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Hydrogeochemical characteristics of groundwater irrigation in the climate change prone areas of Cambodia

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ការសិក្សានេះមានគោលបំណងកំណត់លក្ខណៈគីមីវារីភូមិសាស្ត្រនៃទឹកក្រោមដី ដើម្បីស្វែងយល់ ពីគុណភាពទឹកក្រោមដីនៅតាមតំបន់ដែលប្រឈមនឹងបម្រែបម្រួលអាកាសធាតុ។ សំណាកគំរូនៃទឹកក្រោមដីចំនួន 13 កន្លែងនៅខេត្តតាកែវត្រូវបានយកមកវិភាគរកលក្ខណៈរូប និងលក្ខណៈគីមីរបស់វា។ តម្លៃ pH និង TDS នៃភាគសំណាកស្ថិតក្រោមតម្លៃកំណត់របស់អង្គការសុខភាពពិភពលោក និងស្តង់ដាកម្ពុជាស្តីពីទឹកសម្រាប់ទទួលទាន។ កំហាប់នៃអ៊ីយ៉ុងកាចុងដែលមានកម្រិតខ្ពស់ជាងគេ គឺអ៊ីយ៉ុងសូដ្យូម និងទាបជាងគេគឺ អ៊ីយ៉ុងប៉ូតាស្យូម។ ចំណែកឯកំហាប់នៃអ៊ីយ៉ុងអាញ៉ុងដែលមានកម្រិតខ្ពស់ជាងគេ គឺអ៊ីយ៉ុងអ៊ីដ្រូសែនកាបូណាត និងទាបជាងគេអ៊ីយ៉ុងផូស្វាត ដូចបង្ហាញតាមលំដាប់រៀងគ្នានេះ $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ និង $HCO_3^- > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-}$។ Piper trilinear ដ្យាក្រាមបង្ហាញថា មានទឹកចំនួន4 ប្រភេទត្រូវបានកំណត់ដោយផ្អែកតាមលក្ខណៈគីមីគឺ៖ ប្រភេទ Ca-Mg-Cl, $Ca\text{-}HCO_3$, Na-Cl និង $Na\text{-}HCO_3$។ ដ្យាក្រាម Gibbs បានបង្ហាញថា អត្រារំហួតនិងអន្តរកម្មរវាងថ្មនិងទឹក គឺជាកត្តាចម្បងដែលជះឥទ្ធិពលដល់លក្ខណៈគីមីនៅក្នុងតំបន់ដែលបានសិក្សានេះ។ ដោយយោងតាមតម្លៃនៃសំណល់សូស្យូមកាបូណាត (RSC), ប្រភាគស្រូបដោយសូដ្យូម (SAR) និងសមត្ថភាពចម្លងចរន្តអគ្គិសនី (EC) ភាគច្រើននៃទឹកក្រោមដីទាំងនេះអាចត្រូវបានចាត់ទុកថាល្អប្រសើរ និង ល្អ សម្រាប់ស្រោចស្រពដំណាំ។ ជារួម គុណភាពនៃទឹកក្រោមដីនៅក្នុងតំបន់ដែលបានធ្វើការសិក្សានេះ អាចត្រូវបានចាត់ទុកថាសមស្របសម្រាប់ប្រព័ន្ធស្រោចស្រព និងការធ្វើកសិកម្ម។

ABSTRACT

This research assesses the hydrogeochemical characteristics of irrigation groundwater to understand its quality within climate change prone areas of Cambodia. Thirteen groundwater samples were collected in Takeo province to analyze for major physicochemical properties. Both pH and TDS were below the maximum permissible limit of drinking water set by the World Health Organization (WHO) and Cambodia's standard of drinking water quality. The study finds concentrations of cations and anions in order of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3 > Cl^- > NO_3^- > SO_4^{2-} > PO_4^{3-}$, wherein four major hydro-chemical facies (Ca-Mg-Cl, $Ca\text{-}HCO_3$, Na-Cl and $Na\text{-}HCO_3$ types) were identified. Application of the

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Gibbs diagram showed evaporation and water-rock interaction as the main factors affecting hydrogeochemical properties in the study area. Furthermore, the majority of groundwater samples were classified to be 'excellent' and 'good' for irrigation purposes, according to the value of residual sodium carbonate (RSC), sodium adsorption ratio, and electrical conductivity. Thus, it can be assumed that the quality of groundwater may be considered suitable for irrigation purpose and agriculture.

1. Introduction

Cambodia is one of Southeast Asia's most disaster-prone countries. Not only have temperatures in Cambodia have risen between 1.35 to 2.50°C per by 2100 (Sok, Choup, & Vol, 2016; Wangwacharakul et al., 2000), more severe lightning storms, floods and droughts,, and shifting rainfall patterns have been linked to climate change (Shrestha, Anal, Salam, & Van der Valk, 2016).

Increased temperatures are expected to cause increased evaporation and possible changes in average rainfall, intensity, and seasonality. This in turn has impacts on soil moisture, stream flow, groundwater recharge, and the occurrence of flooding and droughts. This has had cascading effects on the variability of rice yields in Cambodia which are significantly correlated with climate change. Historically, production losses of more than 70% and nearly 20%, can be attributed to flooding and drought respectively.

Furthermore, sea level is projected to rise between 0.18 – 0.56m by 2090 under various scenarios within the region (Weiss, 2021); as where a rise of one meter is expected to cause flood or permanent inundation in low-lying areas of Cambodia's coastal zone (Wangwacharakul et al., 2000). Furthermore, increasing sea level threatens seawater intrusion into coastal aquifers. Seawater may be drawn toward the freshwater zone levels with overexploitation of coastal groundwater, resulting in saltwater inflow into coastal groundwater wells, which poses serious risk to the sustainability of coastal cities and small islands that use groundwater for domestic water supplies (Kouadra & Demdoum, 2020). Additionally, climate change poses a threat to the recharge rate of groundwater, renewable groundwater supplies, and groundwater levels.

Groundwater chemistry is largely a function of mineral composition, depending on the interaction between water flows and rocks. Evaporation, concentration and dilution as a result of precipitation may also modify the chemical composition of groundwater, but rock-water interaction remains foremost process because of how solid phases (inorganic and organic matter) function as the primary sources and sinks of dissolved constituents (Elango & Kannan, 2007). Hydrogeochemical study has been extensively used to identify the processes responsible for groundwater chemistry. For instance, Liang et al., (2018) analyses the composition of groundwater in a karst aquifer of Qingyuan that is controlled by the dissolution of evaporite minerals (e.g., calcite, gypsum, and/or anhydrite) and ion exchange processes. Potential contaminants in the groundwater were identified, including Chromium, Zinc, Cadmium, and Lead ions, likely resulting from a combination of agricultural, mining, and industrial activities (Liang et al., 2018).

Groundwater chemical composition is also controlled by mixing of seawater, ion-exchange reactions, dissolution processes and anthropogenic inputs. Ions of Cl^-, K^+ and Na^+ are mainly derived from irrigation return flow and anthropogenic activities inland, and seawater intrusion in coastal areas. Calcium and magnesium are derived mainly from dissolution of carbonate precipitates, along with ion exchange process in the groundwater. Nitrate, lead, and nickel are derived from irrigation return flow and anthropogenic activities. Groundwater can also be polluted by open sewage systems and by various agricultural activities (Elango & Kannan, 2007; Liang et al., 2018). The most serious pollution threat to groundwater is from nitrate ions associated with sewage and fertilizer application (Sok et al., 2016).

A variety of chemical processes occur during rock-water interaction including dissolution, precipitation, ion exchange processes, oxidation, and reduction. Chemical weathering resistance determines whether minerals from igneous, metamorphic, and sedimentary rocks dissolve fully or partially in water. During the repetition throughout these chemical processes, the concentration of ions in groundwater may increase or decrease, the mobility of the dissolved constituents may be affected, and the pH of groundwater may change in the system. Changes in season can potentially affect the hydrogeochemical properties of groundwater, especially where there is a distinct differentiation between dry and rainy seasons (Sok et al., 2016). Hence, investigation of the seasonal change groundwater hydrochemistry may facilitate data collection programs for groundwater assessment and enable better use of groundwater supplies in Cambodia. Moreover, very little is currently known about the quality of irrigation groundwater in climate change prone areas of Cambodia. The amount of shallow groundwater used to irrigate the paddy field has remarkably increased in the last decade, and yet despite this, its monitoring remains lacking. This study thus contributes to addressing the lacuna of information surrounding the quality of groundwater used for irrigation in the climate change prone areas of Cambodia.

In Cambodia, there are five major river basin groups: the Coastal Zone sub river basin, Northeastern sub river basin, Upper Mekong sub river basin, Tonle Sap sub river basin and Mekong Delta sub river basin **(Fig. 1)** (King, 2004). The geology of rock formations in Cambodia has been classified into quaternary alluvium and other rock formation types as seen in **Table 1**. There are three sub-classes of quaternary alluvium: (i) alluvium, (ii) basalt, and (iii) post-Triassic sandstone and conglomerate. Other igneous rock has three sub-classes: (i) limestone, (ii) Triassic metamorphic rock, and (iii) other igneous rock. The Coastal Zone sub-river basin's geological formations consist mostly of post-Triassic sandstone and conglomerate, with claystone, shale, sandstone, and conglomerate accounting for 67% of the total area. Recent alluvium formations comprise another 27% of the total area in the valleys of the Krovang Mountain ranges and coastal areas.

The geological formations in the Northeastern sub-river basin consist mostly of lower-middle Jurassic formations known as 'Terrain Rouge', covering large areas of Mondulkiri and Ratanakiri provinces, and spreading westwards into Stung Treng and Preah Vihear provinces. A quarter of the region is made up of post-Triassic sandstone and conglomerate. Old alluvium formations can also be found on floodplains along rivers and drainage lines, accounting for 20% of the total area. In the Upper Mekong sub-river basin, the Triassic and lower-to-middle-Jurassic (Terrain Rouge) are the most dominant formations, accounting for 46% of the total area. Both old and recent Alluvium is the second most common formation, and can be found in the north along the Mekong River's floodplain, and in the valleys of the Terrains Rouges Plateau, constituting 23% of the total area, followed by 16% Post-Triassic sandstone and conglomerate **(Table 1)**.

Table 1. Classification of geology formations for groundwater study in Cambodia

Main Classes	Sub Classes	Description
Quaternary alluvium	Alluvium	Alluvial formations include recent alluvium, alluvial sand, laterite and lateritic crust, and old alluvium
	Basalt	All Basalt including Quaternary basalt and Pleistocene basalt
	Post-Triassic Sandstone and Conglomerate	Includes Jurassic Cretaceous clay stone, sandstone, and conglomerate
Other Formation	Other Igneous Rock	All magmatic rock excluding basalt
	Limestone	All limestone and calcareous rock
	Triassic Metamorphic Rock	Triassic or older sedimentary rock and metamorphic rock

The Tonle Sap sub-river basin is predominantly a quaternary sediment formation that consists of both recent and old alluvium and comprises 86% of the total area. Old alluvium extends to the foothills of the surrounding mountain ranges (Krovang and Dangrek Range), overlaid by recent alluvium in the area below the permanent Tonle Sap Great Lake area. In the Mekong Delta Basin Group, Alluvium, including recent alluvium, old alluvium, and laterite, is the most extensive geological

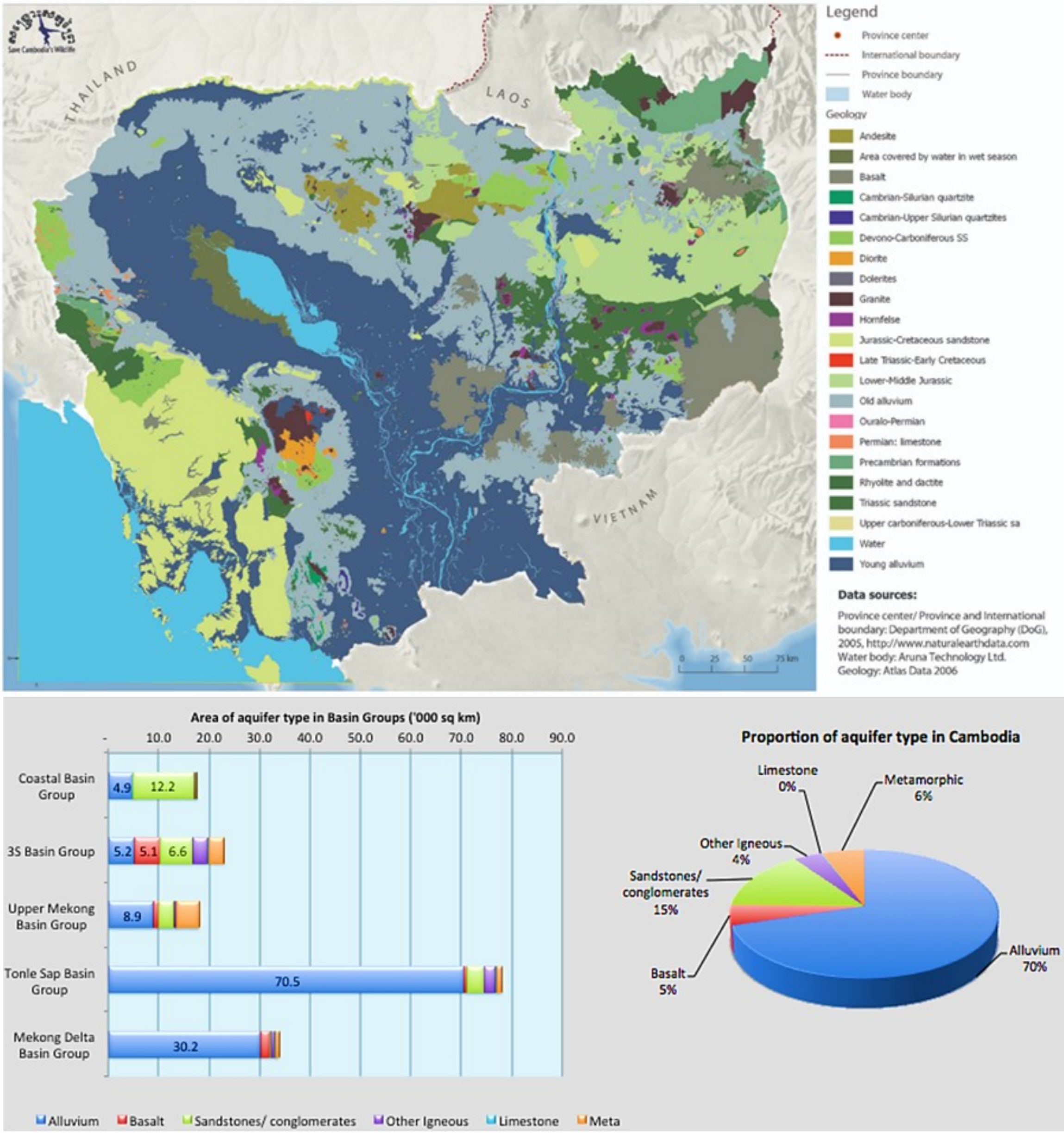

Fig 1. Geological map of Cambodia and areas of aquifer type per basin group (UNDP, 2006) in (Development of Groundwater Management Strategy in Cambodia: Institutional Assessment, Capacity Building Plan and Proposed Key Components of Ground Water Management in Cambodia).

formation, accounting for 84% of the total area. The second most dominant formation is Basalt and volcanic rock, which make up 5% of the region and can be found in the east (Lwimbo, Komakech, & Muzuka, 2019; Organization, 2017). The geological formations map of Cambodia is shown in **(Fig. 1)**.

The Mekong lowland consists of broadly alluvial material overlying shale, slate, and sandstone bedrock, featuring low hills and plateaus that are comprised of basalt, other igneous rocks, and limestone. Rivers to the south, reflect a complex pile of unconsolidated to semi-consolidated alluvial sediments, varying in depth from a few meters to more than 160 meters. In Vietnam, the eight major depositional sequences can be found from Miocene to present (Singh et al., 2008), that host five main aquifers from the Holocene, Upper-Middle Pleistocene, Lower Pleistocene, Pliocene, and Upper Miocene (Ruos et al., 2020). Whereas in Cambodia, depositions reflect a simpler division between young alluvium (finer grained Holocene River and floodplain deposits) and old alluvium (coarser sediments from Pleistocene to Miocene terrace and platform deposits). The distinction between the two alluvium types is made by defining young as finer grained clays and silts that form a poor aquifer, that can yield good groundwater when lenses and sand mix. The coarse old alluvium yields aquifers that are larger and have better water quality, albeit their yield and quality depend on the area. The upper part of the alluvium is constituted of sandy silt up to one meter of thickness, while the lower part is made up of clayey silt (UN.ESCAP, 1993; UNDP, 2020). Whilst alluvium geological formations are the most dominant in Cambodia, accounting for approximately 70% of the total area of the country, Tertiary basalts (in eastern and central Cambodia) and Permian karsts (in Battambang and Kampot) have potential uses for irrigation. Groundwater irrigation in similar basalt terrains has supported the development of important coffee growing areas in the Central Highlands of Vietnam and the Bolaven Plateau in Lao PDR.

2. Materials and methods

2.1 Study Area and Research Methodology

Takeo province, Cambodia is located in the south of the Phnom Penh Municipality bordering Kampot to the west, Kampong Speu to the northwest and Kandal to the north and east; its southern boundary borders Vietnam. Flood levels in this province are exceptionally high to the extent that living with flooding can be considered a way of life (An, Tsujimura, Le Phu, Kawachi, & Ha, 2014). Takeo is 3,563 square kilometers in total, and is home to 844,906 persons based on the results of the 2008 Population Census. The province has 10 districts, 100 communes including Sangkats and 1,115 villages. The province consists of the typical plain wetland area, covering rice fields and other agricultural plantations (NIS, 2013). Takeo is one of the most severely affected provinces by climate change due to its flat and low-lying land; four districts of Takeo are exceptionally flood prone: Andeth, Borei, Kirivong and Koh.

Groundwater samples were collected from a total of 13 sites within Takeo province. In these study areas, the tropical monsoon climate is characterized by high wet season rainfall volume that originates from south-westerly weather systems and a dry season dominated by northeasterly weather systems (Nguyen et al., 2014). Groundwater was collected using an electrical pump from the tube wells used for irrigation purposes. Samples were taken after ten minutes of pumping to remove any standing water from the tube. The samples were stored in polypropylene bottles (cleaned with a metal-free nonionic detergent solution, rinsed with tap water, soaked in acid, and then rinsed with metal-free water). Anions and alkalinity were determined by using a non-acidified and non-filtered water. The analysis of cations was completed using 0.45 µm of nylon filter, filtered and acidified to reach a pH bellow 2.

Physiochemical parameters like pH, ORP and temperature were measured by utilizing a Hanna pH/ORP/ISE Meter (HI, 98191); furthermore, total dissolved solids (TDS), electrical conductivity (EC), salinity in situ at the time of sample collection using the Hanna EC/TDS/NaCl/Resistivity Meter (HI, 98192). All of the collected water samples were be kept in an ice box during field sampling and then transferred to a refrigerator where they were stored at 4^{o}C until analysis could be done.

2.2 Microelement and physical properties of groundwater.

Turbidity, sulfate and nitrate were determined by using a DR/850 Colorimeter (Hach, USA) with the respective reagents supplied by Hach. Groundwater of 10ml were place in the sample cell and allowed to stand at room temperature. Nitrate content was determined using the cadmium reduction method (method 8039, Hach, USA). A sample cell was filled with 10ml of sample and nitrate indicator was added. The mixture was left to stand for one minute and then a five minutes reaction. Sulfate content was conducted by using the same protocol as nitrate (method 8051, Hach, USA).

Both the bicarbonate concentration and carbonate ion concentration were calculated using a measurement of alkalinity. The alkalinity of groundwater was determined by using a digital Titrator (HACH, USA). Groundwaters of 100mL were titrated against 8M KOH until pH reached to 8.3 then the residual of KOH was titrated with 0.08M EDTA until pH 4.5. The concentration of total alkalinity (mg/L as CaCO3) was recorded and expressed as bicarbonate and carbonate.

Sodium was measured by the FC300 electrode (Hanna, HI 98191). Subsequently, Potassium and chloride were analyzed by an ion chromatography mass spectrometry (IC-MS). Standard reference materials were treated in the same manner as the samples to certify the accuracy of the analytical method. Sodium was measured by using ion selective electrode (HI, 98191). The ISE electrode was submerged into the sample, where it was stirred gently for a few seconds before for the reading to stabilize, upon which it was recorded.

Multiparameter Bench Photometer (HI 83099) was used to measure calcium, magnesium and phosphate. Color or suspended matter in large amounts was removed by filtration prior to analyzing. Calcium content was examined by oxalate method using multiparameter bench photometer (HI 83099). A 3ml of sample was placed in a capped cuvette, then calcium buffer (HI 93752A-0) was added to fill the volume up to 10 ml, and 1ml of calcium oxalate reagent (HI 93752B-0) was added to the cuvette and mixed for 15 seconds and the absorbent was recorded according to the calcium parameter of the instrument. Magnesium content was evaluated by Calmagite method. 1 ml of Mg buffer reagent (HI 93752A-0) was added into a capped cuvette then filled up to 10 ml with Mg indicator reagent (HI 93752B-0). Then, 0.5 ml of sample was added and mixed several times before taking a reading. Phosphate content was evaluated by using the amino acid method. 10 ml of sample was filled in the cuvette, followed by 10 drops of molybdate reagent (HI 93717A-0) and one portion of phosphate reagent (HI 93717B-0). Once these were added, the mixture was then shaken to completely dissolve the mixture before recording reading.

To characterize different water types, Piper (1944) proposed a diagram where the concentration of cations and anions are plotted in diagram. For measurement in the context of irrigation, residue sodium carbonate (RSC) and EC were calculated based on Food Agriculture Organization (FAO). Sodium adsorption ratio (SAR) calculated based on US salinity laboratory (USSL) standards. Sodium adsorption ratio (SAR) of water is a useful parameter used to assess the suitability of groundwater for agricultural activities (Allison, 1954). It is calculated by using the Equation:

$$\text{SAR} = \frac{\boldsymbol{Na}}{\sqrt{(\boldsymbol{Ca}+\boldsymbol{Mg})/2}}$$

Residual sodium carbonate (RSC) can be calculated as follows:

RSC = (HCO3- + CO32-) – (Ca2+ +Mg2+)

All ion concentrations are expressed in meq/L.

All statistical data analyses were employed using MS Excel 2016. Significance will be considered in circumstance where $p< 0.05$.

3. Results and discussion

3.1 Groundwater chemistry

The average physio-chemical properties of the study area are presented in Table 2. The depth of dug wells varies from 4m to 7m for an average of 5.13m whereas, tube wells range from 30m to 40m for an average of 34.57m. The average temperature in tube wells (32.02^{o}C) was 2.83% higher than that of the dug wells (31.14^{o}C). In dug wells, pH ranged from 6.24 to 7.31 and 6.78 to 7.35 in tube wells. Thus, our findings indicate that with the average pH in dug wells (6.80) being slightly lower than that of in tube wells (7.14), groundwater in the study area is weakly alkaline. The Electrical Conductivity (EC) in groundwater samples ranged from 61.06 µs. cm-1 to 1204.33 µs.cm^{-1}. On average EC of tube well was 653.56 µs.cm^{-1}, followed by 155.33 µs cm^{-1} in dug wells; where the majority of high EC in tube wells occurred at depths of 30 meters or more where EC reached up to 1.2 mS/cm.

The Total Dissolved Solid (TDS) was found to be in the range of 30.62 to 132.57 mg/L in dug wells whereas, in tube wells it ranged from 218.5 to 598.07 mg/L wherein the highest value of TDS was found. Turbidity (NTU) was found to range from 0 to 7 NTU in the tube well, and between 15.67 and 324.33 NTU in dug wells. The Oxidation Reduction Potential (ORP) of tube wells ranged from -64.33 mV to 55 mV, and between 10.93 mV to 32.8 mV in dug wells. The mean of salinity percentage in tube wells (1.44%) is higher than that of dug wells (0.30%) reflecting to dissolution of

Table 2. Physio-chemical properties of tube and dug well in study area.

	Dept (m)	Tem. (°C)	pH	ORP (mV)	TDS (mg/L)	Tur. (NTU)	EC (μs/cm)	Salinity (%)
Dug well (n=6)								
Min	4.00	30.57	6.24	10.93	30.62	15.67	61.06	0.10
Max	7.00	31.93	7.31	32.80	132.57	324.33	265.77	0.60
Mean	5.13	31.14	6.80	24.30	67.07	122.08	134.41	0.30
Median	4.50	30.90	6.89	27.13	51.95	67.34	104.58	0.25
SD	1.36	0.59	0.43	9.08	42.76	131.01	85.80	0.20
Tube well (n=7)								
Min	30.00	30.97	6.78	-64.33	218.50	0.00	437.67	1.00
Max	40.00	32.73	7.35	55.00	598.07	7.00	1204.33	2.70
Mean	34.57	32.02	7.14	8.35	323.97	1.57	653.56	1.44
Median	35.00	31.97	7.15	13.90	260.97	1.00	521.63	1.20
SD	3.31	0.64	0.19	35.78	135.35	2.51	273.00	0.61

Min = minimum, Max = Maximum, SD = standard deviation, Tem. = Temperature, Tur = Turbidity

soluble salts and minerals, evaporation of groundwater, and infiltration of wastewater as factors that contribute to the high salinity of groundwater (Li et al., 2016). **Table 2** presents a statistical summary of chemical compositions of major ions in the 13 groundwater 13 samples collected in Takeo. Na+, K+, Ca2+, and Mg2+ concentrations were observed in the ranges of 25.1 – 428, 0.6 – 56, 10 –100, 5 – 40mg/L, respectively. The variations of Na+, HCO3- and Cl- concentrations were higher compared to other ions as shown by the standard deviations. The most abundant cation is Na+ followed by Ca2+, Mg2+, and K+. Furthermore, the concentrations of HCO3-, SO42-, and Cl- in the study area which range from 31 – 710, 1 – 16, to 28.33 – 440.4 mg/L with means of 231.38, 5.64, and 135.9 mg/L. Cations concentrations are seen to trend downwards from Na > Ca > Mg> K and major anion concentrations are as follows HCO3- > Cl- > SO42-. The contents of NO3- and PO43- in groundwater samples varied from 1.77 – 47.09 and 0.4 – 2 mg/L with means of 9.55 and 0.84 mg/L, respectively. Of these, any nitrate value above 10 mg/L is geochemically considered pollution as a result of external factors (Karagüzel & Irlayici, 1998). Among 13 groundwater samples, 15% exceeded the 10 mg/L threshold. Thus, groundwater in the study area may not considered to be seriously polluted by nitrate overall.

3.2 Hydrogeochemical Facies

Using the results from the hydro-chemical analysis, a Piper diagram was created for the study area. The sample points can be classified into 6 fields; 1. Ca-HCO_3 type, 2. Na-Cl type, 3. Ca-Mg-Cl type, 4. Ca-Na-HCO_3 type, 5. Ca-Cl type, 6. Na-HCO_3 type. Groundwater quality data of the study was plotted on the Piper trilinear diagram shown in **Fig. 2**. The diagram reflects a dominance of Na^+ + K^+ type cations in a maximum number of samples whereas the anion plot is Cl^- type dominant. Water types were confined to Ca-HCO_3 type, Na-Cl type, Ca-Mg-Cl type, Na-HCO_3 type. The majority of ground water samples (46%) fall in mixed Ca-Mg-Cl, while the 23% of groundwater is characterized by fresh water with the presence of Ca-HCO_3 and may be considered suitable for drinking purposes (An et al., 2014).

This Gibbs diagram **(Fig. 3)** shows that predominant samples fall in the rock-water interaction and evaporation dominance fields, which suggest the evolution of groundwater chemistry is affected by rock weathering and evaporation. Gibbs diagrams are an effective tool for determining the major factors that influence groundwater chemistry, such as atmospheric precipitation, evaporation, and rock weathering. However, they are unable to analyze the impacts of human activities on groundwater

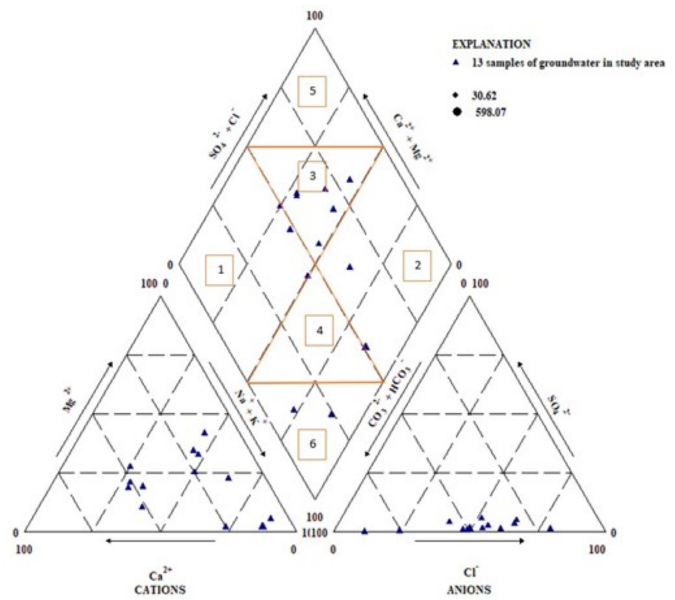

Figure 2. Piper diagram shows the classification based on the hydro-chemical facies of the groundwater.

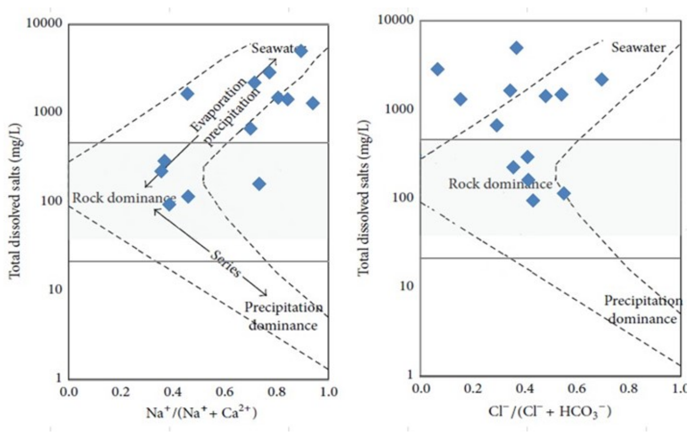

Figure 3. Gibbs diagram for controlling factor of groundwater quality, the left-hand side representing cations and the right-hand side reflecting anions

chemistry. In the Gibbs diagrams, the ratio of dominant anions [Cl^-/ (Cl^--HCO_3)] and cations [Na^+/ (Na^+ + Ca^{2+})] are plotted against the value of total dissolved solids (TDS).

Below we discuss the parameters of water quality within the context of safety for potable usage. A comparison of physicochemical parameters of climate change prone area with other studies are presented in **Table 3**. The mean pH of the 13 samples collected meets the recommended limit of pH (6.5 to 8.5) of drinking water guidelines suggested by WHO (2017) and Cambodia's drinking water quality standard (MIME, 2004). These pH readings from Takeo match data from studies in Malaysia and are higher than other studies in Laos and Bangladesh. 46.15% of turbidity is lower than the permissible limit of drinking water quality standards (5 NTU) of Cambodia and WHO. However, average TDS of samples met the CDWQS 2004 and WHO'S DWQ Guidelines, indicating that the ground-water in the study area can be considered fresh water (UN.ESCAP, 1993; UNDP, 2020). TDS was found to be much lower than in India and China, and likewise, EC is much lower than that of Vietnam and India. The major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) were not found to exceed the permissible standards of CDWQS (2004), and the WHO'S DWQ (2017). Similarly, K^+, Ca^{2+}, Mg^{2+} are significantly lower than in Asia's largest countries using groundwater, India and China. Furthermore, mean SO_4^{2-}, Cl^- and NO_3^- of groundwater samples were below the water quality standards of Cambodia, WHO Guidelines, and even further lower than in Vietnam, India and China.

An outlier was phosphorus; on average concentrations of PO_4^{3-} in the 13 samples were higher than in India and Bangladesh, the likely reason for which can be attributed to intensive fertilizer usage for crop production, which was found to leach through irrigation and rainfall into groundwater in the study area similar to the report of Lwimbo et al. (2019). Moreover, HCO^{3-} content in this study area is comparatively higher than the other area in Laos, Malaysia and Bangladesh. Although there is no national and international standard limit for HCO^{3-} in drinking water, it was one of the most prominent anions, primarily originating in water from the CO_2 of soil in the region and dissolution of CO_3 and silicate reactions with HCO^{3-} within (Singh et al., 2008). The residue sodium carbonate (RSC) stretches from -4.39 to 6.25; based on this, water can be classified as mostly safe, and thus suitable for irrigation and agriculture. Only 23% of RSC in groundwater samples was considered unsuitable for irrigation purposes, as a RSC concentration greater than 5meq/l is considered harmful to the growth of plants (Karagüzel & Irlayici, 1998).

The values of Sodium adsorption ratio (**SAR, Table 4**) in the studied groundwater ranged from 0.92 to 15.41, with 84% of samples measuring below 10, meaning that vast majority of irrigation groundwaters in this present study are considered excellent for irrigation. Thus, sodium levels may be considered as 'low risk', and thus the water in the area can be used for irrigation for both soil and crops, provided that Electrical conductivity (EC), one of the most important factors to consider when assessing water quality, is also within safe parameters. When calculating the EC, water was divided into five classes from good to unsuitable for irrigation according to the World Food and Agricultural Organization (FAO) (Ayers & Westcot, 1985). The five categories comprise of "excellent" (< 250 mS/cm), 'good' (250–750 mS/cm), "permissible" (750-2000 mS/cm), "doubtful" (2000–3000 mS/cm) and "unsuitable" (>3000 mS/cm) water. Based on EC values of this study area, water quality varies from 'excellent', to 'permissible' for irrigation, with no sample being considered doubtful or unsuitable.

4. Conclusion

The study reveals that the mean of pH and TDS are below the maximum limit of WHO's and Cambodia's drinking water quality standards. The average concentration of cations and anions fall below those from studies from other Asian countries. Furthermore, the concentration of all cations and anions but PO_4^{3-} fall below the permissible quality standards of the WHO and

Parameter	Sample Range	Range	Classification	% of sample
Residual sodium carbonate (RSC) (meq/l)	-4.39 - 6.25	<1.25	Good	76.92%
		1.25-2.5	Medium	0%
		>2.5	Bad	23.07%
EC (µS/cm)	61.06 - 1204.33	<250	Excellent	38.46%
		250-750	Good	46.15%
		750-2000	Permissible	15.38%
		2000-3000	Doubtful	0%
		>3000	Unsuitable	0%
Sodium adsorption ratio (SAR)	0.92 - 15.41	<10	Excellent	84.61%
		10-18	Good	15.38%
		18-26	Doubtful	0%
		>26	Unsuitable	0%

Table 4. Classification of groundwater for agricultural purposes.

Table 3. Physicochemical groundwater characteristics and their comparison with drinking water standards of MIME (2004), WHO (2011) and other studies.

	This Study	La	VN	Ma	Ba	In	Ch	CDWQS	WHO DWQG
pH	6.98	4.1-6.2	7.32	6.98	6.54	7.22	7.74	6.5-8.5	6.5-8.5
EC (□s/cm)	409.48	7.56-	1821	126.27	459	907.26	-	-	-
TDS (mg/L)	203.16	-	-	81.82	321.3	635.18	1216.87	800	600
Ca (mg/L)	46.15	0.5-48.3	52.1	8.55	37.82	110.21	114.61	-	75
Mg (mg/L)	16.92	0.4-3.6	51.5	2.16	12.79	53.25	64.99	-	50
K (mg/L)	1.05	0.4-12.7	19.6	2.27	2.13	30.51	17.29	-	12
Na (mg/L)	117.63	1.2-15.1	335.	8.01	28.65	99.99	196.62	200	200
HCO_3 (mg/L)	231.38	12.2-	332.	43.21	184.95	493.45	446.55	-	-
SO_4 (mg/L)	5.64	3-4.5	127.	5.76	11.23	53.89	333.72	250	250
Cl (mg/L)	135.95	1.2-134	489.	8.91	21.22	161.23	210.98	250	250
NO_3 (mg/L)	9.55	BDL-12	10.7	2.28	-	82.39	61.84	50	50
PO_4 (mg/L)	0.84	BDL-0.4	-	-	0.06	0.33	-	-	-
Ref.		(Rajaveni, Brindha, & Elango, 2017)	(An et al., 2014)	(Hamzah, Aris, Ramli, Juahir, & Sheikhy Narany, 2017)	(Zakir, Sharmin, Akter, & Rahman, 2020)	Srivastava, 2019	(Li et al., 2016)	(MIME, 2004)	(WHO, 2017)

La = Laos, VN=Vietnam, Ma = Malaysia, Ba = Bangladesh, In = India, Ch = China, BDL= Below Detectable Limit, CDWQS = Cambodian Drinking Water Quality Standard, DWQG = Drinking Water Quality Guideline

Cambodia, as well as those in other Asian countries as a result of extensive use of fertilizers within Cambodian agriculture. Statistical analysis demonstrates that the abundance of cations within groundwater in the study area follows the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the abundance of anions for groundwater is $HCO^{3-} > Cl^- > SO_4^{2-}$. In this study, the Piper diagram represents the hydrogeochemical characteristic which cations in groundwater were dominated by Na^+ and Ca^{2+}, whereas anions are constituted mainly of HCO^{3-} and Cl^-. The hydrochemical facies are predominantly Ca-Mg-Cl, followed by $Ca\text{-}HCO_3$ which influences groundwater in most sampling sites of the Takeo study area. Despite our findings on hydro-chemical characteristics, our Gibbs diagrams showed that evaporation and water-rock interaction are the main processes affecting groundwater chemistry in the area. We outline that irrigation water quality was determined based on EC, residual sodium carbonate and sodium adsorption ratio. Of all samples, 38.46% and 46.15% of EC are excellent and good, respectively. In conjunction with the majority of SAR (84.61%) in this study being considered excellent, and 76.92% of RSC in the study groundwater being classified as good for irrigation purposes, we conclude that most groundwater is more than suitable for agricultural usage. This study suggests that there should be further research into the groundwater of climate change prone areas of Cambodia to collect further data, particularly for understanding pesticide and other contaminants to comprehensively monitor, regulate and compare the quality of irrigation groundwater for sustainable usage within the country.

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Declaration of competing interest

The authors declare that they have no competing interests.

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