Evaluation of Ground and Surface Water Hydrochemistry for Irrigation Suitability in Borneo: Insights from Brunei Darussalam

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Abstract: Water for irrigation use plays a critical role in agriculture via supporting crop growth and maintaining food production worldwide. Irrigation water quality evaluations provide useful information for sustainable water practices in many agricultural regions. In Brunei Darussalam, the quality of irrigation water is still poorly understood. The present study aims to investigate the hydrochemical characteristics of water resources in Brunei Darussalam and evaluate their quality and suitability for irrigation use. A total of fifteen sampling locations were chosen from selected ground and surface water sources found in all four Brunei districts. The water samples' physicochemical properties, including pH, EC, and major cations and anions, were measured and compared with FAO standards. Hydrochemical classification based on the Piper diagram revealed that water mainly belongs to the calcium-, magnesium-, and bicarbonate-type, or Type IV water class. The evaluation of heavy metals (Fe, Zn, Cu, Cr, As, and Cd) showed concentrations within the FAO's permissible limits. In this regard, iron showed the highest concentration among the investigated metals. Established water quality indices such as SAR, Na%, RSC, MAR, KR, PS, and IWQI were used to evaluate and classify the water's suitability for irrigation use. Overall, our findings revealed that almost all of the analysed water samples in the study area have low salinity and sodicity risks. However, only 27% of the samples passed the magnesium hazard assessment, and one sample showed a very poor IWQI result. Thus, additional testing and treatment are recommended for these cases. This study provides valuable insights on water quality for present and future utilisation, aiming to contribute to the protection of water resources in Brunei Darussalam.

Keywords: hydrochemistry; water quality; irrigation; tropical region; Brunei Darussalam

1. Introduction

Water is essential for all forms of life and is one of the earth's most vital resources. Water is critical for energy and food production, socioeconomic growth, healthy ecosystems, and general human existence [1]. However, water issues persist to be a global concern. From water scarcity and pollution to poor sanitation and waterborne diseases, the challenges vary and are often interlinked [2]. Rapid industrialisation, urbanisation, and intensive agriculture have led to a surge in water contaminations, thus, increasing the demand for clean water supply [3]. A growing population is expected to further increase water

supply demands in many regions [4]. Therefore, recognizing the significance of water and implementing sustainable practices to maintain its availability and quality are crucial for protecting water resources for both the current and future generations [1,4].

Water quality evaluations play an important role in water conservation and preservation [5]. It involves hydrochemical investigations and characterization of various physicochemical parameters such as pH, electrical conductivity, major ions, and other chemical constituents present in the water [6]. Although heavy metals are typically found in only small concentrations, they are commonly tested when pollution is suspected or wastewater is reused [7,8]. The findings from water quality evaluations have been useful for assessing the suitability of water for various purposes such as for domestic use, agriculture, and industry [9,10].

Irrigation water plays a critical role in agriculture through supporting crop growth and food production worldwide [11,12]. However, low water quality and highly mineralised irrigation water can have negative effects; for example, minerals can accumulate in soils and be absorbed by crops, causing plant toxicity and nutrient imbalance, thus, compromising soil fertility and overall crop productivity [13,14]. Furthermore, water may infiltrate through the soil into shallow aquifers, further altering groundwater quality [15].

An irrigation water quality guideline provides a framework for understanding water quality and suitability for optimizing water use, subsequently improving crop productivity, and minimizing environmental impacts [16]. The Food and Agricultural Organization of the United Nations (FAO) standard is the most widely used standard water quality guideline for assessing water for irrigation purposes [17–19]. Other well-established water quality indices utilised for classifying irrigation suitability include the sodium adsorption ratio (SAR), sodium percentage (Na%), residual sodium carbonate (RSC), magnesium adsorption ratio (MAR), Kelley's ratio (KR), and potential salinity (PS) [20–22]. In addition, the irrigation water quality index (IWQI) is one of the most effective tools used to evaluate irrigation water quality through encompassing selected key parameters (physical, chemical, or biological) and representing them in a concise and simplified manner [23,24].

Tropical Brunei Darussalam is blessed with abundant rainfall due to its equatorial climate, which provides a substantial surface water resource [25]. In general, surface water resources in Brunei can be considered safe [26]. However, there have been growing concerns about the water quality, especially for residential, agricultural and industrial waterways [27,28]. Furthermore, significant water abstraction from the Tutong River has caused a decrease in water levels, exposing areas of acid sulphate soils [29,30]. As a result, a correlation between low pH values and increased aluminium levels was observed [29]. An investigation of groundwater quality in the Berakas coastal areas further revealed waters with low pH values and high sulphate levels [31]. Moreover, the country's performance with regards to integrated water resource management (IWRM) was assessed as below average in comparison to other countries in Southeast Asia [32], owing partly to the lack of available information.

Surface water is the main source of water supply for agricultural use in Brunei Darussalam [25,33,34]. However, there has been growing interest in the use of groundwater as an alternative water supply for irrigation, especially in water-scarce and rural areas [35–37]. Furthermore, water quality studies for irrigation use in Brunei are limited. The aim of this study is to evaluate the quality and suitability of ground and surface water resources in Brunei Darussalam for irrigation purposes. For a comprehensive overview of the water resources in the country, this study will incorporate samples from groundwater wells, rivers, lakes, and reservoirs found in all four Brunei districts. Results will be compared with the worldwide standard guideline (FAO). Established water quality indices for irrigation such as SAR, Na%, RSC, MAR, KR, PS, and IWQI will be determined. This study will discuss potential risks of contaminants in irrigation water, aiding future decision-making and implementation of appropriate mitigation measures.

2. Materials and Methods

2.1. Study Area

2.1.1. Geographic Location and Climate

The study area Brunei Darussalam, or simply Brunei, is located on the northwestern part of the Borneo Island, overlooking the South China Sea (Figure 1). The country has an area of about 5765 km^2 and is separated into two enclaves [38]. Most of the country's population, administrative, and economic centres are located in the western enclave (Brunei-Muara, Tutong, and Belait districts), which is characterised by steep lowlands. The sparsely inhabited eastern enclave (Temburong District) is hillier and mainly covered by lush woodlands [38].
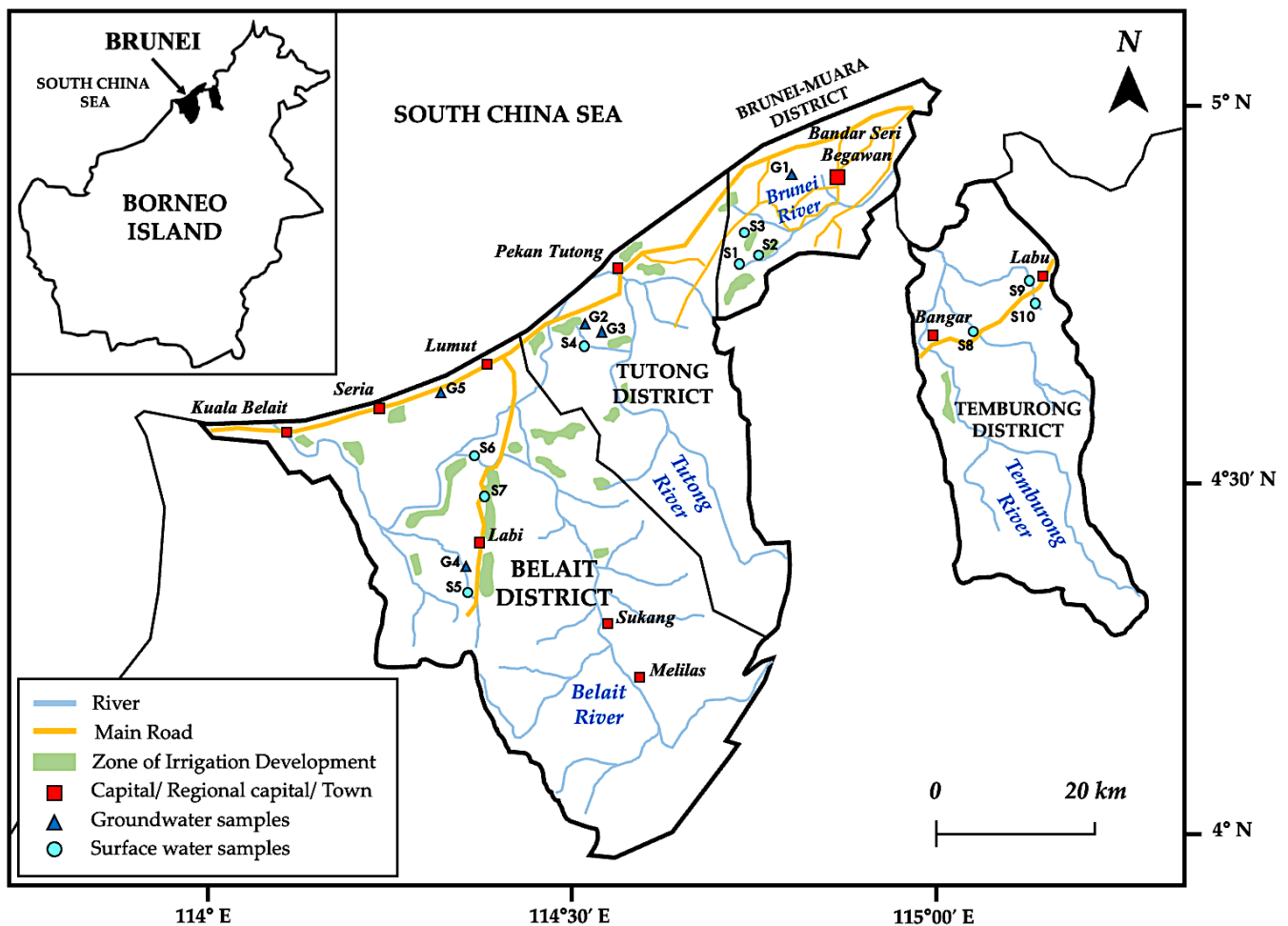

Figure 1. Map of Brunei showing the locations of districts, rivers, and sampling points; inset map of Borneo Island showing the location of Brunei. Modified after [25].

Brunei Darussalam is located in the equatorial tropics, with high temperatures and precipitation all year round [39]. Climatic changes in the region are caused by periodic winds of the northeast monsoon, blowing from December to March, and the southeast monsoon, active between June and October. Between 1984 to 2013, the country recorded an average precipitation of about 2976 mm per year, with an annual average temperature of 27.5 °C [40]. There are two seasonal patterns: wet and dry seasons. May to July and October to January are the wet periods, whereas February through March and June through August are the dry periods [39].

2.1.2. Regional Geological and Hydrological Settings

The geology of Brunei Darussalam is made up of thick deltaic sedimentation that overlies deeper and older rock strata. From the Oligocene to the Holocene, rock units can be up to 15 km thick [38,41]. The Neogene rock units with exposures recorded in the onshore areas of Brunei are divided into the Setap, Belait, Lambir, Miri, Seria, and Liang Formations (Figure 2). The Setap Formation comprises deep marine shales. Thick sandstones are found in the Belait Formation, whereas interbedded sands and shales are found in the Seria, Miri, and Lambir Formations. The Liang Formation consists of loosely cemented sands and sandstones with occasional clays and conglomerates. From the Pleistocene to the Holocene, sediments are made up sands and clays [38]. Faults that evolved in deep sedimentary strata are excellent traps for hydrocarbon reserves found in the basin [42].
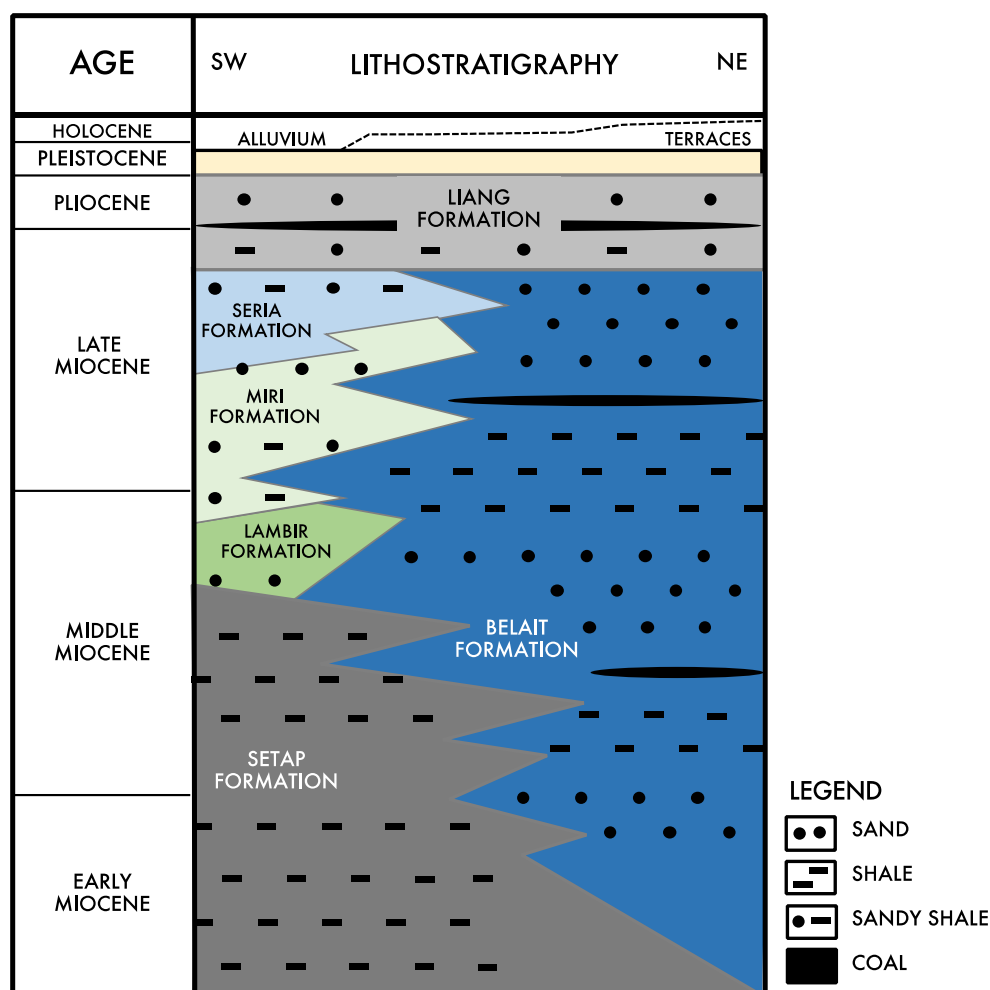
Figure 2. Chrono-lithostratigraphy of central onshore Brunei. Modified after [36].

The hydrological setting of Brunei suggests that the country has abundant surface water resources. The current geomorphology of the country was formed during the last significant sea level fall, around 6000 years ago [36]. The four major rivers in Brunei are the Belait River (209 km), Tutong River (137 km), Temburong River (98 km), and Brunei River (41 km) (Figure 1). The Brunei River and the Tutong River serve as the main sources of water supply for domestic, industrial, and agricultural purposes [43]. Additionally, limited groundwater reserves have been identified in the Liang area for potable drinking [25]. Groundwater resources are found mainly within loosely cemented sandstones and fractures along the existing rock formations. The Liang Formation is believed to be the most prolific groundwater formation [43]. Furthermore, the groundwater recharge rate in the country

could be as high as 800 mm/a, with groundwater depths ranging from 10 to 20 m below ground level [44].

2.2. Chemical Analysis

A total of five groundwater samples and ten surface water samples were collected in the study area (Figure 1). The coordinates and characteristics of groundwater wells and surface sampling sources are given in Tables 1 and 2. There were no known groundwater wells available for sampling in the Temburong district. The sample coordinates were taken using a digital GPS device (GPSMAP 64S, Garmin, UK). Samples were collected twice in January and in September of 2022. The sample dates were chosen to correspond to the wet season and an increase in irrigation use. Samples were collected and stored in sterile polyethene bottles (500 mL and 1000 mL; unfiltered) and sample vials (15 mL; filtered; 0.45 μm). Filtered samples were treated with nitric acid (0.15 mL). A portable pH/conductivity digital meter (MW801, Milwaukee, USA) was used for pH and EC measurements at the site. The remaining chemical parameters were analysed in the laboratory according to the International Standardization Organization (ISO) and Americal Public Health Association (APHA) [45]. The Jan-2022 samples were analysed at the Eawag Swiss Federal Institute of Aquatic Science and Technology laboratory in Switzerland, whereas the Sept-2022 samples were analysed at the ALS Technichem Sendirian Berhad laboratory in Malaysia. Analytical methods are described in Table 3.

Table 1. Coordinates and characteristics of groundwater wells in this study.

| District | Sample ID | Coordinates | | Characteristics |
		Latitude	Longitude	
Brunei-Muara	G1	4°56′06.8″ N	114°52′49.4″ E	Flowing artesian; irrigation use. Water flow rate of 0.5 m^3/h; well depth of 50 m bgl.
Tutong	G2	4°42′00.6″ N	114°38′18.6″ E	Flowing artesian; potable water. Water flow rate of 1–2 m^3/h; well depth of 20 m bgl.
	G3	4°41′59.5″ N	114°38′20.1″ E	Flowing artesian; potable water. Water flow rate of 1–2 m^3/h; well depth of 25 m bgl.
Belait	G4	4°23′07.4″ N	114°27′11.6″ E	Irrigation use; water flow rate of 5–12 m^3/h [37]. Well depth of 80 m bgl; submersible pump depth of 60 m bgl.
	G5	4°39′07.4″ N	114°25′32.4″ E	Flowing artesian; potable water. Water flow rate of 28.8 m^3/h; well depth of 200 m bgl.

Note: m bgl: metres below ground level.

Table 2. Coordinates and characteristics of surface water sources in this study.

| District | Sample ID | Coordinates | | Characteristics |
		Latitude	Longitude	
Brunei-Muara	S1	4°47′19.9″ N	114°48′58.7″ E	Wasan river; drainage and source for paddy field irrigation.
	S2	4°47′38.5″ N	114°49′17.4″ E	Panchor river; drainage and source for paddy field irrigation.
	S3	4°48′05.9″ N	114°48′06.2″ E	Imang reservoir; main source for irrigation in Brunei-Muara. Reservoir capacity of 8 million cubic metres [46].
Tutong	S4	4°41′57.6″ N	114°38′19.3″ E	Penapar river; located near construction site of new dam.
Belait	S5	4°22′04.3″ N	114°27′23.6″ E	Rampayoh river; drainage and source for paddy field irrigation.
	S6	4°32′20.5″ N	114°28′04.7″ E	Belait river; located near residential area.
	S7	4°30′56.1″ N	114°28′28.9″ E	Luagan lake; located near recreational area.
Temburong	S8	4°43′02.7″ N	115°06′33.0″ E	Lamaling river; located near residential and commercial areas.
	S9	4°45′50.2″ N	115°11′10.8″ E	Labu river; located near recreational area and paddy field.
	S10	4°45′04.0″ N	115°12′07.7″ E	Senukoh river; located near recreational area and paddy field.

Table 3. Water quality parameters, analytical methods and detection limits.

Sampling Event	Parameters	Method	Reference	Detection Limits *
January-2022	Sodium, magnesium, calcium, potassium	Ion chromatography	EN ISO 14911	0.5, 1.5
	Chloride, sulphate	Ion chromatography	EN ISO 10304-1	0.5, 0.1
	Bicarbonate, carbonate	Titration	EN ISO 9963-1	1
September-2022	Sodium, magnesium, calcium, potassium	Ion chromatography	APHA 3120-N	0.1
	Chloride	Titration	APHA 4500-Cl-E	1
	Sulphate	Turbidimetric	APHA 4500-SO-E	1
	Bicarbonate, carbonate	Titration	APHA 2320B	1
	Iron, zinc, lead, copper, chromium, cadmium, arsenic	Ion chromatography	APHA 3125B	0.001, 0.0005

Note: * Unit: mg/L.

Charge balance errors (CBE) were calculated using PHREEQC software [47] to ensure the validity of the chemical analysis of the water samples. The ionic charge balance error of all analysed water samples in this study ranged between ±10%, which is acceptable as per research publication standards [48,49].

2.3. Water Classification

Prior to data classification, mean results were calculated for each measured parameter and compared with the FAO standard guideline [16] (Table 4). Water classification for irrigation suitability was conducted using various established water quality indices: SAR [50], Na% [51], RSC [52], MAR [53], KR [54], PS [51], and IWQI [55,56]. The Piper diagram [57] was used for plotting and classifying the water hydrochemistry, while the USSL diagram [58] and Wilcox diagram [59] were used for suitability classification for irrigation use.

Table 4. Mean physicochemical properties of ground and surface water samples in Brunei Darussalam based on sampling campaigns in January and September 2022.

Sample	Sample ID	pH	EC µS/cm	Na⁺	Mg²⁺	Ca²⁺	K⁺	SO₄²⁻	Cl⁻	HCO₃⁻
				Na^+	Mg^{2+}	Ca^{2+}	K^+	SO_4^{2-}	Cl^-	HCO_3^-
							mg/L			
Groundwater	G1	4.8	28.5	0.7	0.2	0.4	0.1	1.5	1.9	15.5
	G2	4.6	50.0	0.8	0.7	0.8	0.4	5.0	1.2	10.0
	G3	5.2	68.5	0.9	2.7	1.5	0.5	17.5	1.2	28.0
	G4	6.3	1127	190	7.4	2.1	2.8	1.0	306	198
	G5	6.5	85.0	3.5	2.3	4.3	1.3	9.0	1.0	36.0
Surface Water	S1	6.1	90.5	5.3	3.4	2.5	1.7	17.5	4.0	44.0
	S2	6.6	133	6.7	4.3	5.5	2.4	15.5	5.9	53.5
	S3	6.9	51.0	2.8	2.1	1.1	0.9	5.0	0.8	19.5
	S4	4.6	51.5	0.6	1.1	1.1	0.3	9.0	1.2	11.0
	S5	5.4	38.0	0.7	1.3	0.8	0.6	8.0	0.9	28.0
	S6	4.9	30.0	0.1	0.3	0.5	0.1	3.0	0.5	73.0
	S7	4.8	39.0	0.7	0.2	0.7	1.3	1.0	1.0	5.0
	S8	6.8	32.0	1.4	1.4	1.2	0.2	3.5	1.0	36.5
	S9	6.3	202	27.0	3.1	0.9	1.1	5.5	46.1	47.0
	S10	6.8	51.5	4.0	1.2	0.8	0.5	3.7	2.8	34.5
				Worldwide Standard Limits						
FAO *		6.5–8.4	<750	<920	<60	<400	<30	<960	<1050	<150

Note: * Standard permissible limits are those provided by the Food and Agriculture Organisation of the United Nations (FAO) [16].

3. Results and Discussion

3.1. General Characteristics of Water Quality

3.1.1. Chemical Composition

General water quality characteristics of ground and surface water samples in Brunei Darussalam are presented in this section. The mean results of measured pH, EC, and major cations (sodium, magnesium, calcium, and potassium) and anions (sulphate, chloride, and bicarbonate) are listed in Table 4 and plotted in the boxplots shown in Figure 3.
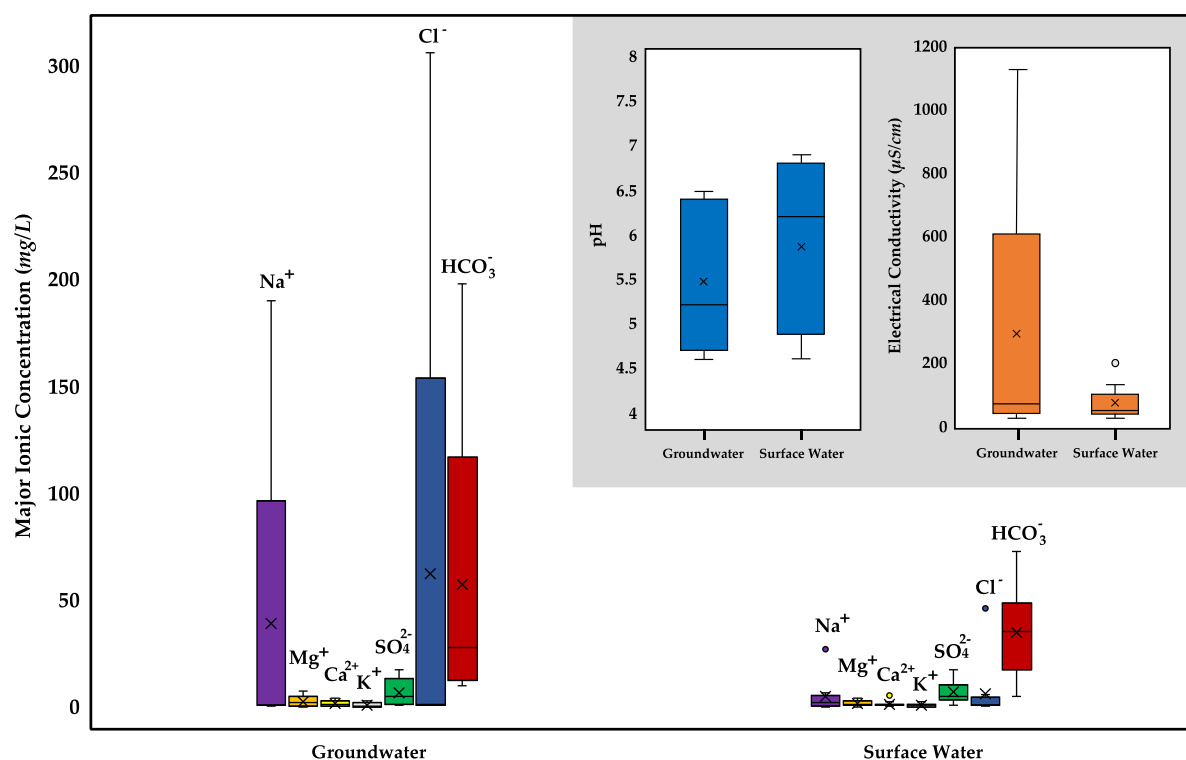
Figure 3. Hydrochemistry of ground and surface water (major ionic concentration); inset box plots showing the pH and EC values. Outliers are represented by 'o', and mean values are represented by '×'.

The pH results of samples in this study are slightly to moderately acidic, with pH values ranging from 4.6 to 6.5 for the groundwater samples and from 4.6 to 6.9 for the surface water samples. According to the FAO standard guideline, the normal pH range for irrigation water is 6.5 to 8.4 [16]. Irrigation water with pH outside this normal range may result in plant toxicity leading to nutritional imbalance in plants [60]. Therefore, pH values outside this range warrant further investigation and evaluation.

The EC of the analysed water samples in this study ranged from 28 to 1127 μS/cm for the groundwater samples and from 30 to 202 μS/cm for the surface water samples. According the FAO's permissible limits for irrigation use, EC values should be less than 750 μS/cm [16]. Higher EC values are indicative of a higher salt concentration in the water [50,61].

The ionic constituents of the analysed water samples indicate that the general abundance order for major cations is sodium > magnesium > calcium > potassium (Figure 3). Sodium ions vary from 0.7 to 190 mg/L for the groundwater samples and from 0.1 to 27 mg/L for the surface water samples. The results of magnesium ion concentration range from 0.2 to 7.4 mg/L for the groundwater samples and from 0.2 to 4.3 mg/L for the surface water samples. Calcium concentrations in the groundwater and surface water samples range between 0.4 to 4.3 mg/L and 0.5 to 5.5 mg/L, respectively. Among the analysed cations, potassium ions are the lowest in concentration, with values ranging from 0.1 to

2.8 mg/L for the groundwater samples and 0.1 to 2.4 mg/L for the surface water samples. Results show that all the measured cations in the water samples are lower than the FAO permissible limits, thus, suggesting their suitability for irrigation use.

The general order of abundance for major anions in the analysed water samples is bicarbonate > sulphate > chloride > carbonate (Figure 3). Bicarbonate is the most dominant anion, with values ranging from 10 to 198 mg/L for the groundwater samples and from 5 to 73 mg/L for the surface water samples. Results show that the bicarbonate concentrations of most of the analysed water samples are lower than the FAO's permissible limits (<150 mg/L), except for the groundwater sample G4 (198 mg/L) (Table 4). The range in concentrations of sulphate and chloride ions in the groundwater samples are 1 to 18 mg/L and 1 to 306 mg/L, respectively. In comparison, the range in the concentrations of sulphate and chloride ions in the surface water samples are 1 to 18 mg/L and 0.9 to 46 mg/L, respectively. Results showed that the sulphate and chloride concentrations in the analysed samples are lower than the FAO standard limits, suggesting their suitability for irrigation use. In addition, carbonate ions were absent in all the analysed samples.

3.1.2. Hydrochemical Facies

The major ionic constituents of the analysed water samples in this study were plotted on the Piper trilinear diagram for hydrochemical facies analysis [57]. Each facies type indicates the predominant cations and anions that affect the hydrochemistry of a sample [21,62]. The four major facies types represented in the Piper diagram are the calcium-, magnesium-, sulphate-, and chloride-type (Type I); sodium-, chloride-, and sulphate-type (Type II); sodium-, potassium-, and bicarbonate-type (Type III); and calcium-, magnesium-, and bicarbonate-type (Type IV). Results revealed that most of the analysed water samples belong to the 'Type IV' water category, two samples (S9 and G4) show a 'Type II' water category, one sample (S4) show a 'Type I' water category, and two samples (S10 and S7) show a 'Type III' water category (Figure 4).
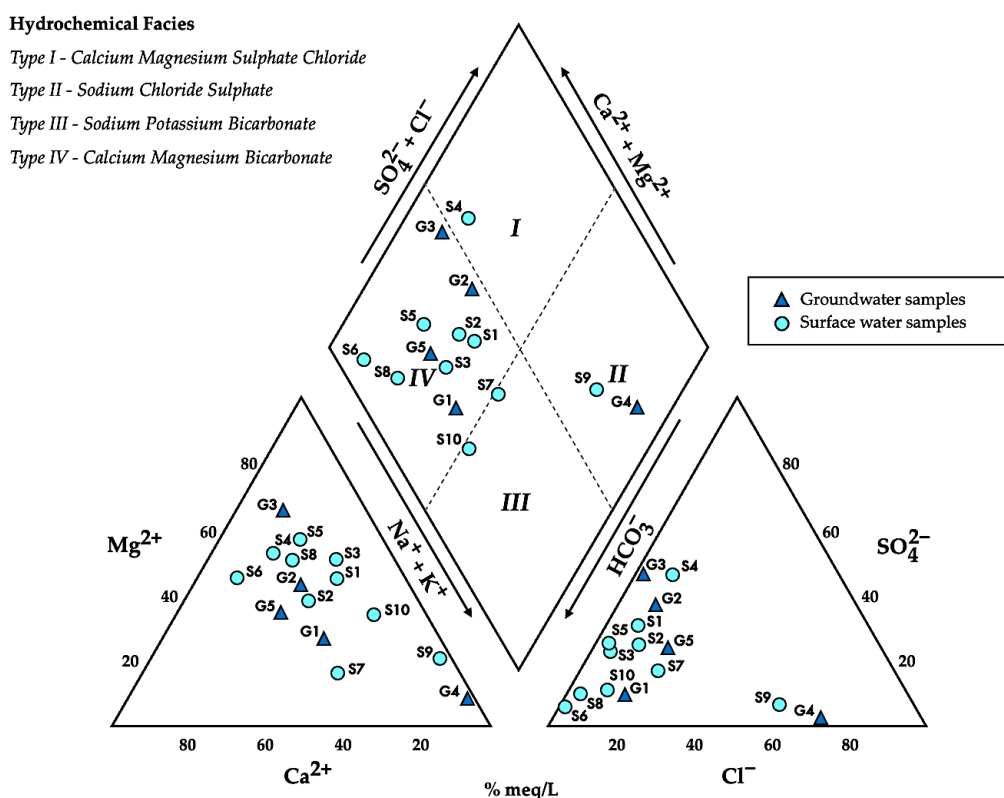
Figure 4. Piper trilinear diagram showing the hydrochemical facies of the analysed ground and surface water samples in the study area. Arrows are showing increasing amounts of the ions.

3.1.3. Heavy Metals Assessment

The measured concentration of heavy metals in the analysed ground and surface water samples are given in Table 5. The abundance order of measured metals in the analysed samples is Fe > Zn > Cu > Cr > As > Pb > Cd. Results showed that the measured heavy metal concentrations are within the FAO permissible limits and are deemed safe for irrigation use [16,62].

Table 5. Heavy metals concentration of ground and surface water samples in Brunei Darussalam.

Sample	Sample ID	Fe	Zn	Pb	Cu	Cr	Cd	As
					mg/L			
Groundwater	G1	0.78	0.007	<0.001	<0.001	<0.001	<0.0005	<0.001
	G2	0.19	0.029	<0.001	<0.001	<0.001	<0.0005	<0.001
	G3	1.53	0.016	<0.001	<0.001	<0.001	<0.0005	0.002
	G4	2.92	0.005	<0.001	<0.001	<0.001	<0.0005	<0.001
	G5	1.17	0.008	<0.001	<0.001	<0.001	<0.0005	<0.001
Surface Water	S1	0.94	0.018	0.0005	0.0065	0.0016	<0.0001	0.0028
	S2	0.73	0.012	0.0002	<0.0001	0.0011	<0.0001	0.0012
	S3	0.10	0.009	0.0002	<0.0001	0.001	<0.0001	0.0012
	S4	0.39	0.037	<0.0001	<0.0001	0.0009	<0.0001	0.001
	S5	0.10	0.041	0.0001	<0.0001	0.0007	<0.0001	0.0002
	S7	0.64	0.051	0.0004	<0.0001	0.001	<0.0001	0.0009
	S8	0.10	0.014	<0.0001	0.0016	0.0007	<0.0001	0.0004
	S9	0.60	0.012	0.0002	<0.0001	0.001	<0.0001	0.0004
	S10	0.09	0.017	<0.0001	<0.0001	0.0007	<0.0001	0.0004
Worldwide Standard Limits								
FAO *		<5.0	<2.0	<5.0	<0.2	<0.1	<0.01	<0.1

Note: * Standard permissible limits are those provided by the Food and Agriculture Organisation of the United Nations (FAO) [16].

3.2. Classification for Irrigation Suitability

Calculated water quality indices (SAR, Na%, RSC, MAR, KR, TH, PS, and IWQI) for classifying water suitability for irrigation use in this study are given in Tables 6 and 7. The general details of water quality indices are discussed in the sub-sections below:

Table 6. Irrigation water quality indices of ground and surface water samples in Brunei Darussalam.

Sample	Sample ID	SAR	Na%	RSC	MAR	KR	TH	PS	IWQI
Groundwater	G1	0.2	42.6	0.22	45.2	0.64	1.5	0.07	3.1
	G2	0.1	28.2	0.14	59.1	1.31	4.5	0.09	2.9
	G3	0.1	13.0	0.36	74.8	0.32	14.7	0.22	5.8
	G4	11.1	90.4	3.15	85.3	78.8	35.7	8.64	80
	G5	0.3	27.8	0.31	46.9	0.43	20.2	0.12	7.7
Surface Water	S1	0.4	36.1	0.42	69.2	0.61	20.2	0.29	9.1
	S2	0.4	32.0	0.17	56.3	0.33	31.3	0.33	11.6
	S3	0.3	34.7	−0.40	75.9	0.14	11.2	0.07	4.5
	S4	0.1	16.5	−0.22	62.3	0.05	7.3	0.13	3.1
	S5	0.1	21.3	0.07	72.8	0.06	7.1	0.11	5
	S6	0.02	10.9	0.78	49.7	0.01	2.5	0.05	11
	S7	0.2	52.9	−0.55	32.0	0.04	2.6	0.04	2
	S8	0.2	23.6	−0.02	65.8	0.08	8.6	0.06	6.1
	S9	2.4	76.4	0.56	85.0	4.41	14.8	1.36	16
	S10	0.5	52.4	0.33	71.2	0.60	6.6	0.12	6.8

Notes: SAR: sodium adsorption ratio, RSC: residual sodium carbonate, MAR: magnesium adsorption ratio, KR: Kelly's ratio, TH: total hardness, PS: potential salinity, IWQI: Irrigation Water Quality Index.

3.2.1. Salinity Hazard

Electrical conductivity (EC) is the most crucial salinity hazard parameter in determining the suitability of water for irrigation use [50,61]. EC is the measure of the capacity of a substance to conduct electric current, which depends upon the temperature and salts present in the water [63,64]. Irrigation water with high salt levels may, in turn, increase the salt concentration in the soils, which can be an issue if the salt accumulates to a level harmful to crops [60]. Based on the classified EC values (Table 7), most of the analysed water samples in this study are generally safe for irrigation use. In contrast, the groundwater sample G4 showed a 'slight to moderate' salinity hazard (EC = 1127 μS/cm), suggesting restriction on the use for irrigation [16,50].

Table 7. Water classification based on the calculated water quality indices of ground and surface water samples in Brunei Darussalam.

Indices	Range	Classification	Reference	Samples	
				Groundwater	Surface Water
Electrical Conductivity (EC)	<750	No problem	[16,50]	G1–G3, G5	S1–S10
	750–3000	Slight to Moderate		G4	-
	>3000	Severe		-	-
Sodium Adsorption Ratio (SAR)	<10	Excellent	[16,50]	G1–G3, G5	S1–S10
	10–18	Good		G4	-
	18–26	Doubtful		-	-
	>26	Unsuitable		-	-
Sodium Percentage (Na%)	<20	Excellent	[64]	G3	S4, S6
	20–40	Good		G2, G5	S1–S3, S5, S8
	40–60	Permissible		G1	S7, S10
	60–80	Doubtful		-	S9
	>80	Unsafe		G4	-
Residual Sodium Carbonate (RSC)	<1.25	Good	[52]	G1–G3, G5	S1–S10
	1.25–2.5	Doubtful		-	-
	>2.5	Unsuitable		G4	-
Magnesium Adsorption Ratio (MAR)	<50%	Suitable	[53]	G1, G5	S6, S7
	>50%	Unsuitable		G2–G4	S1–S5, S8–S10
Kelley's Ratio (KR)	<1	Suitable	[54]	G1, G3, G5	S1–S8, S10
	>1	Unsuitable		G2, G4	S9
Total Hardness (TH)	<75	Soft	[46]	G1–G5	S1–S10
	75–150	Moderately hard		-	-
	150–300	Hard		-	-
	>300	Very hard		-	-
Potential Salinity (PS)	<3	Excellent	[51]	G1–G3, G5	S1–S10
	3–5	Good		-	-
	>5	Unsuitable		G4	-
Irrigation Water Quality Index (IWQI)	0–25	Excellent	[56]	G1–G3, G5	S1–S10
	26–50	Good		-	-
	51–75	Poor		-	-
	76–100	Very Poor		G4	-
	>100	Unsuitable		-	-

### 3.2.2. Sodium Adsorption Ratio (SAR)

Sodium ions occur in water due to natural and anthropogenic processes [50]. However, high sodium levels are undesirable as they can lead to the development of alkaline soils. High sodium ions are more likely to be adsorbed onto clayey soils, replacing calcium and magnesium ions, resulting in poor soil permeability [65]. Therefore, the lower the sodium ions, the safer it is for plant growth [60]. The sodium adsorption ratio provides

a good estimate of sodium hazard in irrigation water [66,67]. SAR has been calculated as follows [50,68]:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{1}$$

where the sodium, calcium, and magnesium concentrations are expressed in meq/L.

SAR results revealed that all the analysed samples are classifiable as 'excellent' water class, except for groundwater sample G4 which is classifiable as a 'good' water class (SAR = 11) for irrigation use (Table 7). The analytical data were also plotted on the US salinity laboratory diagram [58] in Figure 5. The diagram is based on the integrated effects of EC and SAR. EC is representative of the salinity hazard (horizontal axis), and SAR is representative of the sodicity hazard (vertical axis). Each axis is separated into four hazard levels which are low, medium, high, and very high [65]. The application of the USSL diagram showed that most of the water samples are distributed within the C1S1 group, representing waters with low salinity and low sodium hazards, whereas one groundwater sample (G4) is categorised as C3S3, showing high salinity and sodium hazards (Figure 5).
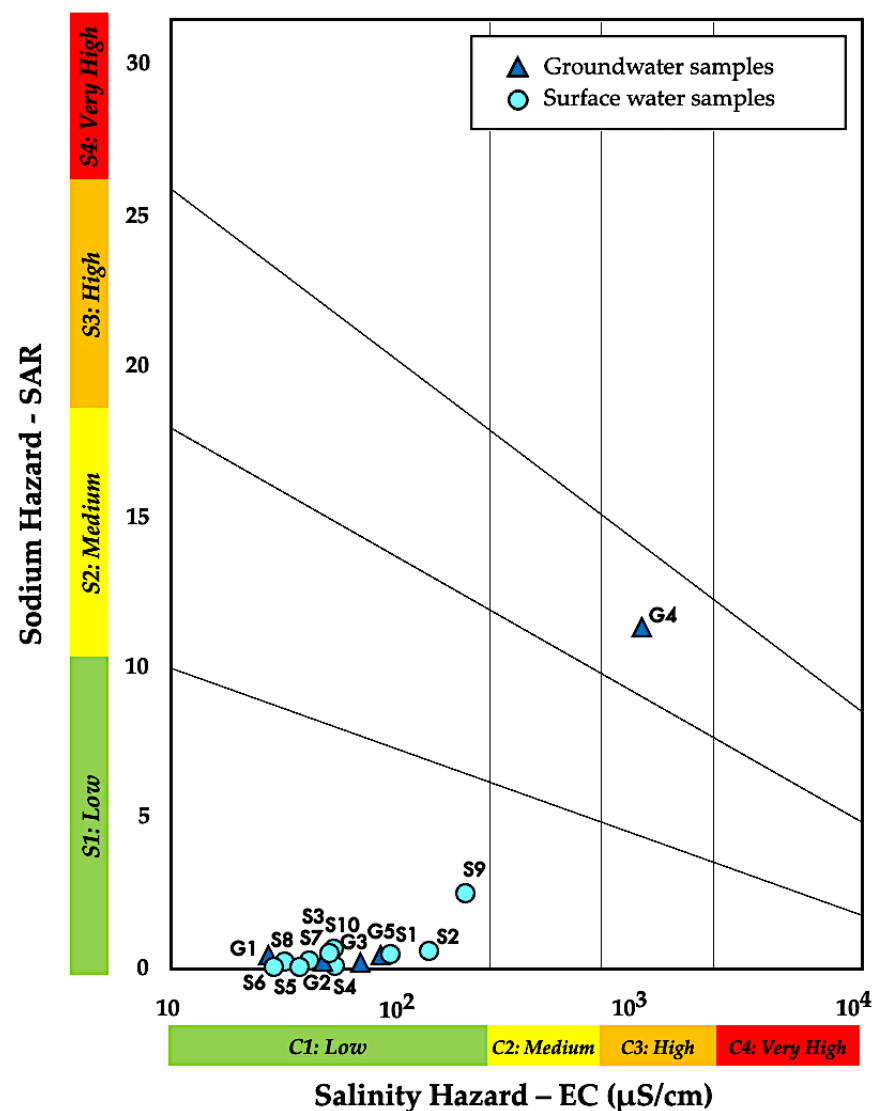
Figure 5. USSL diagram showing the irrigation suitability of the analysed ground and surface water samples in the study area.

3.2.3. Sodium Percentage (Na%)

Sodium percentage, or soluble sodium concentration, is used to evaluate the sodicity hazard of irrigation water [64,66]. Na% is calculated using the expression below [51]:

$$Na\% = \left(\frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \right) \times 100 \qquad (2)$$

where the ionic concentrations are expressed in meq/L.

Based on the calculated Na% values of samples in this study (Tables 6 and 7), the majority of the samples demonstrate 'excellent to permissible' water quality (Na% lower than 60%). One sample (S9) plotted in the 'doubtful' water quality category (Na% = 76%), and one sample (G4) falls within the 'unsafe' water quality category (Na% = 90%). Analytical data were plotted on the Wilcox diagram [59] in Figure 6. The Wilcox diagram is based on the integrated effects of the EC and Na% indicators to classify water quality for irrigation use [66]. Results show that almost all the samples fall within the 'excellent to good' water quality category, except for the groundwater sample G4, which has been classified in the 'doubtful to unsuitable' water quality category (Figure 6).
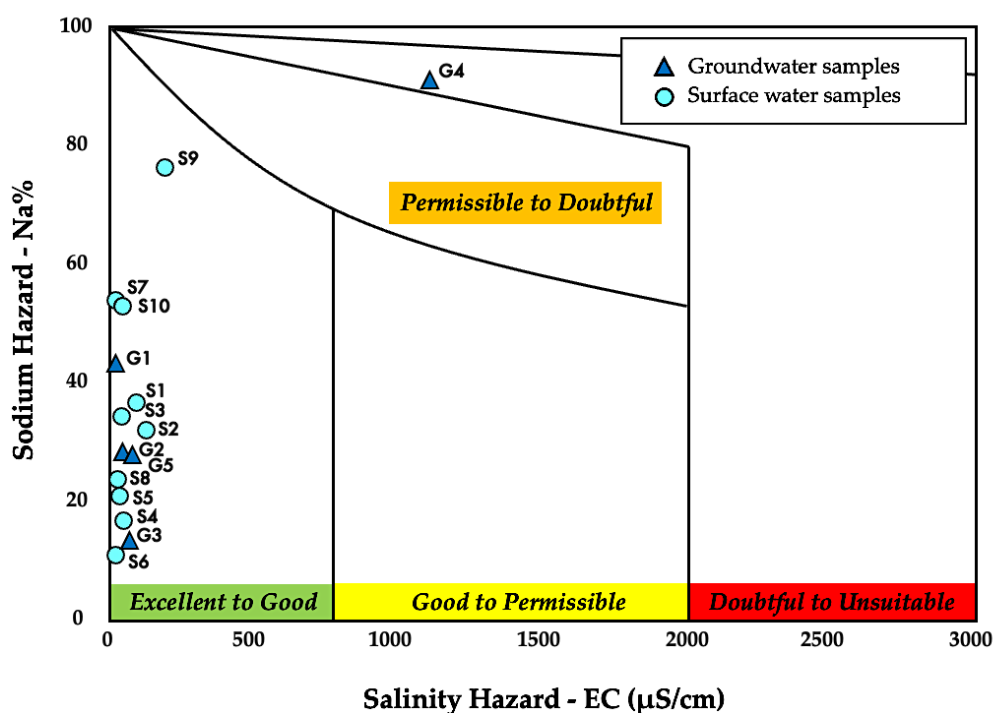
Figure 6. Wilcox diagram showing the irrigation suitability of the analysed ground and surface water samples in the study area.

3.2.4. Residual Sodium Carbonate (RSC)

Residual sodium carbonate is the difference between the total carbonate and bicarbonate ions minus that of alkaline earth elements (calcium and magnesium) [52,53]. Excess carbonate and bicarbonate ions (high RSC index) indicate that calcium and magnesium ions precipitate from the solution, resulting in higher sodium concentrations, thus increasing the potential sodium hazard [65,69]. The residual sodium carbonate (RSC) index is expressed as follows [52]:

$$RSC = \left(CO_3^{2-} + HCO_3^- \right) - \left(Ca^{2+} + Mg^{2+} \right) \qquad (3)$$

where the ion concentrations are expressed in meq/L.

The RSC values of all of the analysed ground and surface water samples are representative of the 'good' water category (RSC < 1.25 meq/L), except for sample G4 (RSC = 3.15 meq/L), which can be classified as unsuitable for irrigation use (Tables 6 and 7).

3.2.5. Magnesium Adsorption Ratio (MAR)

The magnesium adsorption ratio index indicates the magnesium hazard of irrigation water [70]. High magnesium levels in irrigated soils are usually caused by an ionic exchange with sodium ions, resulting in poor soil permeability [64]. MAR ratios higher than 50% are deemed harmful and unsuitable for irrigation [64,70]. MAR is calculated as follows [53]:

$$\text{MAR} = \left(\frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \right) \times 100 \tag{4}$$

where the calcium and magnesium ions are expressed in meq/L.

MAR values of the analysed ground and surface water samples in this study ranged between 32% to 85% (Table 6). Results showed that only 27% of the samples (G1, G5, S6 and S7) are classified as 'suitable' water for irrigation use, while others with MAR values higher than 50% are classified as 'unsuitable' for irrigation use (Table 7).

3.2.6. Kelley's Ratio (KR)

Kelley's ratio is an essential water quality index for determining water suitability for irrigation use [70]. Irrigation water quality is considered suitable if the KR is less than one and unsuitable if the KR is more than one. KR is expressed as follows [54]:

$$\text{KR} = \frac{Na^+}{Ca^{2+} + Mg^{2+}} \tag{5}$$

where the sodium, calcium, and magnesium concentrations are expressed in meq/L. KR values of the analysed water samples in this study varied from 0.01 to 78 meq/L (Table 6). Results show that most of the analysed samples are classified as 'suitable' water, except for the groundwater samples G2 and G4 and surface water sample S9, which are classified as 'unsuitable' waters for irrigation use (Table 7).

3.2.7. Total Hardness (TH)

Total hardness has been estimated from calcium and magnesium ions using the following equation and is calculated as mg/L $CaCO_3$ [46,63]:

$$\text{TH} = 2.497 \, Ca^{2+} + 4.118 \, Mg^{2+} \tag{6}$$

The TH of water can be classified into 'soft' or 'hard'. TH of less than 75 mg/L is for 'soft' water, 75 to 150 mg/L is for 'moderately hard' water, 150 to 300 mg/L is for 'hard' water, and more than 300 mg/L is for 'very hard' water [19,70]. The TH values of water samples in this study varied from 1 to 36 mg/L (Table 6). Results show that all the analysed samples in this study are classified as 'soft' water (Table 7).

3.2.8. Potential Salinity (PS)

The PS index is used for classifying irrigation water based on chloride ion concentrations and half of the sulphate ion concentrations. PS values lower than five are deemed suitable for irrigation use [69]. PS is calculated using the formula [51]:

$$\text{PS} = Cl^- + \frac{1}{2} SO_4^{2-} \tag{7}$$

The ionic concentrations of chloride and sulphate are expressed in meq/L.

In this study, the value of PS varied from 0.06 to 8.6 meq/L (Table 6). Results suggest that most of the analysed water samples fall within the 'excellent' water class, except for

the groundwater sample G4 (PS = 8.6 meq/L), which can be classified as 'unsuitable' water for irrigation use (Table 7).

3.2.9. Irrigation Water Quality Index (IWQI)

The IWQI is a single dimensionless number used to evaluate the health or condition of a water body through integrating multiple water quality parameters, providing a comprehensive assessment of water quality in a simplified manner [24,71]. In the present study, the irrigation water quality index was calculated based on the standard three-step methodology [56].

First, specific parameters were identified and assigned a weight (w_i) according to the relative importance to the overall water quality [69]. The specific parameters used for calculating the IWQI in the present study are EC, sodium, chloride, bicarbonate, and SAR [72,73]. For each of the chosen parameters, the standard limit is prescribed by the FAO [16]. The relative weight (W_n) was calculated for each parameter based on the following equation [56]:

$$W_n = \frac{k}{S_n} \tag{8}$$

where W_n is the unit weight factors for the nth parameter and S_n is the standard desirable value of the nth parameter. k is the proportionality constant and was calculated using the following formula:

$$k = \frac{1}{\sum \frac{1}{S_n}} \tag{9}$$

On summation of all selected parameters' unit weight factors, $W_n = 1$.
Secondly, the sub-index value (Q_n) was calculated as follows:

$$Q_n = \frac{[(V_n - V_o)]}{[(S_n - V_o)]} \times 100 \tag{10}$$

where Q_n is the sub-index value, V_n is the mean concentration of the nth parameter, and V_o is the actual values of the parameters in pure water.

Thirdly, through combining the first and second steps, the overall IWQI was calculated using the following formula:

$$IWQI = \frac{\sum W_n Q_n}{\sum W_n} \tag{11}$$

The IWQI values obtained from the analysed water samples in the study area varied from 8 to 80 (Table 6). Water classification based on IWQI revealed that most of the analysed samples are of 'excellent' water quality, except for the groundwater sample G4, which showed 'very poor' water quality (Table 7).

3.3. The Impact of Water Quality on Agricultural Development

Water quality has a significant impact on agricultural development as it directly affects crop growth and productivity [16,64]. Contaminants such as salts and heavy metals present in water can hinder nutrient uptake, impair plant health, and reduce crop yields [60]. Poor water quality can lead to soil degradation, nutrient imbalance, and equipment clogging in irrigation systems. Furthermore, water pollution from agricultural runoff could also degrade water quality in its path and harm ecosystems [74]. Therefore, good quality water is crucial for ultimately driving agricultural development towards a more productive and sustainable future.

In the present study, hydrochemical evaluations revealed that waters in the study area primarily belong to the calcium-, magnesium-, and bicarbonate-type, or Type IV water category. There was no clear distinction between the ground and surface water types (Figures 3 and 4). In general, the analysed groundwater samples can be considered more mineralised compared to the surface water samples, and their pH levels are also more acidic in comparison (Figure 3). Although most of the investigated water is considered safe for

irrigation use and is not highly mineralised based on the FAO standard, potential harmful effects to crops and soil may only show after years of using the water for irrigation [66]. Low-pH waters also require further treatments to avoid increasing the soil acidity in the long run [14]. Furthermore, assessments of heavy metals revealed that all the analysed water samples are deemed safe for irrigation use (Table 5). Iron is the most-detected heavy metal in all the analysed samples. In the study area, trace metals are notably higher in residential, agricultural, and industrial waterways [26]. Iron is also present in the sandstones of Brunei [75].

Our findings revealed mainly low salinity and sodicity risks in all the analysed samples as evident from the EC, SAR, Na%, RSC, KR, and PS values and classifications (Tables 6 and 7). However, for sample G4, high salinity and sodicity concerns have been observed. It is believed that groundwater contamination has occurred at the well site due to anthropogenic activities such as the overuse of fertilisers and infiltration of mineralised irrigation water into the aquifer [37]. Based on the magnesium hazard assessment (MAR), our findings showed that only 27% of the analysed water samples in this study are considered suitable for irrigation use. Therefore, implementation of appropriate water management practices in the study area will help mitigate the potential impacts of magnesium hazard in the irrigation water [14]. Limitations on the use of highly mineralised waters should be considered, preferably for salt-tolerant crops. A good drainage system is also required to further prevent soil salinisation [61,64].

The general water quality index (WQI) system has found significant application in Southeast Asia due to the region's abundant water resources and the need for reliable water management [23,76,77]. The application of WQI in Brunei Darussalam, however, has not been investigated before. In this study, we employed the irrigation water quality index (IWQI) to evaluate the water quality status of selected ground and surface water resources gathered from all four districts of Brunei. Results showed 'excellent' water quality for the majority of the analysed samples, except for the groundwater sample G4, which placed in the 'very poor' water class (Table 7). Poor water class based on the IWQI indicates that the water is polluted or deteriorated and is deemed unsuitable for irrigation use [56,69]. Regular water quality monitoring is therefore recommended in areas with poor MAR and IWQI results.

Future water quality studies in the country should focus on the impact of land use practices, such as deforestation for agriculture and urban development [78,79]. Addressing water quality issues in Brunei Darussalam also requires a comprehensive and integrated approach involving government agencies, industries, communities, and stakeholders [27,32]. An integrated approach for water quality monitoring through combining traditional sampling methods and advanced technologies, such as remote sensing, drones, and sensor networks, should be utilised [48,80]. Furthermore, the use of real-time data collection, data analytics, and modelling techniques could further enhance water quality monitoring efficiency, improve data accuracy, and facilitate timely decision-making.

4. Conclusions

Water quality evaluations for classifying water suitability for irrigation use, in particular, were conducted in Brunei Darussalam. Based on the measured pH, water samples in the study area are slightly to moderately acidic. Most of the samples are classified as Type IV water class: calcium-, magnesium-, and bicarbonate-type water. Our assessments of heavy metals (Fe, Zn, Cu, Cr, As, and Cd) revealed that the water samples are generally safe for irrigation use. Salinity and sodicity hazard assessments based on EC, SAR, Na%, KR, and PS showed that almost all the analysed water samples are classified as suitable for irrigation. However, magnesium hazards based on MAR were observed in most of the samples. Overall, the IWQI of water samples in this study showed 'excellent' water, except for sample G4 which showed 'very poor' water. It is therefore recommended to apply suitable treatment to these water resources before using them for irrigation, particularly for waters with poor MAR and IWQI results. Moreover, potentially harmful effects to soils

and crops may only show after years of using the water for irrigation. Our findings show that the water resources in Brunei Darussalam are stressed and, to some degree, impacted by natural and anthropogenic causes. Future studies should include regular water quality monitoring to ensure sustainable management of water resources in the country.

References

1. Hanjra, M.A.; Qureshi, M.A. Global water crisis and future food security in an era of climate change. *Food Policy* **2010**, *35*, 365–377. [CrossRef]
2. Eliasson, J. The rising pressure of global water shortages. *Nature* **2015**, *517*, 6. [CrossRef] [PubMed]
3. Gude, V.G. Desalination and water reuse to address global water scarcity. *Rev. Environ. Sci. Biotechnol.* **2017**, *16*, 591–609. [CrossRef]
4. Essink, G. Improving fresh groundwater supply—Problems and solutions. Contribution of working group II to the third assessment report of the intergovernmental panel on climate change. *Ocean Coast Manag.* **2001**, *44*, 429–449.
5. Kumar, L.; Kumari, R.; Kumar, A.; Tunio, I.A.; Sassanelli, C. Water Quality Assessment and Monitoring in Pakistan: A Comprehensive Review. *Sustainability* **2023**, *15*, 6246. [CrossRef]
6. Mester, T.; Benkhard, B.; Vasvári, P.; Csorba, P.; Kiss, E.; Balla, D.; Fazekas, I.; Csépes, E.; Berkat, A.; Szabó, G. Hydrochemical assessment of the Kisköre Reservoir (Lake Tisza) and the impacts of water quality on tourism development. *Water* **2023**, *15*, 1514. [CrossRef]
7. Mehmood, A.; Mirza, M.A.; Choudhary, M.A.; Kim, K.H.; Raza, W.; Raza, N. Spatial distribution of heavy metals in crops in wastewater irrigated zone and health risk assessment. *Environ. Res.* **2019**, *168*, 382–388. [CrossRef]
8. Hashem, M.S.; Qi, X. Treated Wastewater Irrigation—A Review. *Water* **2021**, *13*, 1527. [CrossRef]
9. Das, A.; Das, S.S.; Chowdhury, N.R.; Joardar, M.; Ghosh, B.; Roychowdhury, T. Quality and health risk evaluation for groundwater in Nadia district, West Bengal: An approach on its suitability for drinking and domestic purpose. *Groundw. Sustain. Dev.* **2020**, *10*, 100351. [CrossRef]
10. Abbasnia, A.; Yousefi, N.; Mahvi, A.H.; Nabizadeh, R.; Radfard, M.; Yousefi, M.; Alimohammadi, M. Evaluation of groundwater quality using water quality index and its suitability for assessing water for drinking and irrigation purposes: A case study of Sistan and Baluchistan province (Iran). *Hum. Ecol.* **2018**, *25*, 988–1005. [CrossRef]
11. Gordon, L.J.; Finlayson, C.M.; Filkenmark, M. Managing water in agriculture for food production and other ecosystem services. *Agri. Water Manag.* **2010**, *97*, 512–519. [CrossRef]
12. Syed, A.; Sarwar, G.; Shah, S.H.; Muhammad, S. Soil Salinity Research in 21st Century in Pakistan: Its Impact on Availability of Plant Nutrients, Growth and Yield of Crops. *Commun. Soil Sci. Plant Anal.* **2019**, *52*, 183–200. [CrossRef]
13. Zhu, D.; Ryan, M.C.; Sun, B. The influence of irrigation and Wuliangsuhai Lake on groundwater quality in eastern Hetao Basin, Inner Mongolia, China. *Hydrogeol. J.* **2014**, *22*, 1101–1114. [CrossRef]
14. Jia, H.; Qian, H.; Zheng, L.; Feng, W.; Wang, H.; Gao, Y. Alterations of groundwater chemistry due to modern water transfer for irrigation over decades. *Sci. Total Environ.* **2020**, *717*, 137170. [CrossRef] [PubMed]

15.　Kachi, N.; Kachi, S.; Bousnoubra, H. Effects of irrigated agriculture on water and soil quality (case perimeter Guelma, Algeria). *Soil Water Res.* **2016**, *1*, 97–104. [CrossRef]

16.　Ayers, R.S.; Westcot, D.W. *Water Quality for Agriculture: Irrigation and Drainage*; FAO: Rome, Italy, 1985; pp. 1–117.

17.　Sundaray, S.K.; Nayak, B.B.; Bhatta, D. Environmental studies on river water quality with reference to suitability for agricultural purposes: Mahandi river estuarine system, India—A case study. *Environ. Monit. Assess.* **2009**, *155*, 227–245. [CrossRef]

18.　Salifu, M.; Aidoo, F.; Hayford, M.S.; Adomako, D.; Asare, E. Evaluating the suitability of groundwater for irrigational purposes in some selected districts of the Upper West region of Ghana. *Appl. Water Sci.* **2015**, *3*, 763–771. [CrossRef]

19.　Beyene, G.; Aberra, D.; Fufa, F. Evaluation of the suitability of groundwater for drinking and irrigation purposes in Jimma zone of Oromia, Ethiopia. Groundw. *Sustain. Dev.* **2019**, *9*, 100216. [CrossRef]

20.　Mirzabeygi, M.; Yousefi, N.; Abbasnia, A.; Youzi, H.; Alikhani, M.; Mahvi, A.H. Evaluation of groundwater quality and assessment of scaling potential and corrosiveness of water supply networks, Iran. *J. Water Supply.* **2017**, *66*, 416–425. [CrossRef]

21.　Singh, K.K.; Tewari, G.; Kumar, S. Evaluation of Groundwater Quality for Suitability of Irrigation Purposes: A Case Study in the Udham Singh Nagar. *Uttarakhand. J. Chem.* **2020**, *15*, 6924026. [CrossRef]

22.　Aouiti, S.; Azaza, F.H.; Melki, F.E.; Hamdi, M.; Celico, F.; Zammouri, M. Groundwater quality assessment for different uses using various water quality indices in semi-arid region of central Tunisia. *Environ. Sci. Pollut. Res.* **2021**, *28*, 46669–46691. [CrossRef] [PubMed]

23.　Wong, Y.J.; Shimizu, Y.; He, K.; Sulaiman, N.M.N. Comparison among different ASEAN water quality indices for the assessment of the spatial variation of surface water quality in Selangor River basin, Malaysia. *Environ. Monit. Assess.* **2020**, *644*, 192. [CrossRef] [PubMed]

24.　Chidiac, S.; Najjar, P.E.; Ouaini, N.; Rayess, Y.E.; Azzi, D.E. A comprehensive review of water quality indices (WQIs): History, models, attempts and perspectives. *Rev. Environ. Sci. Biotechnol.* **2023**, *22*, 349–395. [CrossRef] [PubMed]

25.　Food and Agriculture Organisation of the United Nations. *AQUASTAT Country Profile—Brunei Darussalam*; FAO: Rome, Italy, 2011; 8p.

26.　Abdul Aziz, H.M.M. Baseline Study of the Chemical Composition of Brunei Darussalam Rivers. PhD Thesis, Brunel University, Uxbridge, UK, 2005; 218p.

27.　Hj Kamis, M.; Zaini, A.F.; Yahya, M.A.Y.; Abas, M.A.N.; Hassan, M.A.S. Causes and Impacts of Water Crisis and Achieving Water Security: Application to Brunei. 2021. Available online: https://www.researchgate.net/publication/356419567_Causes_and_Impacts_of_Water_Crisis_and_Achieving_Water_Security_Application_to_Brunei_17b8525_Mubarak_bin_Haji_Kamis_17b8526_Akhimullah_Farhan_bin_Zaini_17B8532_Muhammad_Aizuddin_Yaqin_bin_Haji_Yahaya?channel=doi&linkId=6199ceecd7d1af224b11eff6&showFulltext=true (accessed on 5 March 2022).

28.　Khalid, M. Plans to Prevent the Degradation of Water Quality in Brunei. The Borgen Project. Available online: https://borgenproject.org/water-quality-brunei/ (accessed on 5 March 2022).

29.　Gödeke, S.H.; Malik, O.A.; Lai, D.T.C.; Bretzler, A.; Schirmer, M.; Mansor, N.H. Water quality investigation in Brunei Darussalam: Investigation of the influence of climate change. *Environ. Earth Sci.* **2020**, *79*, 18. [CrossRef]

30.　Grealish, G.J.; Fitzpatrick, R.W. Acid sulphate soil characterisation in Negara Brunei Darussalam: A case study to inform management decisions. *Soil Use Manag.* **2013**, *29*, 432–444. [CrossRef]

31.　Azhar, A.S.; Abdul Latiff, A.H.; Lim, L.H.; Gödeke, S.H. Groundwater investigation of a coastal aquifer in Brunei Darussalam using seismic refraction. *Environ. Earth Sci.* **2019**, *78*, 220. [CrossRef]

32.　Shams, S.; Napiah, M.N. Status and Challenges of Integrated Water Resources Management (IWRM) in Brunei Darussalam. *Int. J. Adv. Sci. Technol.* **2019**, *28*, 437–443.

33.　Shafiuddin, K.B.M. Supplementary irrigation to rain-fed paddy: A case study of Kg Bebuloh paddy scheme. In Proceedings of the 12th International Water Technology Conference (IWTC), Alexandria, Egypt, 27–30 March 2008; Volume 12, pp. 83–99.

34.　Shafiuddin, K.B.M. Rain harvesting and stream storage for supplementary irrigation to rain-fed paddy schemes: A case study of Selapon Paddy Scheme. *Sustain. Irrig. Drain. WIT Trans. Ecol. Environ.* **2014**, *185*, 133–141.

35.　Azffri, S.L.; Azaman, A.; Sukri, R.S.; Jaafar, S.M.; Ibrahim, M.F.; Schirmer, M.; Gödeke, S.H. Soil and groundwater investigation for sustainable agricultural development: A case study from Brunei Darussalam. *Sustainability* **2022**, *14*, 1388. [CrossRef]

36.　Azffri, S.L.; Ibrahim, M.F.; Gödeke, S.H. Electrical resistivity tomography and induced polarization study for groundwater exploration in the agricultural development areas of Brunei Darussalam. *Environ. Earth Sci.* **2022**, *81*, 233. [CrossRef]

37.　Azffri, S.L.; Ali Ahmad, A.S.; Ibrahim, M.F.; Khalid, A.A.; Murphy, J.J.; Gödeke, S.H. Groundwater exploration through 2D electrical resistivity tomography in Labi agricultural site, Belait District, Brunei Darussalam. *Thai Geos. J.* **2022**, *3*, 1–9. [CrossRef]

38.　Sandal, S.T. *The Geology and Hydrocarbon Resources of Negara Brunei Darussalam*; Brunei Shell Petroleum Company: Bandar Seri Begawan, Brunei, 1996; 243p.

39.　Brunei Darussalam Meteorological Department. Climate. Available online: www.bruneiweather.com.bn (accessed on 7 January 2022).

40.　Hasan, D.; Ratnayake, U.; Shams, S. Evaluation of rainfall and temperature trends in Brunei Darussalam. In Proceedings of the AIP Conference, Bali, Indonesia, 29 September 2015. [CrossRef]

41.　Hutchison, C.S. *Geology of North-West Borneo: Sarawak, Brunei and Sabah*; Elsevier: Amsterdam, The Netherlands, 2005; 421p.

42. Morley, C.; Back, S.; Van Rensbergen, P.; Cravello, P.; Lambiase, J. Characteristics of repeated, detached Miocene-Pliocene tectonic inversion events in a large delta province on an active margin, Brunei Darussalam, Borneo. *J. Struct. Geol.* **2003**, *25*, 1147–1169. [CrossRef]

43. Chuan, G.K. Hydrological Characteristics and Water Resources. Singapore. *J. Trop. Geog.* **1992**, *13*, 1.

44. Moeck, C.; Grech-Cumbo, N.; Podgorski, J.; Bretzler, A.; Gurdak, J.J.; Berg, M.; Schirmer, M. A global-scale dataset of direct natural groundwater recharge rates: A review of variables, processes, and relationships. *Sci. Total Environ.* **2020**, *717*, 137042. [CrossRef]

45. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*, 23rd ed.; American Public Health Association: Washington, DC, USA, 2017.

46. Hill, M.J.; Carter, I.C.; Davison, I.; Bridle, R.C. The Staged Construction of Imang Dam. Ensuring Reservoir Safety into the Future. 2008. Available online: https://www.icevirtuallibrary.com/doi/10.1680/ersitf.35225.0030 (accessed on 5 March 2022).

47. Parkhurst, D.L.; Appelo, C.A.J. Description of Input and Examples for PHREEQC Version 3: A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, Inverse Geochemical Calculations. In *Modeling Techniques*; Techniques and Methods, 6-A43; US Geological Survey: Reston, VA, USA, 2015. [CrossRef]

48. Li, P. Groundwater quality in Western China: Challenges and paths forward for groundwater quality research in Western China. *Expos. Health* **2016**, *8*, 305–310. [CrossRef]

49. Fritz, S.J. A survey of charge balance errors on published analyses of potable ground and surface waters. *Groundwater* **1994**, *32*, 539–546. [CrossRef]

50. Richards, L.A. *Diagnosis and Improvement of Saline and Alkali Soils*; Agricultural handbook 60; USDA and IBH Pub. Coy Ltd.: New Delhi, India, 1954; pp. 98–99.

51. Doneen, L.D. The influence of crop and soil on percolating water. In Proceedings of the Biennial Conference on Groundwater Recharge, Davis, CA, USA, 28 June 1961; pp. 156–163.

52. Eaton, F.M. Significance of carbonate irrigation water. *Soils Sci.* **1950**, *69*, 123–133. [CrossRef]

53. Raghunath, I.I.M. *Groundwater*, 2nd ed.; Wiley Eastern Limited: New Delhi, India, 1987; pp. 344–369.

54. Kelley, W.P. Permissible composition and concentration of irrigated waters. *Proc. Am. Soc. Civ. Eng.* **1940**, *66*, 607–613.

55. Horton, R.K. An index-number system for rating water quality. *J. Water Pollut.* **1965**, *37*, 292–315.

56. Brown, R.M.; McClelland, N.I.; Deininger, R.A.; Tozer, R.G. A water quality index-do we dare. *Water Sew Work* **1970**, *117*, 339–343.

57. Piper, A.M. A graphic procedure in the geochemical interpretation of water analyses. *EoS Trans. Am. Geophys. Union* **1944**, *25*, 914–928. [CrossRef]

58. US Salinity Laboratory. Diagnosis and improvement of saline and alkali soils. In *United States Development Agency Handbook 60*; Government Printing Office: Washington, DC, USA, 1954; p. 147.

59. Wilcox, L.V. *Classification and Use of Irrigation Water*; US Department of Agriculture: Washington, DC, USA, 1955; 969p.

60. Pascale, S.D.; Orsini, F.; Pardossi, A. Irrigation water quality for greenhouse horticulture. In *Good Agricultural Practices for Greenhouse Vegetable Crops. Principles for Mediterranean Climate Areas*; Food and Agriculture Organisation of the United Nations (FAO): Rome, Italy, 2013; pp. 169–204.

61. Gebremeskel, G.; Gebremicael, T.G.; Kifle, M.; Meresa, E.; Gebremedhin, T.; Girmay, A. Salinization pattern and its spatial distribution in the irrigated agriculture of Northern Ethiopia: An integrated approach of quantitative and spatial analysis. *Agric. Water Manag.* **2018**, *206*, 147–157. [CrossRef]

62. Khawla, K.; Mohamed, H. Hydrogeochemical assessment of groundwater quality in greenhouse-intensive agricultural areas in the coastal zone of Tunisia: Case of Taboulba region. *Groundw. Sustain. Dev.* **2020**, *10*, 100335. [CrossRef]

63. Todd, D.K. *Groundwater Hydrology*; John Wiley and Sons Inc.: New York, NY, USA, 1980; pp. 10–138.

64. Fipps, G. Irrigation water quality standards and salinity management strategies. *Agrilife Ext.* **2003**, *1667*, 18. Available online: https://hdl.handle.net/1969.1/87829 (accessed on 5 March 2022).

65. Srivastava, A.K.; Parimal, P.S. Source rock weathering and groundwater suitability for irrigation in Purna alluvial basin, Maharashtra, central India. *J. Earth Sci.* **2020**, *129*, 59. [CrossRef]

66. Etteieb, S.; Cherif, S.; Tarhouni, J. Hydrochemical assessment of water quality for irrigation: A case study of the Medjerda River in Tunisia. *Appl. Water Sci.* **2017**, *7*, 469–480. [CrossRef]

67. Sharma, C.M.; Kang, S.; Tripathee, L.; Paudyal, R.; Sillanpaa, M. Major ions and irrigation water quality assessment of the Nepalese Himalayan rivers. *Environ. Dev. Sustain.* **2020**, *23*, 2668–2680. [CrossRef]

68. Rhoades, J.D. Quality of water for irrigation. *Soil Sci.* **1972**, *113*, 227–284. [CrossRef]

69. El-Amier, Y.A.; Kotb, W.K.; Bonanomi, G.; Fakhry, H.; Marraiki, N.A.; Abd-ElGawad, A.M. Hydrochemical Assessment of the Irrigation Water Quality of the El-Salam Canal, Egypt. *Water* **2021**, *13*, 2428. [CrossRef]

70. Yang, Q.; Li, Z.; Xie, C.; Liang, J.; Ma, H. Risk assessment of groundwater hydrochemistry for irrigation suitability in Ordos Basin, China. *Nat. Hazards* **2020**, *101*, 309–325. [CrossRef]

71. Gamvroula, D.E.; Alexakis, D.E. Evaluating the Performance of Water Quality Indices: Application in Surface Water of Lake Union, Washington State-USA. *Hydrology* **2022**, *9*, 116. [CrossRef]

72. Meireles, A.; Andrade, E.M.; Chaves, L.; Frischkorn, H.; Crisostomo, L.A. A new proposal of the classification of irrigation water. *Cienc. Agron.* **2010**, *413*, 349–357. [CrossRef]

73. Yıldız, S.; Karakuş, C.B. Estimation of irrigation water quality index with development of an optimum model: A case study. *Environ. Dev. Sustain.* **2020**, *22*, 4771–4786. [CrossRef]

74. Akhtar, N.; Syakir Ishak, M.I.; Bhawani, S.A.; Umar, K. Various Natural and Anthropogenic Factors Responsible for Water Quality Degradation: A Review. *Water* **2021**, *13*, 2660. [CrossRef]

75. Gödeke, S.H.; Jamil, H.; Schirmer, M.; Anja Bretzler, A.; Shamsuddin, N.; Mansor, N.H. Iron and manganese mobilisation due to dam height increase for a tropical reservoir in Southeast Asia. *Environ. Monit. Assess.* **2022**, *194*, 358. [CrossRef]

76. Wong, Y.J.; Shimizu, Y.; Kamiya, A.; Maneechot, L.; Bharambe, K.P.; Fong, C.S.; Sulaiman, N.M.N. Applications of artificial intelligence methods for monsoonal river classification in Selangor River basin, Malaysia. *Environ. Monit. Assess.* **2021**, *194*, 438. [CrossRef]

77. Chia, S.L.; Chia, M.Y.; Koo, C.H.; Huang, Y.F. Integration of advanced optimization algorithms into least square support vector machine (LSSVM) for water quality index prediction. *Water Supply* **2022**, *22*, 1951–1963. [CrossRef]

78. Khatri, N.; Tyagi, S. Influences of natural and anthropogenic factors on the surface and groundwater quality in rural and urban areas. *Front. Life Sci.* **2015**, *8*, 23–39. [CrossRef]

79. Suhip, M.A.A.B.H.; Gödeke, S.H.; Cobb, A.R.; Sukri, R.S. Seismic refraction study, single well test and physical core analysis of anthropogenic degraded Peat at the Badas Peat Dome, Brunei Darussalam. *Eng. Geol.* **2020**, *273*, 105689. [CrossRef]

80. Ahmed, U.; Mumtaz, R.; Anwar, H.; Mumtaz, S.; Qamar, A.M. Water quality monitoring: From conventional to emerging technologies. *Water Supply* **2021**, *20*, 28–45. [CrossRef]