence, the zero-lateral flow recharging of the groundwater was supposed as deep groundwater wells were excavated along the eastern border of the Gaza Strip to catch the water before passing to the Gaza Strip and this, in turn, causes seawater intrusion which is the most dominant phenomenon impacting the quality of the groundwater by lifting the chloride concentration to an acceptable level. In comparison with the Mediterranean Sea countries, the groundwater level investigations show significant depression below sea water level where in Cairo the drop could reach –27.81 m (Mohamed Ibrahim

2020). In Jordan, the groundwater is being rapidly depleted with observed groundwater level declines of 0.9–3.5 m per year (Yoon *et al.* 2021).

5. CONCLUSION AND RECOMMENDATIONS

The environment of the Gaza Strip is changing dramatically as a result of global warming, putting a strain on the Gaza coastal aquifer, which is the only viable water source. Furthermore, the rapid increase in groundwater pumping operations in tandem with the rapid increase in population has a direct impact on the coastal aquifer's long-term productivity. The lack of a reliable simulator to research groundwater behavior for the Gaza coastal aquifer inhibits proper knowledge of groundwater dynamics through time and space. The stochastic and ANN models are both capable of simulating data and identifying abnormal data values. The modeling outputs reveal the following points:

- The period 2020–2040 is critical for climate and water security in the Gaza Strip, as monthly average precipitation will be assigned to about 21–33 mm by 2040, and the temperature is expected to increase by +1 °C by 2040.
- The low recharge rate due to the decrease in rainfall and the high temperature and evaporation rate are causing a depression in the groundwater level to reach a low level of about –28 m in 2040.
- The variation in the groundwater distribution pattern of the Gaza coastal aquifer will alter by about 51%, indicating greater deterioration.
- At all areas in the Gaza Strip, the groundwater table will be below the MSL. In this context, rapid water intervention plans and optimal management strategies are strongly required to support the coastal aquifer's long-term sustainability and to boost the Gaza Strip's economic activity. The management measures should primarily improve the manner of groundwater use, while also encouraging the use of non-conventional resources like seawater desalination and wastewater reclamation.
- To stop the groundwater decline in the southern governorates a quantity of water equaling 60 and 90 million cubic meters per year is needed by 2020 and 2040, respectively. However, at present, the whole area of the Gaza Strip needs a quantity of water equal to 123 million cubic meters, and by 2040 the quantity should be 193 million cubic meters.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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