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Isotopic Assessment of Shallow Groundwater Resources in the Cagayan Valley Region, Philippines

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Effective groundwater management is of high importance, particularly in the light of the changing climate and increasing demand due to the increasing population. This study found that the main source of water for both surface and groundwater from the selected water samples over the Cagayan Valley Region is of meteoric origin. A local meteoric water line (LMWL) of δ2H = 8.22 δ18O + 12.31 was developed in this study which closely resembles the Philippine Meteoric Water Line (δ2H = 8δ18O + 12). Stable isotope analysis also revealed that surface water and groundwater can have considerable connection. Supported by tritium analysis, the groundwater age implies that the groundwater is recharged with new water making shallow well water relatively young where the selected wells record a young groundwater age from 2 years to more than 22 years. The estimated average recharge rate is 197.96 mm/year, accounting for 9.89% of the region's average annual rainfall. Further analysis also implies that the altitude effect also prevails over the region where higher altitude provinces have a more depleted isotopic composition. The result of the study supports the applicability of isotope hydrology in a more comprehensive groundwater evaluation.

Keywords: tritium analysis; stable isotope; recharge rate; groundwater age; shallow well; isotope signature

I. INTRODUCTION

Water resources have now become the new gold in the contemporary world. It is the most vital resource that encompasses every industry from agriculture to semiconductors (Liu *et al.*, 2024). Globally, the growing population has always been the leading cause of the weight that is imposed upon the water resources reserve which is affected by transboundary drivers of water stress (Sabale *et al.*, 2023; Munia *et al.*, 2016). Water is present and available in different forms. Van de Gaun (2020) specified that among terrestrial waters, surface water and groundwater were the most exploited resources – blue water is often dealt with separately as opposed to the conjunctive water principle. It is recognised that water resources management is a complex endeavour where the level of difficulty significantly increases from local to regional scale. Groundwater, the world's largest freshwater reserve, has been highly threatened for many years which is mainly attributed to anthropogenic impacts from unregulated agricultural wells to industry-level heavy groundwater abstraction (de Graaf *et al.*, 2017).

Groundwater and surface water management – conjunctive management relies on how well-established the connection between groundwater and surface water is, as knowing such information is a key factor in managing water resources against natural and man-made disasters such as droughts, pollution transport, and water supply degradation (Sekar *et al.*, 2024). Increasing groundwater abstraction can be traced

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to the mismanagement of water resources, which tend to be lost non-beneficially on the surface. Dependency on groundwater can stem from different causes stretching from the geographically defined parameters such as rainfall scarcity and factors increasing water demand (Dangar *et al.*, 2021; Wada, 2015). The interaction between groundwater and surface water pertains to the influx of water from an aquifer system to a surface water system, like lakes or rivers, and vice versa. Recharge sources are identified to quantify the potential amount of water that can be exploited for community development. The connection between groundwater and surface water is not often studied, even in first-world countries, but is recognised to be a vital factor in establishing a more comprehensive integrated water resources management (Larocque & Broda, 2016).

In the Philippines, groundwater, precipitation, and surface water are essential to ecological and social systems. Rising demand from population growth, urbanisation, and agriculture has intensified management challenges (Groundwater Foundation). The Cagayan Valley, located in northeastern Luzon, spans 2.68 million hectares and is the country's fourth-largest region, with a 2020 population of 3.68 million. Its economy is agriculture-driven, focusing on food security and crop diversification (Aquino *et al.*, 2014; Calderon *et al.*, 2018).

Though endowed with abundant water resources both in surface water and groundwater, the region faces the threat of water scarcity due to over-abstraction, pollution, and seawater intrusion. Several municipalities, especially remote areas, depend on groundwater. The increasing population and uncontrolled urban development have in some cases resulted in the decline of groundwater levels (Castañeda *et al.*, 2016). Research indicates that climate change is expected to increase drought vulnerability in river basins within the region by as much as 30% under future climate scenarios (Felipe *et al.*, 2023). These alarming problems, exacerbated by climate change, need urgent action in an unobstructed, simple, fast, and easy way to make groundwater mechanics visible.

Existing studies focus on specific aspects, such as groundwater levels or agricultural impacts, but do not provide a comprehensive assessment of water resources in the region. Crisologo and Prado (2001) assessed the groundwater resources in Aurora, Isabela, and Aritao, Nueva Vizcaya, in terms of the water table, aquifer, and discharge capacities of groundwater wells in the areas. A recent study on the Cagayan Valley Aquifer System highlights the critical state of groundwater resources in Metropolitan Tuguegarao. The area relies heavily on groundwater, with monthly extractions averaging 1.43 million cubic meters. The study indicates that continuous pumping has led to significant declines in groundwater levels, necessitating sustainable management practices to prevent further depletion (Talosig & Soriano, 2024). Rubio (2008) provided some water resources information in the Philippines, highlighting some issues of water quality, the status of water use and water scarcity, and other threats to water availability. Recently, a study assessed the impacts of climate and land use change on the streamflow of Abuan River, a tributary of the Pinacanuan De Ilaguen River (Araza *et al.*, 2020).

Groundwater investigation is one of the most challenging fields in water resources and earth sciences. The exploration of groundwater for sustainable development especially in areas where the economic affiliation relies on the industry that is highly dependent on water, is becoming so imminent that in some countries, overexploitation is becoming so ubiquitous that the designated authorities have often been lost in documenting and regulating of production wells installation (Elshall *et al.*, 2020; Gleeson *et al.*, 2012; World Bank, 2016; Ray, 2019). We are dealing with an invisible resource beneath our feet when we deal with groundwater dynamics. Since groundwater and surface water are most likely to be connected, the impact of human explorations on different industries on water quality and sustainability is of high significance for policy and management interventions (Wada, 2015). The modelling of groundwater and surface interactions is among the leading options in studying groundwater dynamics. However, it requires complete data to be more effective in representing real-world processes (Ntona *et al.*, 2022). Furthermore, there should be adequate knowledge in establishing parameters such as boundary conditions and assumptions that may deviate or lead to better capturing such systems. This is important since surface water and groundwater are highly variable in spatiotemporal aspects and yet known to be intricately connected (Krause *et al.*, 2011).

Among the most reliable methods in understanding the interconnection of groundwater to surface or other subsurface sources is using stable water isotopes. Isotopic fractionation across the water cycle reveals hydrological processes, water origins, and potential contaminants (Chen *et al.*, 2011; IAEA Brief, 2019). Isotope hydrology uses both stable and radioactive environmental isotopes to trace the movements of water in the hydrological cycle (IAEA). Stable isotopes, such as deuterium (δD) and oxygen-18 (δ18O), and radioactive isotope-Tritium serve as valuable tracers in providing insights into water movement, mixing dynamics, and recharge mechanisms of aquifers (Clark & Fritz, 1997). Previous studies indicate that hydrogen and oxygen isotopes are not significantly altered by most forms of water-quality degradation, and instead primarily respond to hydrological and climatic controls through isotope fractionation (Yeh & Jhe-Wei, 2018). Differences in the physical and chemical properties of the environment result in isotope fractionation, which is preserved in the water cycle. Thus, changes in the natural hydrological environment are reflected by changes in the isotope ratios of hydrogen and oxygen, as observed in atmospheric precipitation models.

Several studies on the application of Isotope techniques in water resources have been conducted in the Philippines (IAEA, 2016; Racadio *et al.*, 2020). However, as of the moment, there is no other study that uses stable and radioactive isotopes in tracing groundwater resources in the Cagayan Valley Region. Hence, this study aims to establish and introduce the use of isotope hydrology techniques in the tracing and investigation of the groundwater recharge mechanism of the shallow aquifers that transparently supply a large number of families in terms of agriculture, irrigation and domestic utilisation in the Cagayan Valley Region. This research study will serve as a basis for scientific and political decisions in conserving and protecting our groundwater resources in the region.

II. MATERIALS AND METHOD

A. Study Area

Cagayan Valley is built on a massive geographical resource called the Cagayan River Basin, where the 500 km-long Cagayan River, the longest river in The Philippines is situated. The basin which covers an area of 27,676 square kilometres makes Cagayan Valley one of the most important biodiversity hotspots in the country (Figure 1). It is partially bound by two mountain ranges, the Sierra Madre and the Cordillera Central. The topography is primarily considered to be hilly up to mountainous. According to CRB's topographic data, there are around 6,600 km^2 of land with a slope of less than 8% that has been well developed as agricultural land. About 3,400 km^2 is a hilly area with gradients ranging from 8% to 18%. Significant portions of the steep area have been left as grassland. Mountainous terrain covers the remaining 17,300 km^2.

The climate in the Cagayan River is dominated by monsoons, namely the southwest and northeast monsoons. Typhoons typically strike eight times each year from July to December. El Nino strikes the area every three years or so. The yearly rainfall average is 2,600 mm. The precipitation ranges from less than 2,000 mm in the lowlands to more than 4,000 mm in the mountains. At the mouth of the Cagayan River, yearly discharge is predicted to reach 1,343 m^3/s (Regional Development Council II, 2006).

For this study, several surface water; domestic, and agricultural shallow wells were strategically selected to represent the whole Cagayan Valley where 45% of households rely on well for drinking and domestic-related consumption to which 60% are dependent on groundwater (Paguigan & Afidchao, 2020).

B. Sample Collection

A rain collector was installed at the CVAARRD Experiment Station at Isabela State University, Echague, Isabela. Rain samples were collected at the end of every month, and the volume of rainwater collected is recorded. Samples for stable isotopes and tritium were taken from the collected rainwater and stored in 60-ml and 1-L HDPE bottles, respectively, that were filled to the brim with no headspace.

The sampling sites were scattered across the region to better represent the spatial domain of the study area. Sampling locations are shown in Figure 2. Water samples from shallow wells, hand pumps, rivers, and seawater were collected within the study area twice, once during the dry season and another during the wet season. Before sampling shallow wells and hand pumps, the water level was measured, if possible, using an electric sounder or depth gauge.

Afterwards, the shallow well or hand pumps were purged manually until the measured electrical conductivity (EC) was stable. The pH, EC, total dissolved solids (TDS), dissolved oxygen (DO), and oxidation-reduction potential (ORP) were measured using a portable multimeter. Nitrate concentration was also measured using an ion-selective electrode. Furthermore, bicarbonate-carbonate analysis was conducted in situ using a digital titration method that uses Phenolphthalein and Bromocresol Green-Methyl Red indicators. Samples from rivers were taken by dipping the HDPE bottle where there is flow (e.g., the middle of the river). Seawater samples were taken at a distance away from the coast. Samples for stable isotopes and tritium were taken in 60-ml and 1-L HDPE bottles, respectively, that were filled to the brim with no headspace. Two 500-ml HDPE bottles were used to collect samples for anions and cations analyses after filtration with a 0.45 µm HAWP membrane filter. Samples for cation analysis were acidified to pH 2 by adding concentrated HNO_3.

These samples, together with rainwater samples, were analysed at the PNRI laboratory for stable isotopes, tritium for the age of groundwater, and anions and cations for chemistry analysis.

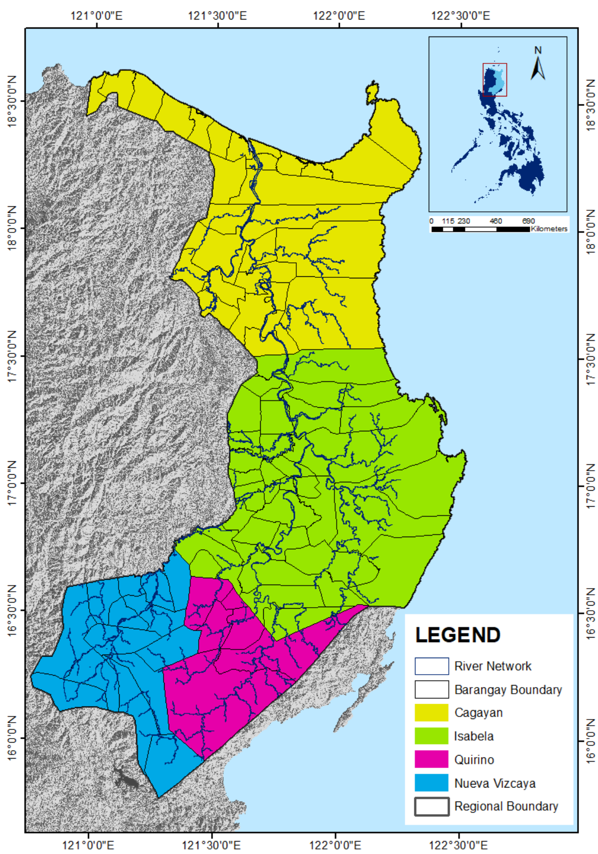

Figure 1. Study Area

C. Isotope Analysis

1. Stable isotope analysis

Stable isotope analysis (δD and δ18O) was conducted at the PNRI Environmental Laboratory using a Los Gatos Research Liquid Water Isotope Analyzer following the method of Wassenaar *et al.* (2014). Isotope compositions are given as δ values, the relative deviations with respect to the standard value, the Vienna Standard Mean Ocean Water. Signifying R as the abundance ratio of the isotopic species, i.e. 2H/1H or 18O/16O, δ is defined by:

$$\delta = \frac{R_{measured} - R_{VSMOW}}{R_{VSMOW}}$$

where δ is reported in ‰ (per mille, equivalent to 10-3). For deuterium-hydrogen (2H/1H), δD is used; for 18O/16O, the notation is δ18O. The reported maximum uncertainty of each measurement is ±0.2 ‰ and ±1.5 ‰ for δ18O and δD, respectively.

2. Tritium Analysis

Samples for tritium analysis were analysed at the PNRI Environmental Laboratory, Quezon City, Philippines based on the method described by Mendoza *et al.* (2010). A 500-ml aliquot from each water sample was taken and the volume of the water was reduced from 500 to about 15 ml by electrolytic enrichment using the Tritium Enrichment Unit (TEU) developed by IAEA (Gröning *et al.*, 2009). The final volume of the water samples was recorded after enrichment, and an 8 ml aliquot was taken after distillation and placed into a 20 ml low-diffusion PE vials (Packard® item no. 6000477). Twelve (12) ml of Ultima Gold LLT (Packard Bioscience®) scintillation cocktail was added to each vial and shaken by hand. Tritium activity was determined by measuring tritium decay events via β-particle counting emission using ultra low-level liquid scintillation counter, TRICARB 3170 TR/SL, with a detection limit of 0.3 Tritium Unit (TU; 1 TU = 0.118 Bq/L).

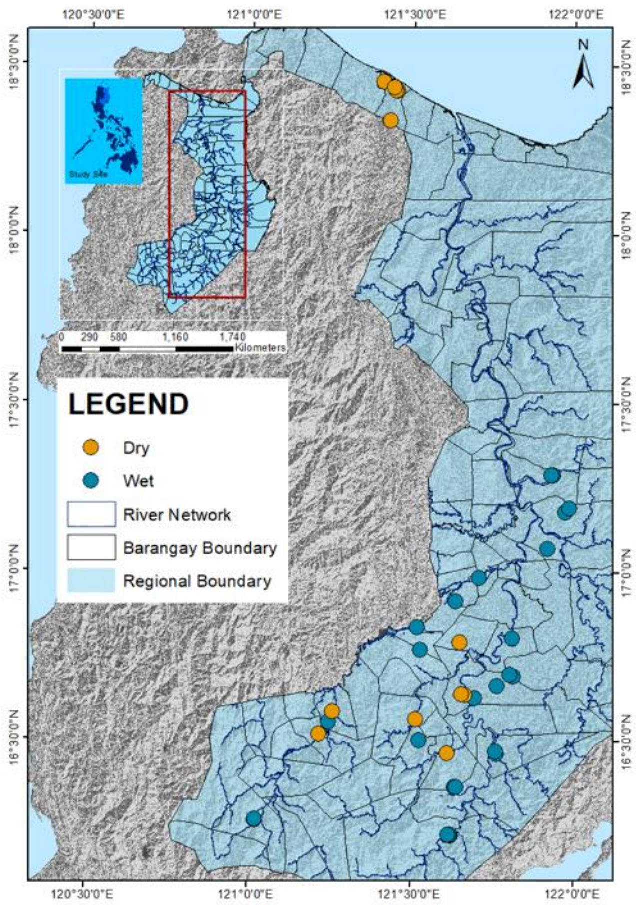

Figure 2. Sampling Location

3. *Recharge rate estimation*

The estimated ages of the samples were then used to infer the movement and recharge of groundwater across the study area using the formula:

$$\hat{R} = \left(\frac{\theta H \ ln\left(\frac{H}{H-z}\right)}{\tau_z}\right)$$

Where r is the recharge rate (mm yr-1), $\boldsymbol{\theta}$ is the porosity of the aquifer, h is the thickness of the aquifer, z is the depth of screen below the water table (calculated by subtracting the static water level from depth to top of well opening), and t, is the groundwater age from tritium analysis (Cartwright *et al.*, 2017; Racadio *et al.*, 2020).

III. RESULT AND DISCUSSION

1. *Stable isotopes*

Table 1. Stable isotopes values of the samples collected during wet Season and Dry Season.

LabID	Description	δ2H, in ‰	δ18O, in ‰
W-1599	Santa Fe River	-59.9	-9.07
W-1607	Nagcuartelan open well	-56.6	-8.06
W-1609	Brgy. Solano hand pump	-55.5	-8.17
W-1620	Singson Residence hand pump	-41.3	-5.94
W-1612	Spring Water Siitan Park	-60.5	-9
W-1617	Cagayan River	-56.5	-8.76
W-1608	MARIIS Main Canal	-65	-9.64
W-1598	Hand pump near MARIIS MC	-39.8	-5.93
W-1611	Hand pump Brgy. Tandul near agri farm	-44.6	-6.43
W-1595	Hand pump Brgy. Concepcion	-38	-5.89
W-1597	Brgy. Salindingan Deep well	-45.5	-7
W-1619	Ilagan Sanctuary Spring Water	-44.4	-6.88
W-1603	Pinsal Falls Ilagan Sanctuary	-42.6	-6.7
W-1613	Tumauini River	-49.5	-7.98
W-1610	Brgy Antagan Hand Pump Tumauini	-39.9	-6.22
W-1601	Cagayan River near Sta. Maria Bridge	-49.9	-7.91
W-1593	Sta. Maria open well	-55	-8.19
W-1618	CSU open well	-46.2	-6.73
W-1614	Brgy. Madurulug hand pump	-47.1	-6.9
W-1604	CSU Piat PS (submersible)	-47.8	-6.81
W-1616	PeÃ±ablanca hand pump	-47.9	-7.5
W-1602	Callao River/Bridge (Pinacanauan River)	-45.2	-7.4
W-1594	Cagayan River mouth	-50.5	-7.87
W-1600	Macanay (Aparri) open well	-37.6	-5.93
W-1605	Mapanao River	-63.4	-8.41
W-1328	San Juan ES, Echague	-40.3	-6.03
W-1329	San Juan Irrigation Well, Echague	-36.2	-5.22
W-1330	Sto. Tomas Fishpond Well, Alicia	-38.8	-5.55

W-1331	Sto. Tomas Fishpond Water, Alicia	-16.8	-1.46
W-1332	Abulug River (Bridge)	-29.8	-5.49
W-1333	Abulug Coast Handpump	-23.3	-4.6
W-1334	Abulug Seawater	-1.9	-0.39
W-1335	Siguiran Tubewell, Abulug	-16.6	-3.22
W-1336	Alinunu Irrigation Well, Abulug	-26	-4.44
W-1337	Palacian, Aglipay (River water)	-36.2	-6.29
W-1338	Palacian, Aglipay (Handpump)	-40.1	-6.49
W-1339	Cajel, Diffun (Handpump)	-46	-6.9
W-1340	Bagabag, NV (Handpump)	-49.7	-7.43
W-1341	Carifang River, NV	-46.3	-7.41

Table 1 shows the groundwater samples for the dry and wet seasons. For the dry season, 3 shallow wells and 1 pond water were sampled in Isabela Province; 1 river sample and 1 shallow hand-pump well were sampled in Nueva Vizcaya Province; and 2 shallow handpump wells and 1 river water were sampled in Quirino Province. Since there were only 11 sampling points to represent the whole of region 2, a follow-up sampling activity was conducted to add 23 more sampling points, including representative points in Cagayan Province. Additional 3 handpump wells and 1 river sample were sampled for Nueva Vizcaya; 1 spring water, shallow tube well, and river sample were sampled for Qurino; 7 wells, 2 irrigation canals, 1 spring water, and 2 river samples were added for Isabela; and 5 well, and 2 river samples were sampled for Cagayan. However, the additional sampling points were sampled during the wet season in November. While it is recommended to have seasonal samples per location – dry and wet season, this study focuses more on distributing the sampling locations all over the Cagayan Valley Region, as it is among the few studies employing isotope techniques. It should be noted that the surface water body samples, such as river samples, were selected as they are near the wells, which we hypothesised to be connected to the corresponding aquifers.

The 1-year stable isotope data from rain samples in ISU Echague from May 2022 to April 2023 resulted in an initial local meteoric water line (LMWL) of $\delta 2H = 8.22\ \delta 18O + 12.31$. While the LMWL data is still subject to update following the analysis of the remaining samples, it can be inferred that it does not differ much from the global meteoric water line, GMWL (Craig, 1961), and the Philippine Meteoric Water Line, PMWL (Gerardo-Abaya, 2005), implying that GMWL and PMWL hold their validity over study area conditions, Echague being situated within the Cagayan valley surrounded by mountain ranges. As a standard, this study will be using the GMWL to assess the sources of shallow groundwater. By convention, if the water sample has the same isotopic signature as that of the GMWL, the water is of meteoric origin, or the rainfall in the area serves as the main source of recharge. Surface water samples may be depleted with lighter isotopes due to evaporation, and if groundwater samples are revealed to have the same isotopic signature similar to surface water samples, a conclusion relating the connection between such surface water body and the shallow groundwater aquifer can be drawn. Other processes can also be deduced, which can result from the fractionation of water isotopes in lieu of the phase change of water from its origin to its current location.

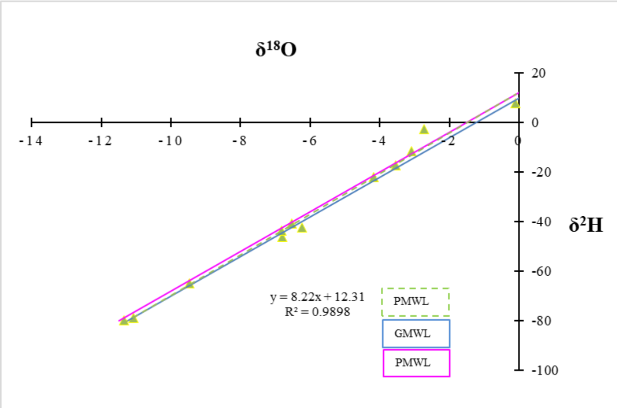

Figure 3. Graph of the LMWL against the GMWL and PMWL.

The isotope signatures of water samples represent the hydrological process that took place. It is unique to the origin, path, geography, and topography of a certain place, which directly contributes to and affects several processes such as rainout. For the initial samples that were gathered through this study, the isotopic values of the samples were plotted on the δD-δ18O plane along with the Global Meteoric Water Line (GMWL). The negative sign implies that the samples are isotopically depleted in heavy water isotopes. The majority of the shallow groundwater samples lie along the GMWL trendline which suggests that most of the wells were recharged by rainfall. The fishpond water sample is found to be less depleted compared to the well samples, which is attributed to the high amount of evapotranspiration that took place as it is directly exposed to sunlight. Hence, the latter serves as the basis for the evaporation line (broken green line). It can also be observed that some wells i.e., Echague, Alicia, plots along the evaporation line. It must be noted that these wells are irrigation wells and are situated inside the paddy fields. The corresponding deviation of the isotopic value of the wells may be due to evaporation occurring due to irrigation return flow. In addition, as the wells serve as the main source of irrigation considering their shallow-depth configuration, they are still mainly being recharged through rainfall, but it is not impossible for excess irrigation water to directly infiltrate and partly recharge the wells after being exposed to considerable evaporation. Moreover, it is also the same for river samples from Abulug River, Curifang River, Nueva Vizcaya, and Palacian River in Aglipay, Quirino. Their noticeable margin from the GWML also suggests that they have undergone through the evaporation process. The possible link between river (surface) water and shallow groundwater should also be considered. However, the number of samples should be increased for proper interpretation.

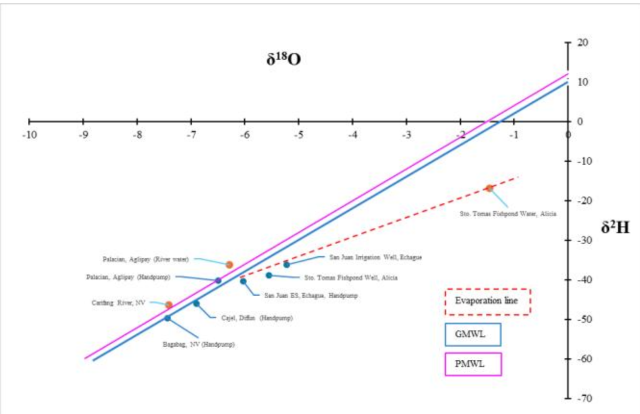

Figure 4. δ2H vs δ18O graph of groundwater and surface water sample sets during the dry season.

The results of the reconnaissance sampling are not that far from what has been established. While a resampling of the same data points was not conducted twice for dry and wet seasons, the spatial coverage of sampling was extended to cover more shallow groundwater areas in the region. During the wet season, the Habagat (Southwest Monsoon) is the prevailing monsoon season, bring a huge amount of rainfall over the Cagayan River Basin. The isotopic signatures of the groundwater and surface water (rivers and lake) generally falls within the PMWL and GMWL indicating rainfall as the major recharge mechanism of the associated shallow well aquifers. The evaporation line drawn across the main canal sample of the Magat River integrated irrigation system which may be affected by relatively higher evaporation incidence as the water is stored as open water from the dam to the canal itself. On the other hand, there was no significant connection established between surface water and groundwater samples even though are in close proximity to each other. This shows that rainfall being infiltrated into the soil profile determines the aquifer recharge of such shallow wells. The isotopic signature of rivers that fall within the meteoric water lines indicates that rainwater directly replenishes the water without significant time for fractionation. It can happen when the soil and geology does not hold water for a long time and immediately discharges it as subsurface flow or runoff happens so fast that the rainwater reaches rivers in a short time before significant fractionation happens, such as evaporation. This proposition is still subject for verification, but the isotopic signatures reveal as much information. It can also be inferred from the same figure that the isotopic signatures of wells below the GMWL may indicate evaporation process. Given that the main source of groundwater recharge is rainfall, and that there is no defined connection between groundwater and nearby surface water samples in terms of isotopic signatures, the well samples below the GMWL indicates evaporation process and is hypothesised to be recharged by the rains during the dry season. The lack of seasonal samples per sampling location is a recognised limitation of this study.

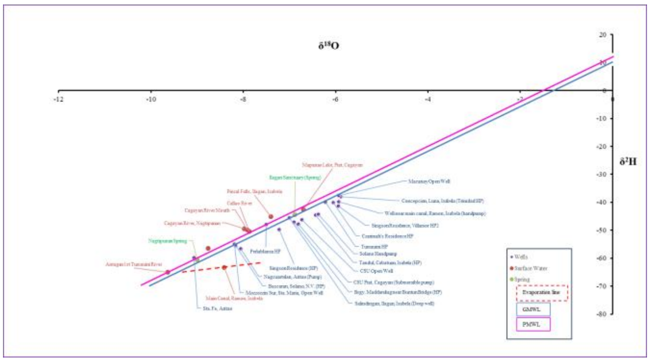

Figure 5. δ2H vs δ18O graph of groundwater and surface water sample sets during the wet season.

It was noted that the δ2H concentration for groundwater samples during the wet season has a lower mean of -46.49‰ compared to -41.85 during the dry season. On the other hand, the δ18O concentration is lower during the dry season at -6.27‰ compared to -5.94‰ for the wet season. For the surface water, however, both δ2H and δ18O values are measured during the wet season. This is not unusual, as isotope fractionation during the dry months is more likely to cause enrichment of heavy isotopes. Follow-up sampling should be done on the selected well locations to gather isotopic data for both the dry and wet seasons so that the seasonal variation can be assessed. Since this study only focuses on shallow wells, it can be inferred that it would benefit a great population that depends on shallow groundwater sources, particularly for domestic and agricultural consumption.

The wet season sampling sites are denser than the dry season. By comparing the average δ2H and δ18O per province, it was found out the higher elevation provinces – Nueva Vizcaya and Quirino ((δ2H= -54.07‰, δ18O = -7.92‰ and δ2H= -55.15‰, δ18O = -8.11‰, respectively) has a more depleted isotopic composition than those that are in lower elevations – Isabela and Cagayan (δ2H= -46.74‰, δ18O = -7.16‰ and δ2H= -47.25‰, δ18O = -6.98‰, respectively). This can be attributed to the altitude effect which denotes that water at higher altitudes are more depleted with heavy isotopes compared to lower altitudes.

2. *Tritium analysis*

Tritium occurs in nature due to anthropogenic such as the detonation of nuclear bombs during World War II w and natural production which is attributed to cosmic ray interaction with atmospheric molecules. As a radioactive hydrogen isotope, the Tritium (3H) in this study was analysed using a liquid scintillation counter (LSC) which measures Tritium decay events based on beta-particle emission. The half-life is 12.3 years, and it is the basis of its application as a tracer for groundwater dynamics. In the country, Tritium concentrations range from 1 to 1.5 tritium units (TU) in rainwater and 0.1 to 1 TU in usual groundwater. Sea water is characterised by 1 TU and 0 TU is attributed to deep groundwater (Racadio *et al.*, 2023). The long-term precipitation average tritium concentration in the area was about 1.2 Tritium Units (TU) based on Quezon City Tritium Rainfall Data.

Tritium analysis was primarily used to estimate groundwater age and assess recharge processes by measuring tritium concentrations in various water sources. Since tritium is a short-lived isotope, its presence in groundwater indicates recent recharge, while lower concentrations suggest older water. In this study, water samples were analysed for tritium using LSC, and the results were compared with decay models to estimate groundwater age.

Selected groundwater samples (Table 2) were subjected to tritium analysis. Among the samples, the pump well in Salindigan, Ilagan City, Isabela has the oldest groundwater, which is estimated to be more than 22 years old, and the youngest is the one gathered at a dug well at Sta Maria, Isabela. Generally, the calculated groundwater ages of the shallow well water samples were considered the water to be young. The tritium analysis supports the stable isotope analysis, implying that the groundwater samples are plotted within the limits of the GWML and that the shallow aquifers tapped for abstraction of water have a meteoric origin, hence, a young groundwater age.

Table 2. Groundwater Age of Selected Shallow Wells in Cagayan Valley.

Sample	**Date of Sampling**	**Tritium Concent ration (TU)**	**Expanded Uncertainty (TU)**	**Estimated GW Age (years)**
San Juan Handpu mp, Echague	April 2022	0.63	0.05	11
San Juan Agri Well, Echague	April 2022	0.57	0.06	13

Bagabag Handpump, N. Vizcaya	November 2022	1.00	0.11	3
Singson Residence, Quirino	November 2022	1.01	0.10	3
MARIIS Main Canal	November 2022	0.84	0.1	6
Salindingan, Ilagan City	November 2022	Less than MDC; MDC = 0.35	N/A	Probably >22 years
Antagan	November 2022	0.75	0.09	8
Sta Maria, Isabela	November 2022	1.09	0.12	2
CSU Piat, Cagayan	November 2022	0.73	0.11	9
Macanay, Cagayan	November 2022	0.79	0.11	7

Remarks:
(1) long-term precipitation average tritium concentration in the area was about 1.2 Tritium Units (TU) based on Quezon City Tritium Rainfall Data
(2) Tritium half-life used was 12.32 years

3. Recharge rate

Recharge rates were estimated using the groundwater age and aquifer parameters from literature (Cartwright *et al.*, 2017; Racadio *et al.*, 2020). The computed recharge rates ranged from 46.35 mm/year (SJES Handpump) to 536.03 mm/year (Sta. Maria well). Wells with younger groundwater, such as Sta. Maria (536.03 mm/year) and Bagabag Handpump (383.58 mm/year), exhibited higher recharge rates, likely due to their proximity to active recharge areas. In contrast, Salindingan well had a relatively low recharge rate (214.56 mm/year), consistent with its older groundwater age.

To estimate the percentage of recharge from rainfall, the computed recharge rates were compared with the regional annual precipitation. Based on PAGASA's climatological data, the Cagayan Valley region receives an average annual rainfall of approximately 2,000–3,500 mm. The estimated recharge rates from this study, ranging from 46.35 to 536.03 mm/year, and an average of 197.96 mm. This corresponds to approximately 5.7%–9.9% of annual rainfall contributing to groundwater recharge, with an average recharge contribution of ~9.5%. These values closely align with the estimated recharge rate of 10.60% for the Cagayan Valley Aquifer System in Metropolitan Tuguegarao, derived from MODFLOW modelling (Talosig & Soriano, 2024). The slight variation may be due to localised differences in aquifer characteristics, land cover, and seasonal variations in infiltration rates. Despite these differences, the findings remain consistent with expected infiltration rates in the region, supporting the reliability of the recharge estimates. The computed values in this study generally align with findings in localised areas but may differ due to variations in aquifer characteristics, porosity, and precipitation input across the broader Cagayan Valley region.

IV. CONCLUSION

This study found that the rainfall recharge is the main source of groundwater. Water infiltration may find its way directly from the surface to the shallow water table and others may travel or traverse soils of different texture that delays its movement. Nevertheless, this study can also imply that surface pollutants can in fact be carried away by the infiltrating water and may eventually reach the shallow groundwater. Further studies regarding this matter are also encouraged. In addition, the variability in rainfall and the intensification brought by climate change can indeed be an imminent threat on the sustainability of shallow groundwater sources. A more comprehensive assessment is needed to quantify the changes in groundwater storage under different climatic scenarios where rainfall can be limiting is highly encouraged.

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