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RESEARCH

Numerical Verification of Groundwater Suitability for Irrigation Around the Subsurface Dam Area of Miyako Island, Japan

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Abstract

The sustainable management of water resources is essential for agricultural productivity, especially in areas with scarce water availability. This study focused on assessing groundwater quality for irrigation near the subsurface dam area of Miyako Island, Japan. Water samples from three observation points were tested for various parameters, including electrical conductivity (EC), sodium adsorption ratio (SAR), soluble sodium percentage (SSP), residual sodium bicarbonate (RSBC), permeability index (PI), Kelley's ratio (KR), and magnesium adsorption ratio (MAR). EC values ranged from 270 to 800 μS/cm, suggesting water quality ranging from doubtful to good. SAR values between 0.23 and 1.49 suggested excellent quality. SSP ranged from 7.90% to 31.71%, mostly indicating good to excellent quality. RSBC values fluctuated between -1.57 to 1.45 epm, largely within safe limits. PI values varied from 40.34 to 75.83, indicating good permeability. Total hardness (TH) ranged from 105.50 to 326.45 ppm, classifying the water as hard to very hard. MAR values were below 50, suggesting potential soil issues. A numerical model confirmed observed Ca^{2+} concentrations, showing an increasing trend due to enhanced CO_2 emissions and lower pH. The data analysis revealed strong positive relationships between SSP and KR (r = 0.984), SAR and SSP (r = 0.951), and SAR and KR (r = 0.960). Despite generally acceptable values, continuous monitoring is recommended, especially for hardness, to ensure sustainable crop production. This study underscores the need for regular assessment and management of groundwater quality in subsurface dam areas to mitigate potential adverse effects on soil and agricultural productivity.

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Statement of Sustainability: This research presents a novel approach to evaluating groundwater quality for irrigation around the subsurface dam area of Miyako Island, Japan, using comprehensive numerical verification. By focusing on key parameters such as electrical conductivity, sodium adsorption ratio, and calcium ion concentration, the study aligns with Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation) and SDG 2 (Zero Hunger). The findings highlight the importance of sustainable water management practices, offering crucial insights for improving agricultural productivity and soil health in regions reliant on groundwater, thereby supporting long-term food security and environmental sustainability.

1. Introduction

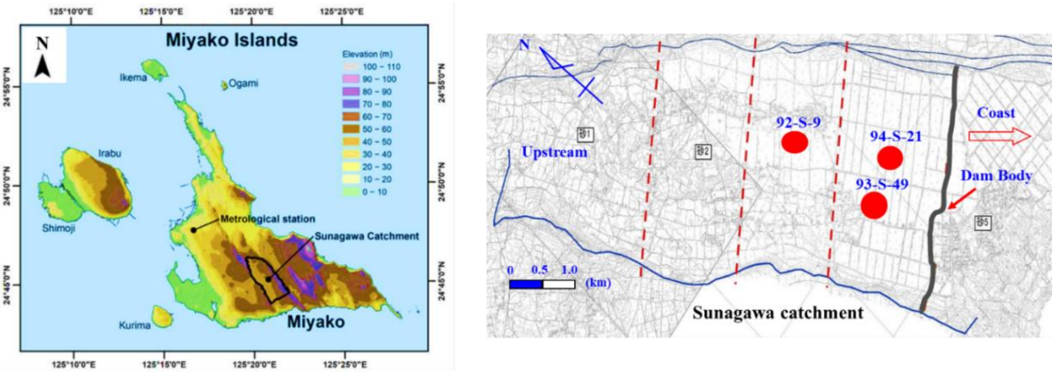
Irrigation water is vital for successful crop production, but its utility can be severely compromised if it contains dissolved or toxic substances (Islam et al., 2015; Islam et al., 2017; Das et al., 2018; Rana et al., 2019). The utilization of low-quality water for irrigation deteriorates soil quality, adversely affecting crop production (Hasan et al., 2016; Islam et al., 2023). Therefore, evaluating water quality is crucial not only for irrigation but also for drinking, domestic use, and industries related to agriculture (Jahan et al., 2020; Ameta et al., 2023). In many regions, including Miyako Island, Japan, surface water sources are often inadequate for irrigation due to the limited water quantity that can safely be drawn from rivers or perennial streams (Guyo et al., 2024). Consequently, groundwater is considered the only reliable source of water for successful crop cultivation. However, as groundwater travels through different geological formations, it can dissolve various minerals, with the specific types and concentrations of dissolved salts being contingent upon the groundwater's environment, movement patterns, and origin (Zhou et al., 2020). If the water used for irrigation is of substandard quality, it can have a direct adverse impact on crop development and degrade the physical characteristics of the irrigated soil, ultimately diminishing the productivity of the agricultural land (Mohanavelu et al., 2021). To address water scarcity challenges, particularly in islands and isolated peninsular regions of Japan, numerous subsurface dams have been constructed (Ishida et al., 2011; Liu et al., 2023). These structures are designed to artificially recharge natural aquifers and store groundwater within geological strata by creating a "cut-off wall" across a groundwater channel (Yang et al., 2023). However, the quality of the water stored by these subsurface dams critically depends on the chemical reactions occurring within the environment, especially the chemical dissolution of bedrock and minerals such as limestone. When rocks come into contact with water, they become the primary sources of dissolved species in natural water, initiating water-rock reactions that move towards equilibrium by dissolving or leaching bedrock minerals into the water. The concentration of solutes in the water is proportional to the reactivity of the bedrock minerals forming the catchments (Yadav and Chakrapani, 2006; Adham et al., 2010).

The underground geology of Miyako Island is predominantly composed of limestone, making the reactions between limestone and other minerals in contact with water significant (Tsujino et al., 2024). Assessing the quality of groundwater in this area is thus critical. Additionally, ongoing climate change is altering geo-environmental conditions, thereby modifying the chemicals dissolved in water. Previous research (Adham and Kobayashi, 2010; Adham et al., 2010) using numerical simulations has demonstrated that global CO_2 emissions led to increased Ca^{2+} levels in water due to higher temperatures, extreme rainfall, and lower pH levels. This excess Ca^{2+} can deteriorate groundwater quality in subsurface dam areas. Despite the crucial need for understanding groundwater quality for irrigation in Miyako Island, there has been a lack of specific research addressing this objective in the targeted domain. This study aims to fill this gap by numerically verifying the results of observational investigations regarding groundwater quality at the subsurface dam area of Miyako Island, Japan, specifically for irrigation purposes. This research holds significant importance as it offers valuable insights into the prospective consequences of groundwater quality on agricultural activities in areas that depend on subsurface dams for irrigation purposes. The findings of this research lay the foundation for the development of sustainable water resource management practices, which are necessary to adapt to the evolving environmental conditions.

2. Material and Methods

2.1. Study Area and Data Collection

This research was conducted to evaluate and verify the suitability of groundwater for irrigation around the subsurface dam area of Miyako Island, Japan. Miyako Island, part of Okinawa Prefecture, is a region heavily reliant on its groundwater resources due to limited surface water availability (Yang et al., 2022). Subsurface dams are particularly significant in this context as they help conserve groundwater by preventing seawater intrusion and loss through sub-surface flow, thus making Miyako Island an ideal case study for evaluating irrigation suitability (Sun et al., 2019). Among the numerous observation points within the Sunagawa dam area, three specific points: 92-S-9, 94-S-21, and 93-S-49 were selected for detailed analysis (Figure 1).



(a) (b)

Figure 1. Maps of the study area: (a) a topographical map of Miyako Island (Yang et al., 2022), and (b) a subsurface dam area showing the three targeted observation points in the Sunagawa catchment, Miyako Island, Japan.

These points were chosen based on their strategic locations which are representative of the overall groundwater conditions in the study area. Data collection involved gathering water samples from these three points, each comprising twenty-eight samples, to ensure a robust dataset for evaluating groundwater quality. The data for these samples were sourced from the Miyako Island Meteorological Department, Japan, which provided comprehensive records of various water quality parameters essential for this study.

2.2. Estimation of Water Quality Parameters

Water quality parameters were derived from the collected data, focusing on electrical conductivity (EC), sodium (Na^+), calcium (Ca^{2+}), potassium (K^+), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) concentrations. These parameters are critical indicators of water's suitability for irrigation, influencing soil structure, permeability, and crop yield (Das et al., 2018; Rana et al., 2019; Yasmin et al., 2019; Ahamad et al., 2023). The sodium adsorption ratio (SAR) stands out as a pivotal metric delineating the interplay between soluble sodium and soluble divalent cations, notably calcium (Ca^{2+}) and magnesium (Mg^{2+}) (Alrajhi et al., 2015). High SAR values can indicate potential soil dispersion issues, which adversely affect soil structure and permeability. The SAR was calculated using the equation (Richards, 1954):

$$\mathrm{SAR} = \frac{\mathrm{Na}}{\sqrt{(\mathrm{Ca+Mg})/2}} \qquad (1)$$

The assessment of irrigation water's sodium hazard relies significantly on the soluble sodium percentage (SSP). Elevated levels of sodium pose the risk of soil sodicity, which in turn diminishes soil permeability and negatively impacts plant development. The determination of SSP involves employing the following equation outlined by Todd (1980).

$$\mathrm{SSP} = \frac{\mathrm{Na+K}}{\mathrm{Ca+Mg+Na+K}} \times 100 \qquad (2)$$

Residual sodium bicarbonate (RSBC) assesses the quality of water for agricultural purposes. High RSBC values can lead to alkalinity hazards, affecting soil structure and crop health. RSBC was calculated as follows (Gupta and Gupta, 1987):

$$\mathrm{RSBC} = \mathrm{HCO_3} - \mathrm{Ca} \qquad (3)$$

where RSBC and the concentration of the constituents are expressed in epm. The permeability index (PI) is a criterion used to evaluate water's suitability for irrigation, highlighting its impact on soil permeability. PI was determined using (Doneen, 1964):

$$\mathrm{PI} = \frac{\mathrm{Na} + \sqrt{\mathrm{HCO_3}}}{\mathrm{Ca+Mg+Na}} \times 100 \qquad (4)$$

Total hardness (TH) measures the concentration of divalent cations, primarily calcium and magnesium, in water. High hardness levels can lead to scaling issues in irrigation equipment and affect soil structure. TH was calculated using (Sawyer, 1967; Raghunath, 1987):

$$\mathrm{TH} = (\mathrm{Ca} + \mathrm{Mg}) \times 50 \qquad (5)$$

where TH is expressed in mg/l or ppm (parts per million). Magnesium adsorption ratio (MAR) indicates the proportion of magnesium relative to calcium. A high MAR can exacerbate soil sodicity issues. MAR was calculated as (Raghunath, 1987):

$$\mathrm{MAR} = \frac{\mathrm{Mg}}{\mathrm{Ca+Mg}} \times 100 \qquad (6)$$

Kelley's ratio (KR) is another index to assess irrigation water suitability, specifically evaluating the sodium hazard relative to calcium and magnesium. KR was determined by (Kelley, 1963):

$$\mathrm{KR} = \frac{\mathrm{Na}}{\mathrm{Ca+Mg}} \qquad (7)$$

2.3. Numerical Simulation

In the study area, the verification of observed Ca^{2+} ion concentrations at designated points were accomplished through a developed numerical model (Adham et al., 2010). This model incorporated various processes, including dispersion/diffusion, advection, ion exchange, the formation of complexes in the aqueous phase, and the dissociation of water. Understanding these complex interactions is crucial for comprehending groundwater chemistry and its suitability for irrigation, especially around the subsurface dam area of Miyako Island, Japan. The numerical model effectively demonstrated the spatial distribution of Ca^{2+} ions under different pH conditions. For this study, the pH of recharged water, specifically rainwater, was assumed to be 5.0, serving as the reference case. This assumption is significant because the pH of rainwater can influence the dissolution and mobility of various ions, including Ca^{2+}, in the groundwater system. The comprehensive numerical simulations were grounded in detailed governing equations, which have been elaborated in earlier studies (Adham et al., 2010; Adham et al., 2011; Hasan et al., 2016). These foundational studies provide an essential framework for understanding the complex hydrogeochemical interactions at play. For instance, Adham et al. (2010) explored the diffusion and advection mechanisms in similar environmental settings, while Adham et al. (2011) delved into the specifics of ion exchange processes that affect groundwater quality.

3. Results and Discussion

3.1. Chemical Constituents and Quality Parameters for Irrigation Purpose

The chemical properties and quality parameters of groundwater samples collected from three observation points around the subsurface dam area of Miyako Island were analyzed and are presented in Table 1. These points are designated as Point 1 (92-S-9), Point 2 (94-S-21), and Point 3 (93-S-49). At Point 1, total sodium concentrations ranged from 0.41 to 1.26 epm, calcium from 1.71 to 6.05 epm, magnesium from 0.40 to 2.37 epm, and potassium from 0.01 to 0.19 epm, with bicarbonate ranging from 2.25 to 5.00 epm (Table 1). Point 2 exhibited sodium levels from 0.65 to 1.25 epm, calcium from 2.96 to 5.11 epm, magnesium from 0.26 to 1.64 epm, potassium from 0.01 to 0.19 epm, and bicarbonate from 3.23 to 4.60 epm. At Point 3, sodium ranged from 0.34 to 2.50 epm, calcium from 1.80 to 5.10 epm, magnesium from 0.28 to 2.50 epm, potassium from 0.01 to 0.20 epm, and bicarbonate from 3.12 to 4.80 epm (Table 1). According to Ayers and Westcot (1985), the levels of positively charged ions (cations) in all samples were within the recommended range for using the water for irrigation purposes. The EC values, which indicate the concentration of dissolved salts, ranged from 270 to 770 µS/cm at Point 1, 280 to 700 µS/cm at Point 2, and 290 to 800 µS/cm at Point 3. Based on the hazard classification proposed by Wilcox (1955) (Table 2), these EC values categorize the water quality as ranging from doubtful to good for irrigation use. These EC ranges suggest that the water's salinity levels are within acceptable limits but highlight the need for regular monitoring to prevent soil salinization.

Table 1. Statistical analysis of chemical constituents and quality parameters of groundwater samples collected from the three observation points around the targeted subsurface dam area.

Chemical Properties	For Point 1: 92-S-9				For Point 2: 94-S-21				For Point 3: 93-S-49			
	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.	Min.	Max.	Av.	S.D.
EC (µS/cm)	270	770	560	120	280	700	530	100	290	800	500	100
Na (epm)	0.41	1.26	0.96	0.18	0.65	1.25	0.98	0.16	0.34	2.50	1.00	0.40
Ca (epm)	1.71	6.05	4.24	0.83	2.96	5.11	4.10	0.49	1.80	5.10	4.10	0.70
Mg (epm)	0.40	2.37	0.78	0.46	0.26	1.64	0.70	0.37	0.28	2.50	0.80	0.50
K (epm)	0.01	0.19	0.08	0.05	0.01	0.19	0.09	0.06	0.01	0.20	0.10	0.00
HCO_3 (epm)	2.25	5.00	4.22	0.47	3.23	4.60	4.01	0.27	3.12	4.80	3.90	0.40
SAR	0.40	0.80	0.61	0.11	0.44	0.84	0.64	0.11	0.23	1.49	0.64	0.22
SSP	11.69	22.61	17.31	2.93	12.49	24.31	18.29	3.13	7.90	31.71	17.52	4.94
PI	40.34	75.83	51.15	6.75	43.28	60.05	52.00	4.68	42.82	71.76	50.88	6.28
RSBC (epm)	-1.30	1.43	-0.03	0.65	-0.96	0.63	-0.08	0.47	-1.57	1.45	-0.18	0.70
TH (ppm)	105.50	326.45	251.35	38.82	182.46	287.77	239.51	23.74	151.37	302.03	244.76	34.68
MAR	7.40	43.81	15.73	8.70	4.87	31.82	14.41	6.98	6.64	41.25	16.18	9.01
KR	0.12	0.25	0.19	0.04	0.14	0.28	0.21	0.04	0.08	0.45	0.21	0.08

Min. = Minimum, Max. = Maximum, Av. = Average, S.D. = Standard Deviation

The SAR values ranged from 0.40 to 0.80 at Point 1, 0.44 to 0.84 at Point 2, and 0.23 to 1.49 at Point 3 (Table 1). According to the classification by Richards (1954), these SAR values indicate that the water quality is excellent concerning sodium hazard (Table 2). The SSP values ranged from 11.69 to 22.61 at Point 1, 12.49 to 24.31 at Point 2, and 7.90 to 31.71 at Point 3 (Table 1). Based on the classification by Wilcox (1955), these SSP values suggest that the water quality is good to excellent for irrigation purposes (Table 2). Additionally, the RSBC values ranged from -1.3 to 1.43 epm at Point 1, -0.96 to 0.63 epm at Point 2, and -1.57 to 1.45 epm at Point 3 (Table 1). Most of the samples were within the safe limits set by the WHO standards (1989), with only three samples marginally exceeding these limits (Table 2). The negative RSBC values, indicating higher dissolved calcium than bicarbonate, are favorable for preventing soil sodicity.

Table 2. Classification of the observed groundwater quality for irrigation purposes based on various parameters.

Different parameters with limits	Water class with its developer	For Point 1: 92-S-9		For Point 2: 94-S-21		For Point 3: 93-S-49	
		NoS	PoS	NoS	PoS	NoS	PoS
EC (dS/cm)	Wilcox (1955)						
< 250	Excellent	-	-	-	-	-	-
250-750	Good	27	96.43	28	100	27	96.43
750-2250	Doubtful	1	3.57	-	-	1	3.57
>2250	Unsuitable	-	-	-	-	-	-
SAR	Richards (1954)						
<10	Excellent	28	100	28	100	28	100
10-18	Good	-	-	-	-	-	-
18-26	Doubtful	-	-	-	-	-	-
>26	Unsuitable	-	-	-	-	-	-
SSP (%)	Wilcox (1955)						
<20	Excellent	22	78.57	20	71.43	23	82.14
20-40	Good	6	21.43	8	28.57	5	17.86
40-60	Permissible	-	-	-	-	-	-
60-80	Doubtful	-	-	-	-	-	-
RSBC (epm)	WHO (1989)						
<1.25	Safe	26	92.86	28	100	27	96.43
1.25-2.50	Marginal	2	7.14	-	-	1	3.57
>2.50	Unsuitable	-	-	-	-	-	-
TH (ppm)	Sawyer (1967)						
0-75	Soft	-	-	-	-	-	-
75-150	Moderately Hard	-	-	-	-	-	-
150-300	Hard	26	92.86	28	100	27	96.43
>300	Very Hard	2	7.14	-	-	1	3.57

NoS = Number of samples, PoS = Percent of samples

Furthermore, the TH levels fluctuated across the sampling points, ranging from 105.50 to 326.45 ppm at Point 1, 182.46 to 287.77 ppm at Point 2, and 151.37 to 302.03 ppm at Point 3 (Table 1). According to the classification by Sawyer (1967), the water quality fell within the hard to very hard range (Table 2), primarily attributed to the presence of calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. Continuous monitoring is imperative to mitigate potential adverse effects on crop yield resulting from this hardness, as noted by Adham and Kobayashi (2010) and Adham et al. (2010), who observed that elevated CO^2 levels can lead to decreased pH and increased Ca^{2+} concentrations in groundwater, adversely affecting crop productivity. Furthermore, the PI values exhibited variation, ranging from 40.34 to 75.83 at Point 1, 43.28 to 60.05 at Point 2, and 42.82 to 71.76 at Point 3 (Table 1). These values, classified according to the criteria by Doneen (1964), predominantly fell within class II, indicating suitability for irrigation. However, the MAR values, ranging from 7.40 to 43.81 at Point 1, 4.87 to 31.82 at Point 2, and 6.64 to 41.25 at Point 3 (Table 1), below the threshold of 50, suggest potential soil harm, as highlighted by Gupta and Gupta (1987). The KR values ranged from 0.12 to 0.25 at Point 1, 0.14 to 0.28 at Point 2, and 0.08 to 0.45 at Point 3 (Table 1), falling within the recommended limit of 1.0 according to Kelley (1963), thus indicating the water's suitability for irrigation. In summary, the groundwater quality parameters in the vicinity of the Miyako Island subsurface dam generally support irrigation activities. However, continual monitoring, particularly of parameters such as TH and RSBC, remains crucial to prevent potential detrimental effects on soil and crop production.

3.2. Comparison Between Model-based and Observed Values of Ca^{2+} Concentration

The targeted domain exhibited a higher range of TH, which is dependent on the concentrations of Ca^{2+} and Mg^{2+} ions (Hasan et al., 2016). The numerical simulation employed in the study revealed that the concentrations of Ca^{2+} ions increase when temperatures are higher and pH values are lower, resulting in a TH value that exceeds the typical range (Hasan et al., 2016). Figure 2 compares numerically induced and observed Ca^{2+} concentration levels, demonstrating typical numerical results. In addition, Table 3 represents the comparison between simulated and actual values of Ca^{2+} ion concentrations. The average actual value of Ca^{2+} ion concentration was observed to be slightly higher than the model-induced value at pH = 5, considered as the reference case. The model study revealed that Ca^{2+} concentration increases due to changes in climatic conditions and CO_2 emissions. This trend was accurately depicted by the numerical model. It is essential to recognize that the lowering of pH due to global CO_2 emissions was overestimated in our study. Therefore, future studies using this model need to correct this overestimation to achieve quantitative accuracy.

Table 3. Comparison between the numerically simulated and actual value of Ca^{2+} concentration.

Ca^{2+} Concentrations (mol/L)			
Actual	Model		
Average value	pH= 6	pH=5 (Reference Case)	pH= 4
4.21	0.27	4.13	205.6

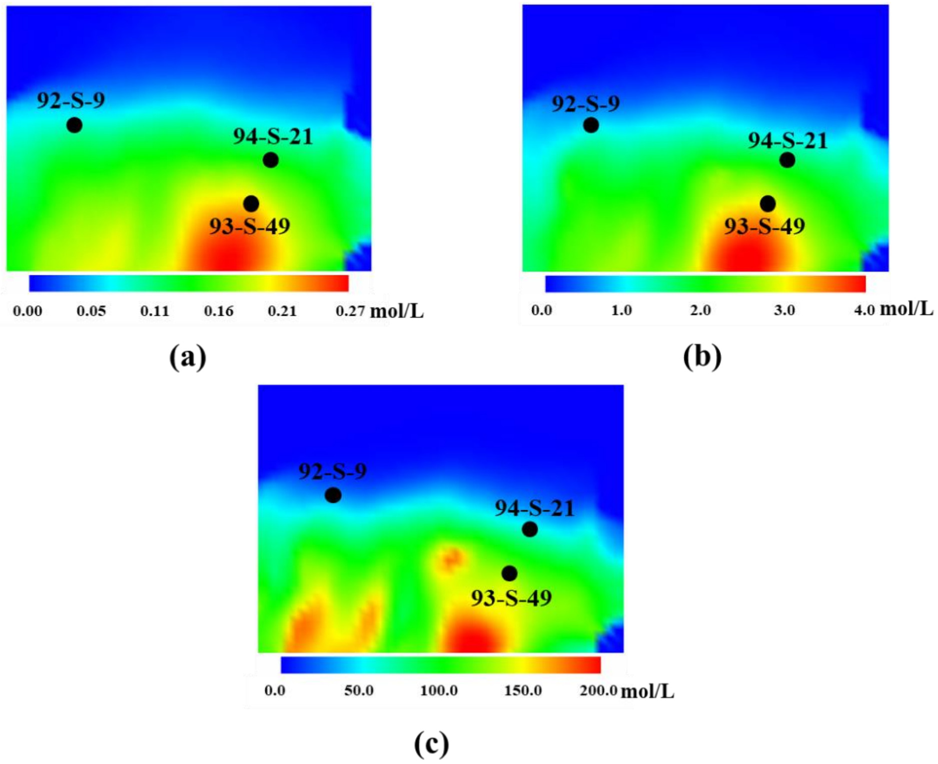


Figure 2. Distribution of simulated Ca^{2+} (450 days) for (a) pH= 6 (after Adham et al., 2011), (b) pH= 5 and (c) pH= 4 (after Adham et al., 2010).

Earlier studies have underscored the profound influence of climatic shifts on the chemical composition of subsurface water reserves. For example, Gao et al. (2022) illustrated that escalating temperatures coupled with heightened atmospheric CO_2 concentrations precipitate an augmentation in the levels of calcium and magnesium ions present in groundwater, thereby substantiating the observations delineated in our study. Additionally, the role of CO_2 in acidifying water bodies and increasing the solubility of Ca^{2+} has been well-documented in the earlier study (Knapp and Tipper, 2022). These factors collectively contribute to the increased hardness of groundwater observed in our study. Further, it is worth noting the implications of elevated Ca^{2+} levels on irrigation practices. High TH can lead to soil permeability issues and affect crop yield (Richards, 1954). Therefore, understanding the dynamics of Ca^{2+} concentration under changing environmental conditions is crucial for sustainable groundwater management, especially in agricultural regions like Miyako Island.

Future research should focus on refining the numerical models to incorporate more accurate pH predictions under varying CO_2 emission scenarios. Moreover, integrating field data with advanced simulation techniques can enhance the reliability of these models. An earlier study by Dai et al. (2020) emphasizes the need for such integrated approaches to predict groundwater quality accurately. In summary, while the numerical model provided a reasonable approximation of Ca^{2+} concentrations, further refinement is necessary to account for the overestimated impact of CO_2 emissions on pH levels. Continuous monitoring and refining of models must occur to guarantee that groundwater remains suitable for agricultural irrigation as climate patterns continue to shift.

3.3. Interrelationship Among Different Water Quality Parameters

The analysis of Pearson's correlation coefficients among the water quality parameters revealed significant interrelationships, indicating intricate interactions among these parameters (Das et al., 2019; Javed et al., 2019; Yasmin et al., 2019). Table 4 (a) showed a strong positive correlation between SAR and SSP (r = 0.899) and KR (r = 0.887) at the 1% significance level, suggesting that as SAR increases, SSP and KR also tend to increase, implying a direct relationship that could affect soil structure and permeability. SSP exhibited a high positive correlation with KR (r = 0.984) and a positive correlation with RSBC (r = 0.522) at the 1% significance level. However, SSP had a negative significant correlation with TH (r = -0.447) at the 5% significance level, indicating that higher SSP might be associated with lower water hardness.

Table 4. Pearson's correlation matrix of different estimated quality parameters of groundwater samples.

(a) For Point 1: 92-S-9

Parameters	SAR	SSP	RSBC	PI	TH	MAR	KR
SAR	1						
SSP	0.899**	1					
RSBC	0.330	0.522**	1				
PI	0.206	0.573**	0.612**	1			
TH	-0.057	-0.447*	-0.584**	-0.964**	1		
MAR	-0.061	-0.004	0.665**	0.059	-0.107	1	
KR	0.887**	0.984**	0.549**	0.625**	-0.496**	0.012	1

(b) For Point 2: 94-S-21

Parameters	SAR	SSP	RSBC	PI	TH	MAR	KR
SAR	1						
SSP	0.957**	1					
RSBC	0.343	0.495**	1				
PI	0.622**	0.744**	0.700**	1			
TH	0.358	-0.534**	-0.622**	-0.919**	1		
MAR	-0.063	0.010	0.477*	-0.181	0.148	1	
KR	0.971**	0.968**	0.465*	0.778**	-0.554**	-0.092	1

(c) For Point 3: 93-S-49

Parameters	SAR	SSP	RSBC	PI	TH	MAR	KR
SAR	1						
SSP	0.951**	1					
RSBC	0.269	0.464*	1				
PI	0.560**	0.756**	0.689**	1			
TH	-0.021	0.259	-0.466*	-0.799**	1		
MAR	0.282	0.335	0.691**	0.237	0.025	1	
KR	0.960**	0.984**	0.397*	0.748**	-0.274	0.325	1

** Significant at the 0.01 level (2-tailed); * Significant at the 0.05 level (2-tailed)

RSBC was positively correlated with PI (r = 0.612), MAR (r = 0.665), and KR (r = 0.549), suggesting that RSBC influences permeability and magnesium adsorption in irrigation water. Conversely, RSBC had a negative significant correlation with TH (r = -0.584) at the 1% level, implying that higher bicarbonate levels might decrease water hardness. PI had a strong negative correlation with TH (r = -0.964) and a positive correlation with KR (r = 0.625) at the 1% significance level, indicating an inverse relationship between water permeability and hardness. Additionally, TH showed a negative significant correlation with KR (r = -0.496) at the 1% level, while MAR was positively correlated with KR but did not exhibit significant correlations with other parameters. Table 4 (b) demonstrated a strong positive correlation between SAR and SSP (r = 0.957), as well as between SAR and KR (r = 0.971), indicating a robust relationship among these parameters. Additionally, a positive correlation was observed between SAR and PI (r = 0.622) at the 1% significance level. SSP exhibited a strong positive correlation with KR (r = 0.968) and positive correlations with RSBC (r = 0.495) and PI (r = 0.744) while showing a negative significant correlation with TH (r = -0.534) at the 1% level. This pattern suggests a robust interplay where sodium and bicarbonate levels in water influence its hardness and permeability. In addition, RSBC displayed a positive correlation with PI (r = 0.700) and a negative correlation with TH (r = -0.622) at the 1% significance level, reinforcing the inverse relationship between bicarbonate content and hardness. Furthermore, RSBC had positive correlations with MAR (r = 0.477) and KR (r = 0.465) at the 5% significance level. PI exhibited a strong negative correlation with TH (r = -0.919) and a positive correlation with KR (r = 0.778) at the 1% significance level. TH's negative correlation with KR (r = -0.554) at the 1% significance level further supports the complex balance between hardness and other water quality parameters, while MAR did not show significant responses with other parameters except RSBC. Table 4 (c) revealed high positive correlations between SAR and SSP (r = 0.951), SAR and KR (r = 0.960), and SSP and KR (r = 0.984) at the 1% significance level, reinforcing the critical relationships among sodium content, soluble sodium, and KR for evaluating water's suitability for irrigation. Furthermore, positive correlations were observed between SAR and PI (r = 0.560), SSP and PI (r = 0.756), RSBC and PI (r = 0.689), RSBC and MAR (r = 0.691), and PI and KR (r = 0.748) at the 1% significance level. These results align with previous studies on groundwater suitability for irrigation, where similar interrelationships among water quality parameters were observed (Das et al., 2019; Javed et al., 2019; Yasmin et al., 2019). The strong correlations between parameters such as SAR, SSP, and KR indicate that managing these variables is crucial for maintaining soil health and crop productivity in subsurface dam areas like Miyako Island, Japan. Such findings provide a valuable framework for developing irrigation strategies that mitigate adverse effects on soil and crop quality.

4. Conclusion

The numerical verification of groundwater suitability for irrigation around the subsurface dam area of Miyako Island, Japan, has provided crucial insights into water quality parameters affecting agricultural productivity. The study revealed that the majority of water quality indicators, including electrical conductivity, sodium adsorption ratio, and soluble sodium percentage, typically remained within the permissible ranges for irrigation use. However, total hardness and residual sodium bicarbonate values indicate a need for continuous monitoring to prevent potential adverse impacts on soil and crop health. The numerical model successfully captured trends in calcium ion concentrations influenced by environmental factors such as CO_2 emissions and pH levels, underscoring the importance of incorporating climate change variables into groundwater quality assessments. The observed correlations among various water quality parameters highlight the complex interactions governing soil structure and permeability, emphasizing the necessity for regular and comprehensive monitoring. This research underscores the critical need for sustainable groundwater management practices in regions relying on subsurface dams for irrigation. By understanding the dynamic nature of groundwater chemistry and its implications for agriculture, stakeholders can implement more effective strategies to ensure long-term soil fertility and crop productivity. Future research should focus on refining numerical models and integrating more field data to enhance predictive accuracy, ultimately contributing to more resilient agricultural systems.

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