SALINATION OF SPRINGS IN THE BAKAR BAY

Davor Mance, Lucija Brevulj, Diana Mance

Abstract: Rising sea levels, increasing air temperatures, and recurring extreme weather events make coastal freshwater more susceptible to salination. This study investigates the relationship between salinity in the Perilo, Dobra, and Dobrica springs in the Bay of Bakar (Croatia) and extreme weather events from June 2005 to June 2020.
Panel analysis, including water temperature (°C), electrical conductivity (μS/cm), hardness (mg/L $CaCO_3$), and chloride (mg/L), showed significant positive correlations between water temperature and chloride content, as well as direct relationships between electrical conductivity and chloride concentration. The study emphasizes the influence of weather on spring salinity and underscores the need for climate change adaptation strategies and sustainable water resource management. The findings hold significant implications for policymakers and stakeholders in water resource management.

Keywords: climate change, springs salination, coastal environmental physics, analysis. of economic environmental impacts.

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Introduction

The salination of freshwater sources is a growing problem in coastal regions around the world, caused by rising sea levels, increasing air temperatures, and extreme weather events [1]. The Bay of Bakar in Croatia is no exception. Understanding the salination process in this region is crucial as it affects the availability and quality of drinking water, which is essential for the local population and the health of the ecosystem. The principles that govern the infiltration of saline seawater into freshwater aquifers are summarized in the Ghyben-Herzberg relationship:

$$z = \frac{\rho_s}{(\rho_m - \rho_s)} \cdot h \quad (1)$$

In which (Fig. 1): z is the depth of freshwater below sea level, h is the height of freshwater above sea level, ρ_s = 1000 g/cm^3 is the density of freshwater at 20 °C, and ρ_m = 1025 g/cm^3 is the density of seawater. Since saltwater is denser than freshwater, a pressure gradient is created that favors the penetration of saline seawater into freshwater aquifers and ultimately leads to the salinization of springs.

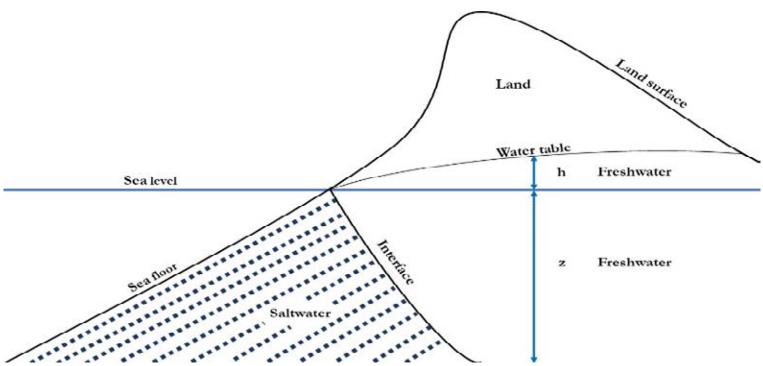

Figure 1 – Salinization of groundwater springs as a Ghyben-Herzberg relationship.

This hydrostatic principle explains that a combination of drop in the groundwater level and higher density of salt water leads to seawater penetrating the freshwater reserves. This process creates a pressure gradient that drives salt water into the coastal aquifers and leads to the salinisation of the springs. In regions such as the Bay of Bakar, this phenomenon poses a significant threat to freshwater resources, especially in times of drought or low rainfall.

The main objective of this study is to investigate the relationship between the salinity of the springs of Perilo, Dobra, and Dobrica in the Bay of Bakar and various extreme weather events recorded from June 2005 to June 2020. In particular, the study aims to answer the following research questions:

1. What are the main variables that contribute to changes in salinity?
2. What are the implications of these findings for climate change adaptation and sustainable management of water resources in coastal areas?

We have already visited the three springs when we analyzed the bacterial contamination of the marine water and stable isotope composition of water at these springs [2]. Through a comprehensive panel analysis of variables such as water temperature, electrical conductivity, water hardness and chloride concentration, this study will provide valuable insights into the dynamics of freshwater salinisation at the three springs. The results will help policy makers and stakeholders to implement effective strategies to mitigate the negative impacts of climate change on freshwater resources.

Materials and Methods

The main focus was on analyzing the relationship between extreme weather events and the salinity of drinking water sources in the Perilo, Dobra, and Dobrica springs in the Bay of Bakar (Fig. 2).

In this study, data collected between June 2005 and June 2020 by the Water Supply and Sewerage Ltd. Rijeka were analyzed. The data set included chloride (mg/L), electrical conductivity (µS/cm), hardness (mg/L $CaCO_3$), and water temperature (°C). The time series of these parameters are shown in Fig. 3 - Fig. 6.

Figure 2 – The location of the Bakar Bay within the Kvarner Bay (Croatia).

Chloride concentration in Dobrica exceeded the safe values on a total of 24 days between 1999 and 2009, reaching a maximum value of 2470.4 mg/L. Due to high extreme values and the adjustment of variables to be commensurate with each other, we cut the panel to the timeline between June 2005 and June 2020 (Fig. 3).

Conductivity is directly related to the presence of dissolved salts, including chlorides. Higher chloride concentrations would contribute to increased conductivity in the springs, as observed in the periodic spikes corresponding to those in chloride levels (Fig. 3 & Fig. 4). Elevated temperatures and salinity can lead to increased dissolution of carbonate minerals, thereby increasing water hardness (Fig. 5).

Spikes in chloride levels, especially during high-temperature periods, may correlate with increased hardness (Fig. 6). Below you will find a description of the statistical tests we used to analyze this data.

Panel unit root (stationarity) tests

To ensure the reliability of the panel data, stationarity tests were performed, including Levin, Lin and Chu (LLC), Breitung, Im, Pesaran and Shin (IPS), Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP). These tests are used to determine whether the variables are stationary, i.e. whether their statistical properties remain constant over time, which is crucial for accurate econometric modelling. The tests consider individual effects, linear trends and use Newey-West bandwidth selection to deal with serial correlation and heteroscedasticity. Rejecting of non-stationarities in data permits the usage of the following test approaches. [3, 4, 5]

Hausman test

The Hausman test is employed to determine whether a fixed effects or random effects model is more appropriate for panel data analysis. This test evaluates if the unique errors are correlated with the regressors. If the errors are uncorrelated, the random effects model is preferred due to its efficiency. By comparing the fixed and random effects models, the Hausman test ensures the selection of the most suitable model, thus enhancing the validity and reliability of the results. [3, 4, 5]

Panel Discrete Threshold Regression

The Panel Discrete Threshold Regression (TR) is a statistical analysis tool that provides a simple but effective approach to understanding nonlinear relationships in data characterized by abrupt changes. This model is characterised by piecewise linear specifications and introduces regime switching that captures shifts in the relationship between variables when certain thresholds are exceeded. The TR model is particularly valuable when investigating scenarios in which the behavior of an observed variable changes in response to unknown or unobservable thresholds such as in our example the changes in salinization as a consequence of changes in temperature. [3, 4, 5]

Cointegration Tests

Cointegration tests were conducted to determine whether a long-term equilibrium relationship exists among the variables: chloride, conductivity, hardness, and temperature. The Johansen Fisher Panel Cointegration Test, which combines both trace and maximum eigenvalue statistics, was utilized for this purpose. The results indicated strong evidence of cointegration, rejecting the null hypothesis of no cointegration at all levels with p-values of 0.0000. This suggests that these variables move together over time, maintaining a stable long-term relationship despite short-term fluctuations. [3, 4, 5]

Chloride

Figure 3 presents the chloride concentration (mg/L) over a period from June 2005 to June 2020 for three different locations: Dobra, Dobrica, and Perilo.

The data indicates that Dobrica experiences significant fluctuations in chloride levels, often peaking sharply, while Dobra and Perilo maintain more stable and lower chloride concentrations throughout the observed period.

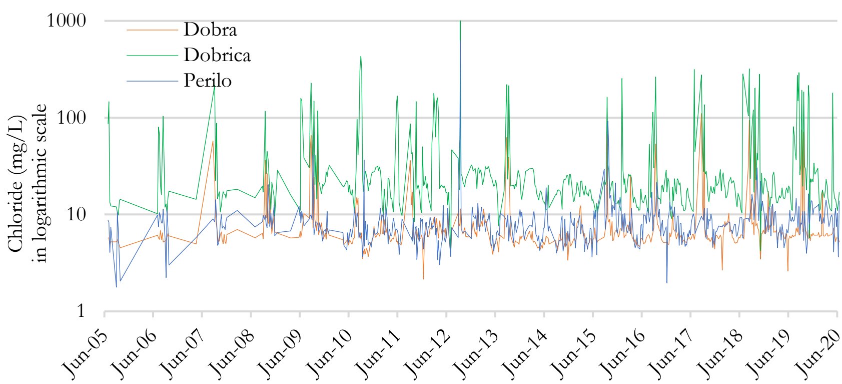

Figure 3 – Salination of Bakar bay springs measured in chloride concentration (mg/L in log).

Conductivity

Figure 4 presents the electrical conductivity (µS/cm) for same locations and time. The data indicates that again Dobrica experiences peaks in electrical conductivity, while Dobra and Perilo maintain more stable and lower conductivity levels throughout the observed period.

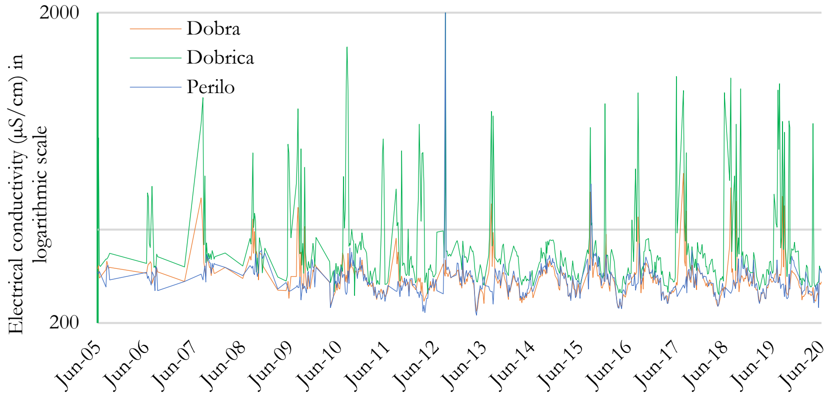

Figure 4 – Conductivity of Bakar bay springs measured in log scale of µS/cm.

Hardness

Figure 5 presents water hardness (mg/L of $CaCO_3$) for same locations and time. The data indicates that Dobrica shows significant fluctuations in water hardness, with several peaks, while Dobra and Perilo exhibit more stable and lower hardness levels throughout the observed period.

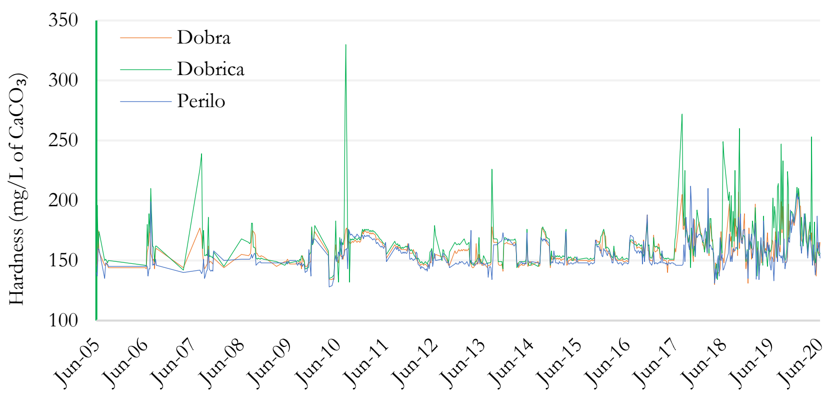

Figure 4 – Hardness of Bakar bay springs' water measured in mg/L of $CaCO_3$.

Water Temperature

Figure 6 shows the temperature measured in °C at the three springs at same dates. The diagram shows the temperature data and the trend lines for each location, indicating a significant increase in temperature during this period, especially after 2015. The trend lines show a consistent upward trend in temperatures for all three locations.

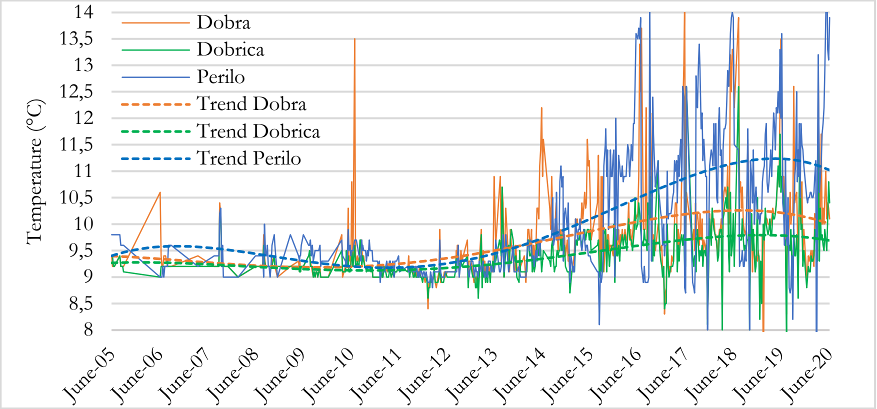

Figure 5 – Temperature of Bakar bay springs' water measured in °C.

Results

Panel unit root tests were conducted to assess the stationarity of the variables and the results are summarized in Table 1.

Table 1 – Panel unit root test: Summary.

Variable	Method	Statistics	Prob.	Cross-sections	Obs.
CHLORIDE	LLC	-22.1560	0.0000	3	1629
	Breitung	-14.3292	0.0000	3	1626
	IPS	-16.1426	0.0000	3	1629
	ADF	215.016	0.0000	3	1629
	PP	637.995	0.0000	3	1641
CONDUCTIVITY	LLC	-20.3214	0.0000	3	1629
	Breitung	-13.2416	0.0000	3	1626
	IPS	-14.2748	0.0000	3	1629
	ADF	178.199	0.0000	3	1629
	PP	490.885	0.0000	3	1641
HARDNESS	LLC	-15.1509	0.0000	3	1629
	Breitung	-8.96694	0.0000	3	1626
	IPS	-10.1439	0.0000	3	1629
	ADF	106.295	0.0000	3	1629
	PP	422.009	0.0000	3	1641
TEMPERATURE	LLC	-11.5181	0.0000	3	1629
	Breitung	-1.43126	0.0760	3	1626
	IPS	-10.5529	0.0000	3	1629
	ADF	111.885	0.0000	3	1629
	PP	447.092	0.0000	3	1641

Exogenous variables: Individual effects, individual linear trends. User-specified lags: 4. Newey-West automatic bandwidth selection and Bartlett kernel. Balanced observations for each test. Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Table 1 shows that all variables: chloride, conductivity, hardness, and temperature, are stationary, as indicated by the LLC, IPS, ADF, and PP tests ($p < 0.01$). Although the Breitung test for temperature has a p-value of 0.0762, the overall results confirm the stationarity of the data, supporting its suitability for further analysis.

The Hausman test was conducted to determine the appropriate model for analyzing the relationship between temperature, chloride concentration, Hardness, and Conductivity in the springs (Table 2). In contrast to ordinary least squares (OLS) regression, which estimates average effects, threshold regression (TR) provides insights into different regimes within the data based on specified thresholds. This method is beneficial for identifying non-linear relationships and abrupt changes in the effects of variables that are common in environmental data. Threshold regression provides a detailed understanding of the varying effects of weather variables on salinity, and can effectively capture the complex interactions and regime shifts in the salinisation process of springs.

Table 2 – Hausman test for temperature as an independent variable

Variable	Fixed	Random	Var(Diff.)	Prob.
CHLORIDE	-1.171309	-1.231331	0.001915	0.1702
CONDUCTIVITY	-6.396700	-6.618855	0.023949	0.1511
HARDNESS	0.869606	0.576539	0.003806	0.0000

Periods included: 548. Cross-sections included: 3. Total panel observations: 1644.

The results indicated that the random effects model is appropriate for chloride and conductivity (p-values > 0.05), while the fixed effects model is preferred for hardness (p-value < 0.05).

Table 3 – Pedroni Residual Cointegration Test Results

Test Statistics Name	Statistic	Prob.	Weighted Stat.	Prob.
Panel v-Statistic	-1.080370	0.8600	-0.883013	0.8114
Panel rho-Statistic	-138.5337	0.0000	-126.3353	0.0000
Panel PP-Statistic	-47.32854	0.0000	-43.45734	0.0000
Panel ADF-Statistic	-23.54387	0.0000	-21.08070	0.0000

Included observations: 1644. Cross-sections included: 3. Null Hypothesis: No cointegration.
Trend assumption: Deterministic intercept and trend. User-specified lag length: 1.

The results from the Pedroni test (Table 3), show mixed outcomes for the panel v-Statistic, which did not reject the null hypothesis of no cointegration. However, all other statistics (panel rho-Statistic, panel PP-Statistic, panel ADF-Statistic, group rho-Statistic, group PP-Statistic, and group ADF-Statistic) strongly rejected the null hypothesis ($p < 0.01$), indicating strong evidence of cointegration among the variables.

Table 4 – Johansen Fisher Panel Cointegration Test.

Hypothesized No. of CE(s)	Fisher Stat.	Prob.	Fisher Stat.	Prob.
None	147.4	0.0000	130.6	0.0000
At most 1	109.3	0.0000	96.28	0.0000
At most 2	105.6	0.0000	115.1	0.0000
At most 3	431.3	0.0000	431.3	0.0000

The Johansen Fisher Panel Cointegration Test was used to evaluate the long-term equilibrium relationships between chloride, conductivity, hardness and temperature. Trace and maximum eigenvalue statistics were combined to evaluate multiple cointegrating vectors (Table 4). The results strongly suggest cointegration between the variables, as the null hypothesis of no cointegration was rejected at all levels with p-values of 0.0000. This indicates a stable, long-term equilibrium relationship, meaning that changes in one variable affect the others over time. Preliminary tests, including stationarity tests, confirmed that the panel data variables are stationary, validating their use in further econometric modelling.

Table 5 – Discrete Threshold Regression of chloride (CL) as a dependent variable.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
	CL (-4) < 5.599999 -- 262 obs.			
CONDUCTIVITY	0.076054	0.006079	12.51019	0.0000
TEMPERATURE	1.225970	0.226935	5.402296	0.0000
	5.599999 <= CL (-4) < 7.3199999 -- 408 obs.			
CONDUCTIVITY	0.187795	0.008406	22.34006	0.0000
TEMPERATURE	-1.660537	0.250935	-6.617392	0.0000
	7.3199999 <= CL (-4) < 13.949999 -- 465 obs.			
CONDUCTIVITY	0.295647	0.002596	113.9006	0.0000
TEMPERATURE	-4.577445	0.181765	-25.18338	0.0000
	13.949999 <= CL (-4) < 22.339999 -- 253 obs.			
CONDUCTIVITY	0.281083	0.005435	51.71731	0.0000
TEMPERATURE	-4.334709	0.244777	-17.70881	0.0000
	22.339999 <= CL (-4) -- 244 obs.			
CONDUCTIVITY	0.322294	0.002015	159.9697	0.0000
TEMPERATURE	-5.695948	0.202588	-28.11586	0.0000
	Non-Threshold Variables			
HARDNESS	-0.168869	0.011382	-14.83609	0.0000
R-squared	0.965210	Mean dependent var		18.92897
Adjusted R-squared	0.964996	S.D. dependent var		45.50902
S.E. of regression	8.514473	Akaike info criterion		7.128129
Sum squared resid	117516.4	Schwarz criterion		7.164510
Log likelihood	-5805.554	Hannan-Quinn criterion		7.141625

Sample (adjusted): 8/30/2005 6/30/2020. Included observations: 1632 after adjustments. Variable chosen: CL (-4). Selection: Trimming 0.15, Max. thresholds 5, Sig. level 0.05.

Discrete threshold regression analysis for chloride (CL) and two-time points, CL (-3) and CL (-4), from 30 August 2005 to 30 June 2020, revealed a strong (R^2 = 0.965) and statistically significant (p<0.0001) association (Table 5). We used 1632 observations after adjustment and divided the data into five groups based on these time points whereby the EViews software at the end selected only 4 groups. A discrete threshold regression analysis was performed to examine the relationship between chloride concentration (CL) and the independent variables conductivity and temperature, with hardness serving as a non-threshold variable. Based on 1632 adjusted observations from August 2005 to June 2020, the EViews software identified significant thresholds for CL (-4) at 5.60, 7.32, 13.95 and 22.34. Conductivity had a consistently positive effect on CL, while temperature had a positive effect below 5.60 and a negative effect above this threshold. Hardness showed a consistently negative effect. The model showed a high explanatory power with an R-squared value of 0.965, which confirms the robustness of the results.

Table 6 – Discrete Threshold Regression of conductivity as a dependent variable.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
CONDUCTIVITY (-2) < 253 -- 231 obs.				
CL	12.58846	0.409719	30.72459	0.0000
HARDNESS	0.857694	0.106579	8.047521	0.0000
TEMPERATURE	3.660592	1.546475	2.367056	0.0180
253 <= CONDUCTIVITY (-2) < 277 -- 468 obs.				
CL	2.976138	0.064043	46.47065	0.0000
HARDNESS	1.112917	0.069755	15.95475	0.0000
TEMPERATURE	6.957445	1.098548	6.333309	0.0000
277 <= CONDUCTIVITY (-2) < 300 -- 395 obs.				
CL	2.868930	0.065054	44.10066	0.0000
HARDNESS	1.034912	0.084580	12.23584	0.0000
TEMPERATURE	9.565714	1.358750	7.040084	0.0000
300 <= CONDUCTIVITY (-2) < 330 -- 269 obs.				
CL	3.139500	0.029975	104.7387	0.0000
HARDNESS	0.760754	0.121149	6.279496	0.0000
TEMPERATURE	14.85469	2.012303	7.381934	0.0000
330 <= CONDUCTIVITY (-2) -- 275 obs.				
CL	3.088912	0.030758	100.4273	0.0000
HARDNESS	0.159836	0.090387	1.768344	0.0772
TEMPERATURE	25.48100	1.525076	16.70802	0.0000
R-squared	0.955543	Mean dependent var		311.5806
Adjusted R-squared	0.955159	S.D. dependent var		148.6999
S.E. of regression	31.48819	Akaike info criterion		9.746217
Sum squared resid	1609214.	Schwarz criterion		9.795679
Log likelihood	-7967.152	Hannan-Quinn criterion		9.764562

Sample (adjusted): 7/12/2005 6/30/2020. Included observations: 1638 after adjustments. Variable chosen: CONDUCTIVITY (-2). Selection: Trimming 0.15, Max. thresholds 5, Sig. level 0.05.

Discussion

The analysis shows that the salinisation of the springs in the Bay of Bakar is mainly caused by the intrusion of warmer and saltier seawater and not by the rise in temperature itself. The most important indicators: chlorides, hardness, conductivity and temperature - show the intrusion of seawater into the springs.

Increased temperatures lead to increased evaporation, causing dissolved salts, including chlorides, to accumulate, resulting in higher chloride levels. This increase in chloride concentration directly increases the total ion content and thus the electrical conductivity of the water. In addition, higher temperatures accelerate the dissolution of carbonate minerals, which in turn contributes to increased water hardness. Therefore, the observed peaks in chloride content, especially during periods of high temperatures, correlate with an increase in both conductivity and hardness, indicating a complex interaction between seawater intrusion, temperature and mineral dissolution.

The study shows significant correlations between increasing heteroscedasticity of water temperature and the salinisation of springs in Bakar Bay. Reduced precipitation and increased seawater intrusion are the main causes for the increased chloride levels in these springs [6]. The Ghyben-Herzberg relationship explains how a lowering of the groundwater table due to lower precipitation favors the intrusion of saline seawater into freshwater aquifers. This process is exacerbated by the karstic geology of the region, which favors the dissolution of carbonates, further increasing the chloride concentrations and exacerbating further the evaporation process.

The panel data analysis confirmed significant positive correlations between chloride levels, electrical conductivity and water temperature. These models also showed non-linear relationships and threshold effects, indicating the variable influence of seawater intrusion on salinity. Higher conductivity values are generally associated with increased salinity due to the presence of dissolved salts. This study emphasizes the importance of understanding the dynamic reinforcing and interactions between temperature, seawater intrusion and freshwater quality in coastal karst areas.

Conclusion

A significant portion of Croatia's drinking groundwater is stored in karst aquifers. The rise in chloride concentration in Bakar Bay Springs is due to seawater intrusion according to the Ghyben-Herzberg relationship. Increased temperatures at the springs accelerate dissolution of carbonates, and higher evaporation rates concentrate the dissolved salts accelerating furthermore the effect. These factors highlight the sensitivity of karst regions to temperature changes and the importance of considering geological factors and evaporation rates when assessing climate change impacts on coastal water quality.

Acknowledgments

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