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Hydrological interactions between surface water and groundwater in ancient manmade village tank cascade systems (VTCSs) in the dry zone of Sri Lanka

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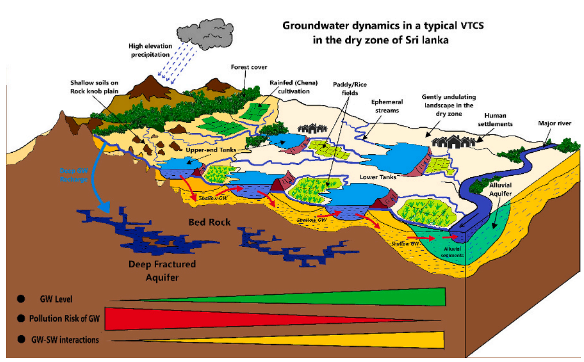
HIGHLIGHTS

- Combinations of ^2H, ^{18}O and Cl^- were used as cost-effective hydrological tracers.
- TCSs have significantly impacted on TDS or Chloride of GW and SW.
- Presence of TCSs makes the GW flow system stable and continuous throughout the year.
- Absence of TCSs creates big spatial and seasonal deviations in the GW flow.

GRAPHICAL ABSTRACT



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ABSTRACT

Sri Lanka, a tropical island, confronts climate-driven water scarcity and is of great concern to building climate-resilient water management to achieve UN SDGs 6 and 13. This study explores the dynamic interaction between surface water (SW) and groundwater (GW) in the dry zone of Sri Lanka, employing a multi-tracer of dual stable isotopes (^{18}O and ^{2}H) and chloride. Two basins, Mahakanadarawa (MK) basin with numerous village tanks and tank cascade systems (VTCSs/TCSs) and Kawudulla (KW) basin serving as a control with a lack of tanks, were selected in this study. Results show that the presence or absence of TCSs emerges as a pivotal factor influencing regional water dynamics. Water quality (TDS and Cl^-) in natural waters between the two basins was significantly different (ANOVA: $p < 0.05$) in both seasons. Statistically uniform dissolved mineral content in tanks and shallow groundwater in the MK basin contrasted with significant regional deviation in the KW basin. ANOVA and Tukey tests showed significant seasonal differences ($p < 0.05$) in mean values of δ^2H and $\delta^{18}O$ compositions of shallow groundwater and tank water within the MK basin, while non-significance in the KW basin. Isotopic mass balance calculations revealed that tank water mixing in the shallow groundwater (f_T: mixed Tank water mass fraction) ranged from 0.9 % to 77.8 % across the MK basin depending on the regional soil characteristics. Lack of tank-aquifer interconnection observed in the shallow soil in rock knob plain results in groundwater depletion while enhanced interconnections within alluvial sediment regions encourage stable and pollution-resistant shallow groundwater bodies. The consistency of the groundwater flow system in TCS regions throughout the year ensures a stable water supply, highlighting the vital synergy between TCSs and regional groundwaters in these arid regions. These results shed insights for policymakers and water managers to implement effective conservation strategies for rehabilitation and restoring these ancient VTCSs/TCSs.

1. Introduction

The dry zone of Sri Lanka has had a sophisticated water management system for over 2400 years called village tank cascade systems (VTCSs/TCSs) identified and named by a researcher (Madduma Bandara, 1985) in 1985, these village tanks are functioning as small clusters within small basins with multiple small reservoirs (Bebermeier et al., 2023), and around 50 % of them are still in operation (Panabokke, 2000; Sakthivadivel et al., 1997). These TCSs feed >35 % of the irrigated paddy lands of the island (Frenken, 2012; Wickramasinghe et al., 2023), and provide economic and social benefits while combining with the natural ecosystem (Geekiyanage and Pushpakumara, 2013). As recognized as a Globally Important Agricultural Heritage System (GIAHS) by the Food and Agriculture Organization (FAO) of the United Nations in 2017 (Pussegoda, 2019), these TCSs have become an integral part of the dry zone environment (Panabokke et al., 2001; Srivastava and Chinnasamy, 2021). TCSs in Sri Lanka have also been identified as a key factor in developing strategies for climate resilience future due to their unique capabilities in water resource management and eco-system protection by flood control, drought management, and waste runoff recycling (Bebermeier et al., 2022; Geekiyanage and Pushpakumara, 2013; Herath and Miyanadeniya, 2015; Mahatantila et al., 2008; Rekha Nianthi and Jayakumara, 2010), and have significant similarities with multi-pond systems in China in agricultural runoff recycling and flood control (Chen et al., 2017; Li et al., 2018; Yin et al., 1993).

As a tropical island, Sri Lanka is highly vulnerable to climate change (Climate Change Secretariat, 2016) on the global climate risk index, indicating a significant susceptibility to climate change-induced risks, particularly in the realm of water (UNDP, 2023). Hence, the water system should be climate resilient for safe drinking water supply based on the UN SDG 6th and 13th goals (United Nations, 2024). In rural areas of Sri Lanka, especially in the dry zone, groundwater is the key drinking water source while urban areas depend on surface water from rivers and manmade reservoirs. However, climate change has a negative impact on the surface water supply. Understanding the interactions between these surface water bodies and the aquifers will be advantageous for making the water management system climate-resilient (Lewandowski et al., 2020; Priyadarshanee et al., 2022; Yang et al., 2021). Thus, in the future TCSs in the dry zone of Sri Lanka, will play a huge role in climate resilience water management strategies.

Groundwater quality contamination via surface water in the dry zone of Sri Lanka which is driven by anthropogenic activities like extensive agricultural practices, has been reported in many previous studies (Cooray et al., 2019b; Indika et al., 2023, 2022; Makehelwala et al., 2019). Common groundwater quality issues like elevated levels of total dissolved solids (TDS), hardness, fluorides and dissolved organic carbon (DOC) have been a major concern in many previous studies which cover the rural areas of the dry zone (Chandrajith et al., 2012; Cooray et al., 2019b; Indika et al., 2023; Makehelwala et al., 2019; Nanayakkara et al., 2020). These water quality contamination issues have been a huge threat to the health of rural communities by spreading fatal diseases like Chronic Kidney Disease of unknown etiology (CKDu) for several decades (Cooray et al., 2019a; Gunarathna et al., 2018; Ranasinghe et al., 2019; Shipley et al., 2022). Even though these groundwater bodies are associated with village tanks and TCSs, no comprehensive investigation has been conducted to understand the hydro-chemical interactions between them. Thus, understanding the hydrodynamic processes, synergistic behaviors and contamination transfer gives a clear picture to mitigate those pollution incidents and is valuable in climate resilience water resource management.

The most common environmental isotope, the dual stable isotopes (^{18}O and ^{2}H) are very popular for tracing natural waters around the world (Cao et al., 2021; Yang et al., 2021). However, some less safe and expensive tracers like artificially produced radionuclides ^{36}Cl, ^{129}I, ^{14}C, ^{222}Rn and ^{226}Ra are also used in hydrological investigations (Clark, 2015; Mook, 2000). Dissolved chloride in the groundwater and surface water shows quite similar performance to the stable isotopes such as ^{18}O, and ^{2}H (Clark, 2015). However, other tracers, such as Ca^{2+} and Na^+ or HCO_3^-, SO_4^{2-} and their isotopes are less reliable due to non-conservative exchange or redox reactions (Mook, 2000). Chloride can be used to trace the natural waters and study their hydro-dynamics such as the mixing process due to its conservative nature in the environment and cost-effectiveness(Clark, 2015). In previous studies stable isotopes were used for studying hydrological dynamics in large-scale river basins (Chen et al., 2023; Hao et al., 2019; Yang et al., 2021). They have assessed the impact of open water evaporation on water balance, explore interactions between surface water and groundwater, and identify pollution sources in groundwater. These comprehensive investigations aided in managing water resources, restoring ecosystems, and improving water quality. Hence, the combined use of dual stable isotopes (^{18}O and ^{2}H) and conservative chlorides could be cost cost-effective measure for tropical countries like Sri Lanka, Hence, this multi-tracer approach, used to investigate the hydrogeochemical interaction between tank water and regional aquifers. In addition, this study's outcomes are intended to assist policymakers and water managers in the implementation of efficient water conservation strategies to protect natural water resources.

2. Materials and methods

2.1. Study area

As chosen for its abundance of village tanks and the prevalence of CKDu disease, the Mahakanadarawa (MK) basin in the dry zone was designated as the study area (Fig. 1a, c). To assess TCSs' impact on regional hydrology, the KW basin, with lower tank density, serves as a controlled environment in the dry zone (Fig. 1b). Similar to the MK basin, it offers insights into groundwater dynamics in the absence of village tank cascade systems, aiding the understanding of geo-hydrology dynamics and water quality changes.

The MK basin is located (N: 8°29′29″-8°15′04″; E: 80°27′37″-8°42′18″) in the Anuradhapura district and is one of the sub-watersheds in the major Malwathuoya basin in Sri Lanka (Fig. 1). This sub-basin is fed by the Lower Weli Oya Stream and two major tributaries Upper Weli Oya and Upper Kanadara Oya Streams. These tributaries have been dammed by the different scales embankments across many locations in the valleys creating a cascading network of surface water reservoirs called TCSs. This watershed has 413 total number of tanks and 35 TCSs. This area has been recognized as one of the high-risk (HR) CKDu regions with the highest CKDu prevalence (Ranasinghe et al., 2019). This basin is situated between 71 m and 240 m elevation within the topographically plain area of Sri Lanka with a gentle slope. The total area of this basin is 438 km^2 and it receives an average of 1190 mm of rainfall annually. Populations of the Divisional secretariat divisions (DSDs) in which this basin is located were 44,874 (Kahatagasdigiliya division) and 39,261 (Mihintale division) by 2022, respectively.

The selected control area, the Kawudulla (KW) basin is located (N: 8°02′37″-8°16′55″; E: 80°45′38″-81°11′51″) in the Polonnaruwa district and within the high-risk CKDu regions (Medirigiya and Lankapura divisions) of NCP (Fig. 1b). It is one of the sub-basins of a major Mahawei river basin and is situated in the plain area of Sri Lanka and in between 20 m and 270 m elevations. The total area of the basin is around 607 km^2 and average annual rainfall is around 1220 mm. The major water reservoir of the KW tank which is located on the west side of the basin is fed by the Gal Oya and Aluth Oya streams. Downstream of the KW tank is drained through the KW Oya and its tributary stream Wan-Oya Stream and finally, they are connected to the Mahaweli River in the eastern direction. Only a few (2–3) TCSs are currently remaining in this watershed but the major KW tank (Upstream) feeds most of the agricultural lands located in the downstream and middle streams. The population of the DSD in which this basin is located was 72,554 (Medirigiriya division) by 2022. This region is also recognized as one of the high-risk (HR) CKDu regions. Due to the lack of village tanks and occupying almost similar climate patterns to the MK basin, this watershed was selected as the control to study the hydrological and hydrogeochemical dynamics without the effect of TCSs in the dry zone.

2.2. Sampling and data collection

Two major sampling campaigns were conducted within the dry

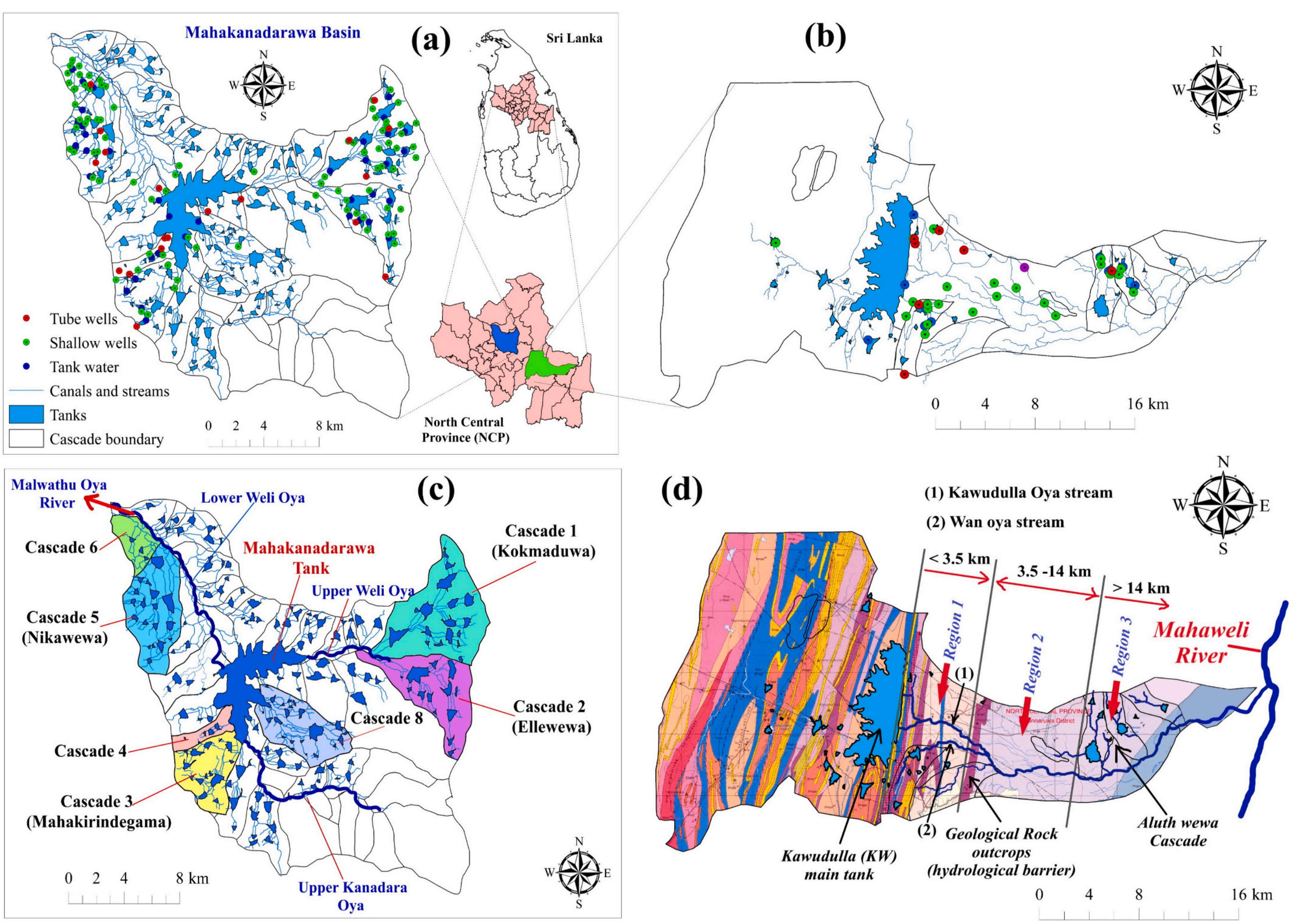

Fig. 1. Study areas with Sample locations in the (a) Mahakanadarawa (MK) basin, (b) Controlled Area: Kawudulla (KW) basin, (c) MK basin with TCSs, and (d) KW basin with different geo-hydrological divisions.

season (August–September 2022) and at the end of the wet season (February 2023) covering the two basins (MK and KW). Water samples were collected from 115 shallow wells, 30 tube wells, and 22 tanks from the MK basin, and 25 shallow wells, 9 tube wells, 6 tanks and 5 canals (Streams) from the KW basin (Fig. 1). Usually shallow wells are 2-10 m in depth while tube wells are deeper than 30 m. Additionally, the total depth of each well, and shallow groundwater water levels were measured during the sampling events, and GPS locations and the elevation (DEM) data were collected using Google Earth Pro (Version: 7.3.6.9345, Google, 2022). More information regarding sample locations is provided in the Supporting information (Table S1).

2.3. Sample analysis

General water quality parameters (pH), electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site using a multi-probe water quality analyzer (WTW, MultiLine Multi 3530, Welheim, Germany) with the standard deviations of ±0.1, ±0.5 %, ±0.5 % mg/L. Chloride (Cl^-) and fluoride (F^-) were analyzed by ion-chromatography (ICS 1000, Dionex, Sunnyvale, CA, USA) equipped with a separator column, chemical suppressor and conductivity cell. Water samples were preserved by acidification, for Cation analysis and all the dominant metals (Ca^{2+}, Mg^{2+}, Na^+, K^+) were measured by an inductively coupled plasma optical emission spectrophotometer (ICP-OES) (Optima 8300, Perkin Elmer, Houston, USA). Total Alkalinity was measured with Hach Alkalinity test kit (TNTplus Vials, Loveland, CO, USA). The DOC level was determined by a TOC analyzer (Elementra, Langenselbold, Germany). All samples (213) were filtered by 0.2 μm cellulose acetate membranes and put into 1.5 mL vials (LLG Labware) and were then analyzed for ^{18}O-H_2O and ^2H-H_2O by a Liquid Water Isotope Analyzer (LWIA) (LGR-V2 100, model no: 908–0008-200) with off-axis integrated cavity spectroscopy (off-axis ICOS) method at IHL, SLAEB (IAEA, 2009). Analyzed isotope results were converted into the delta notation (δ) values which give relative fractions concerning Vienna Standard Mean Ocean Water – 2 (VSMOW-2) standards. Final stable isotopes (^{18}O and ^2H) values of the water molecules were expressed in per-mill (‰) units ($\delta^{18}O$ ‰ and δ^2H ‰). The d-excess value is an indirect parameter that is derived from stable isotope compositions of the water sample using the following equation.

$$d - \text{excess} = \delta^2H - 8 \times \delta^{18}O \tag{1}$$

It contains information about the initial moisture source, evaporation effects during monsoon, and recirculation of moisture from large inland water (Clark, 2015).

2.4. Data analysis

All the statistical analyses (ANOVA, Tukey mean test, PCA, etc..) were performed using Origin Pro (2022, Originlab, U.S.A) software. ANOVA, Tukey mean comparison, and PCA tools facilitated the exploration of significant differences in isotopic signatures among water bodies, considering distinct hydrological patterns, seasons, and spatial distributions in the examined basins. Spatial interpolation maps were created using ArcGIS 10.3 (2014, Esri, CA, USA).

Isotope mass balance for calculating Tank water mixing ratio was conducted using a simple two-component mixing model (Clark, 2015). Simply, the stable isotope concentration of shallow groundwater in the command area below a village tank (δ_C) is the combination of they are in the shallow groundwater from the catchment area (δ_G) and the tank water (δ_T). Thus Eqs. (2) and (3) were used to estimate the fraction of tank water (f_T) and catchment groundwater (f_G) to produce, shallow groundwater in the command area.

$$f_G + f_T = 100\% \tag{2}$$

$$\delta_G.f_G + \delta_T.f_T = \delta_C.100 \tag{3}$$

3. Results

3.1. General water quality status

3.1.1. Water chemistry (tank waters, shallow GW, and deep GW)

Generally, TDS levels in the tank waters were lower in the wet season due to dilution by the precipitation. In the MK basin, the mean level of TDS in village tanks was 268 mg/L (wet) and 412 mg/L (dry), significantly higher than that in the KW basin (128 mg/L and 158 mg/L), respectively. Complex mixing processes between groundwater and tank waters in the MK basin contributed to higher mineral content. Alkalinity in the dry season exceeds the maximum allowable limit (MAL) (SLS 614 (2013) – MAL: 200 mg/L) in 49 % (MK) and 23 % (KW) of village tanks, respectively. Dissolved organic carbon (DOC) levels exceeded the MAL (Chinese standards (GB 5749-2006) - MAL: 5 mg/L) for drinking in 88.5 % (MK) and 16.7 % (KW) during the wet season, respectively. Despite low levels of other contaminants, DOM removal is crucial before consumption.

However, shallow groundwater in the MK basin exhibited higher TDS (592 mg/L dry, 547 mg/L wet) compared to the KW basin (337 mg/L dry, 425.5 mg/L wet). Fluoride ion concentration exceeded the MAL (WHO 2022: 1.5 mg/L) in 33 % (dry) and 20.5 % (wet) of MK samples and 5.7 % (dry) and 8.8 % (wet) of KW samples, respectively. Geohydrological patterns and rock-water interactions influenced groundwater chemistry differently in these areas. Compared to tank water, shallow groundwater had lower DOC levels, making it safer for human consumption. Deep groundwater maintained stable quality due to slower percolation rates in confined aquifers. However, TDS levels were higher in the MK (544 mg/L dry, 526 mg/L wet) than in the KW (352 mg/L dry, 378 mg/L wet). Fluoride exceeded safe limits (WHO: 1.5 mg/L) in 32 % (MK) and few (KW) wells. Alkalinity and total hardness exceeded the MAL in both basins. Mn levels were higher in the MK, but trace elements were within safe levels.

Statistical analysis confirmed the fact that water quality (TDS and Cl^-) of all types of natural waters (tank water, shallow groundwater and deep groundwater) in both MK and KW basins are significantly different (ANOVA: $p < 0.05$) in both seasons. However, in between cascades and main sections of the MK basin (upstream, midstream, and downstream), no significant difference ($p > 0.05$) in TDS level in tanks and shallow groundwater was observed, revealing an almost homogeneous distribution of dissolved minerals. Regions 1, 2 and 3 in the KW basin (Fig. 1d) showed significant differences ($p < 0.05$) in TDS level in the shallow groundwaters (Supporting information Section S3). These differences between the MK and KW basins reflect the capability of TCSs or village tanks to homogenize the water quality throughout the basin.

3.1.2. Hydro-chemical status

Hydrogeochemical processes and anthropogenic influences contribute to the dynamic hydrochemistry of these water bodies. The study emphasizes spatial and seasonal hydro-chemical differences of the MK and KW basins (Fig. S1). In both dry and wet seasons, Ca-HCO_3-type water prevails in shallow groundwater (Fig. 2), aligning with findings from previous studies in the dry zone (Indika et al., 2023; Zheng et al., 2020). However, during the wet season, a notable shift to mixed Na-Ca-HCO_3 groundwater occurs, particularly in areas with dense village tanks (MK basin), indicating increased interaction between shallow groundwater and tank waters (Fig. 2a, c).

In the MK basin, tank waters primarily exhibit Na-Ca-HCO_3 type, especially in the dry season (Fig. 2a). Yet, during the wet season, upper-end tanks of TCSs (42 %), transform into Na-Cl type (Fig. 2c), signifying chloride leaching from fertilizer application in upper paddy field regions. This transformation correlates with changes in the hydrochemistry of groundwater wells in the upstream cascade (26.6 %), highlighting direct hydraulic connections and interactions between tank water and regional shallow groundwater. The dry season sees tanks

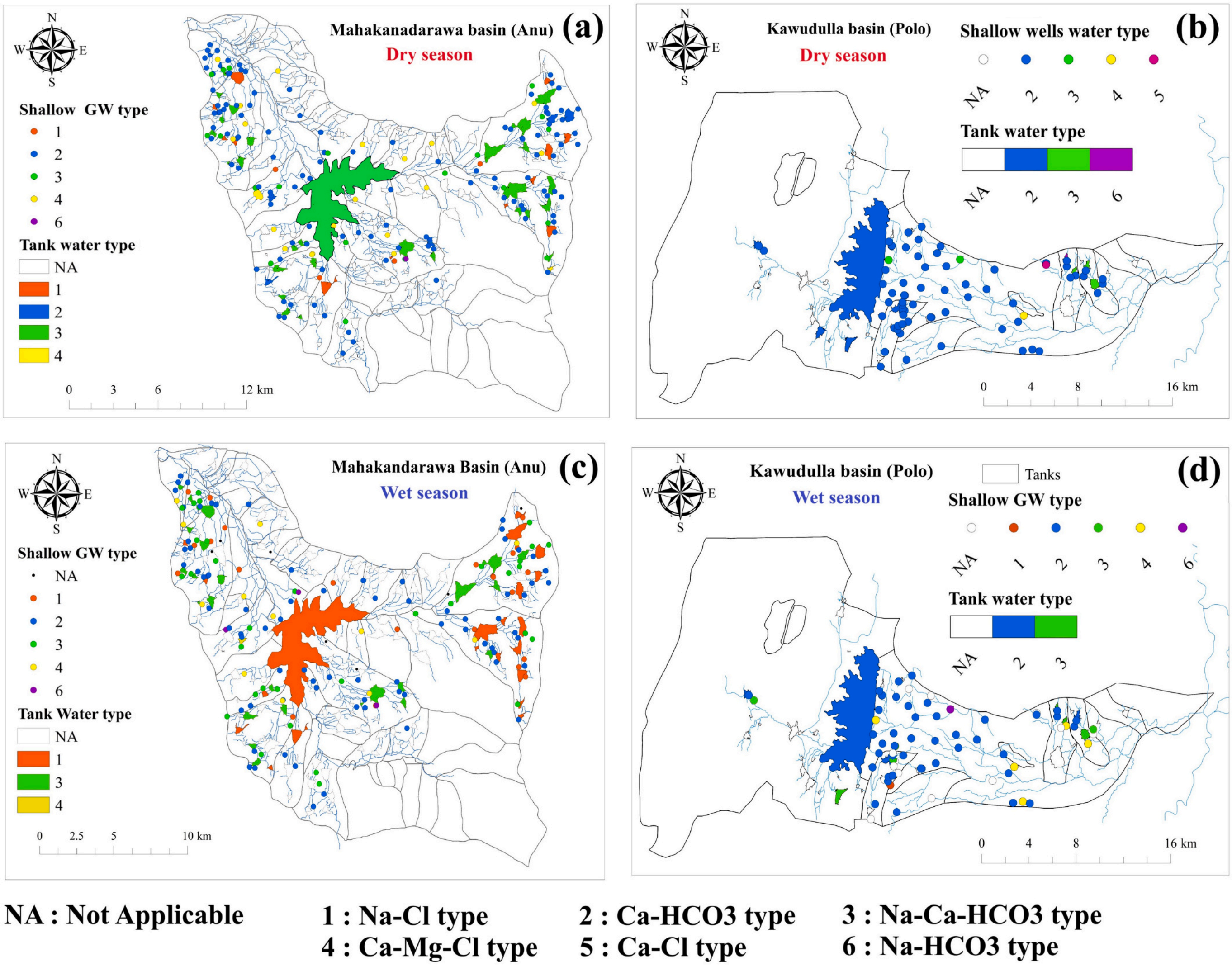

Fig. 2. Spatial variations of hydro-chemical types of groundwater and surface waters in the MK and the KW basins in Dry and Wet seasons.

correlating with regional groundwater, with Na-Ca-HCO_3 as the common water type (Fig. 2a). Notably, some tanks (7 village tanks) in the upper sections of the several cascade systems maintain pure Ca-HCO_3 type water due to minimal cascading effects and direct feeding by surface runoff and shallow groundwater from forestry catchment areas.

In the KW basin's middle stream, it is dominated by Ca-HCO_3-type shallow groundwater (>79 %: Wet and >94 %: Dry), and seasonal hydrochemistry variation is negligible due to increased rock-water interactions and calcite dissolution (Fig. 2b, d). Tanks located farther (Aluthwewa cascade: East) from the KW main tank, display Na-Ca-HCO_3 type, while upstream tanks remain Ca-HCO_3 dominant, indicating the influence of surface water runoff, groundwater flow, and ion exchange processes in saturated sediments.

The above results highlight differences in hydro-chemical behaviors in regions with and without TCSs. TCS regions exhibit Na-Ca-HCO_3-type groundwater, especially in the wet season, emphasizing continuous local groundwater flows. In contrast, regions without TCSs predominantly have Ca-HCO_3 groundwaters, suggesting the dominance of regional groundwater flow.

3.2. Stable isotopic signature of natural waters

In this study, significant spatial variations of stable isotopes in the natural waters were observed in both MK and KW basins due to the spatial deviations in hydrological, geological and lithological settings (Fig. S2c, d).

3.2.1. Tank water

Isotopically enriched tank water dominates the MK basin in the dry season (Figs. 3a and 4a, b) (δ^2H ‰: (−11.2) – (+7.9); δ^{18}O ‰: (−1.9) – (+2.3)) due to the high evaporation rates which is confirmed by their existence along the local evaporation line (LEL) in the dual isotope chart (Fig. 3a) while relatively lower enrichment in the KW basin (δ^2H ‰ < −26; δ^{18}O ‰ < −4) (Fig. 3b). However, rainwater runoff in the wet season (November – February), makes tank water highly depleted in both study areas (δ^2H ‰ < −16.6; δ^{18}O ‰ < −2) (Fig. 4d, e), revealing a higher seasonal effect on tank water compared to the deep and shallow groundwaters (Fig. 3e, f).

3.2.2. Shallow groundwater

In the MK basin, most of these shallow regolith aquifers have originated around village tanks (Panabokke, 2007). As shown in Fig. 3a, c, in both dry and wet seasons, 58 % and 45 % of the shallow groundwater in the MK basin aligns with the LEL, suggesting influence from either evaporated tank water or direct soil layer evaporation. The remaining samples trace the local meteoric water line (LMWL), signifying direct infiltration of rainwater runoff (Fig. 3a, c). Following the infiltration of predominantly depleted rainwater, stability persists unless mixed with

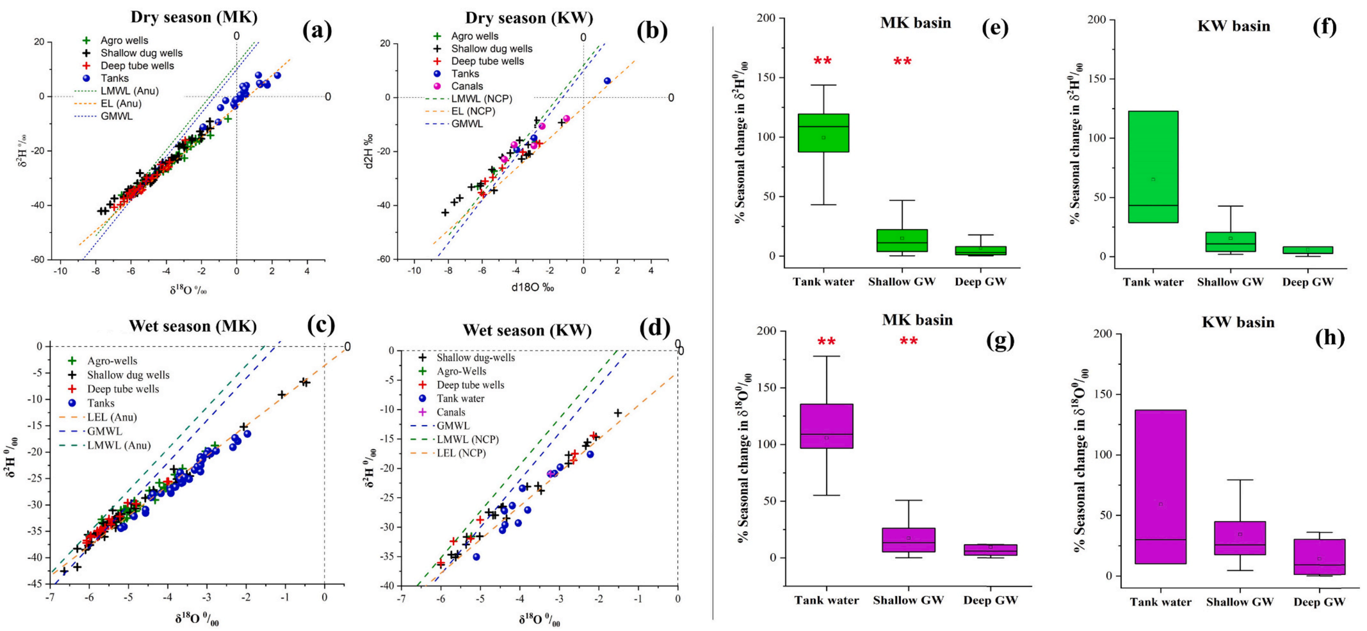

Fig. 3. Dual stable isotope diagrams of natural water bodies in (a, c) MK, (b, d) KW basins and their seasonal change (%) in stable isotopes, (e, f) δ^2H ‰ and (g, h) δ^{18}O ‰.

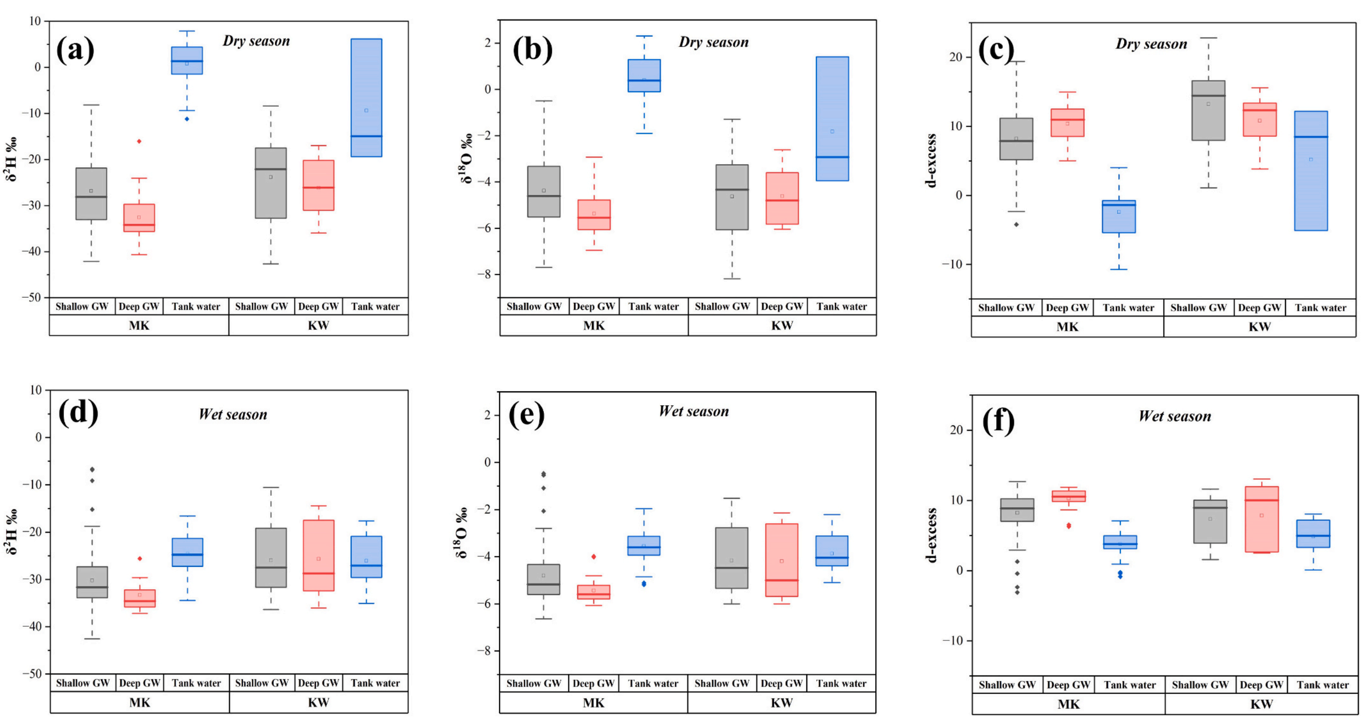

Fig. 4. Comparison of stable isotope signature of natural waters in different seasons (Dry and Wet) and different basins (MK and KW); (a, d) δ^2H ‰, (b, e) δ^{18}O ‰, and (c, f) d-excess.

other water sources or subjected to geochemical reactions like mineral hydration. (Clark, 2015; Li et al., 2022). During the dry season, the shallow groundwater level demonstrated a moderate negative correlation ($r = -0.52$ and $r = -0.51$; $p < 0.01$) with stable isotope ratios. Consequently, even in the dry season, the deepest level exhibits the most depleted isotopic compositions in shallow groundwater (Fig. S3). Refer to Section S1 for additional details on seasonal water table changes.

KW basin which does not have many TCSs, showed clear hydrological divisions along the basin as Region 1: GW mostly fed by the main KW tank, Region 2: middle section of the basin which is fed by both groundwater flow from Region 1 and from regional highland, and Region 3: located further away from KW tank and consist of a shallow TCS (Fig. 1b and see Section S2 for further information). Each region has a different isotopic nature in shallow groundwater. However, stable isotope compositions in the whole basin ranged from δ^2H ‰: (−36.4) – (−10.6) and from δ^{18}O ‰: (−6) – (−1.5) at the end of the wet season and from δ^2H ‰: (−42.6) – (−8.6) and δ^{18}O ‰: (−8.2) – (−1.3) in the dry season (Fig. 3b, d). The apparent isotopic changes due to the seasonality were negligible. However, the dual isotope chart (Fig. 3b, d) showed that 72 % (Dry) and 52 % (Wet) of shallow groundwater followed the LMWL and the rest of them followed the LEL respectively. Groundwater in the KW basin showed a comparatively higher evaporated nature, and more information is described in Section 4.1.3.

3.2.3. Deep groundwater

In the MK basin, higher spatial variation of stable isotopes in deep groundwaters was observed. Approximately 63 % and 90 % of samples align with the LMWL during dry and wet seasons, respectively (Fig. 3a, c). This is an indication of precipitation runoff as the primary recharge source. Conversely, 37 % and 10 % follow the LEL, revealing the hydraulic connection between some of the deep fractured aquifers and regional village tanks. The lowest stable isotope ratios (δ^2H ‰ < -36; δ^{18}O ‰ < -5.9) were found in upper and high-elevation (>100 m) regions, suggesting depleted rainwater recharge (Fig. 5e, f). Significant enrichment was observed downstream and near embankment dams, indicating connectivity between tank water and deep aquifers. Hence, tube wells near dams could be recharged by evaporated tank water in the dry season (Fig. 5e, f). The Mahakirindegama cascade region (Cascade 3) shows the most depleted deep groundwater (Fig. 5e, f), potentially recharged by rainfall or surface water from nearby tanks. Confined aquifers in fractured bedrock regions exhibit lower seasonal changes in stable isotopes, indicating a slower response to seasonal events. Shallow aquifers, connected to surface water sources, show medium sensitivity to recharge, evaporation, and anthropogenic contaminations (Fig. 3e, f).

In the KW basin, deep wells (No 162 and 159) adjacent to the KW main tank exhibit groundwater with stable isotope ratios (δ^2H ‰ > -17.5, δ^{18}O ‰ > -2.6) closely resembling wet season tank water (δ^2H ‰ ≈ -20.4, δ^{18}O ‰ ≈ -3.1). This suggests that they are recharged by tank water, stored during the wet season. The higher water level in the KW tank creates a hydraulic head driving deep groundwater recharge. Vertical groundwater movement generated by tank water seepage could be significant near large-scale tanks (Djuma et al., 2017; Trček and Mesarec, 2023). Similar to the MK basin, the rest of the deep groundwater samples follow the LMWL and show depleted compositions (δ^2H ‰ < -28, δ^{18}O ‰ < -5), indicating rainfall as the main recharge source during the wet season (Fig. 3b, d). This highlights the primary sources of the deep groundwaters as the precipitation and larger and deeper water reservoirs, while shallow GW is mainly recharged by TCSs.

3.2.4. d-Excess values

The d-excess results reveal that all the water bodies in both basins have the same initial water source which is from the northeast monsoon (NEM) and 2nd inter-monsoonal (2nd IM) precipitation in the NCP (Fig. S4). Tank waters have been subjected to the evapo-concentration effect, especially in the dry season (Fig. S4a, b). Most of the deep groundwaters have the most depleted water which was directly recharged by NEM and 2nd IM rainfall which was revealed by having d-excess values similar to the rainwater. Having comparatively lower d-excess values in shallow groundwater which is the result of a reduction of δ^2H, relative to the usual values that match with the regional δ^{18}O, indicates the mineral dissolution process under the lack of groundwater and or Transpiration process within the tree-covered landscapes. Shallow groundwater showed a mixed nature of Surface water and Rain water which indicate the higher interactions and Mixing processes. Mineral dissolution (Rock water interactions) in Shallow GW was higher in the dry season compared to the wet season, especially in cascades 1 and 3 in the MK basin.

Mineral dissolution (Rock water interactions) in Shallow GW was higher in the KW basin compared to the MK basin (Fig. S4b, d). The highest effect (Lowest d-excess) was recorded from the Aluthwewa cascade (>14 km east from the KW tank). Deep GW near KW tank bund had a similar d–excess to KW tank water which reflected the evapo-concentration effect before it recharged. This confirms that the deep fractured aquifer just adjacent to the tank bund recharges by KW Tank. The middle section (3.5 km–14 km) of the KW basin which is having relatively higher d-excess values: Dry season shallow groundwater is received from the Northern base flow, and the wet season is fed by evaporated groundwater flow from the land below the KW main tank (see Section S2).

3.2.5. Statistical analysis of isotopic signature

As shown in Section S3, ANOVA and Tukey tests show significant seasonal differences ($p < 0.05$) in mean values of δ^2H and δ^{18}O compositions of shallow groundwaters and tank water within the MK basin. In contrast, deep groundwater stable isotopes exhibit nonsignificant mean differences ($p \gg 0.05$) in both the MK basin and KW basin. KW basin, lacking many TCSs, reports no significant seasonal difference ($p > 0.05$) in shallow groundwater. Within MK, no significant differences in shallow groundwater isotopes are observed between cascades or basin sections, except between cascades 5–1 and 5–3 in the dry season. Upstream-downstream differences in the MK basin are significant only in the dry season. Tank waters show no significant differences ($p > 0.05$) between cascades and basin sections (Up, middle and down streams). Despite nonsignificant ANOVA results, Tukey comparisons reveal significant differences ($p < 0.05$) in deep groundwaters between downstream (cascade 5) and middle-stream (cascade 3 and 4) in both seasons. KW basin displays three distinct regions with significantly different ($p < 0.05$) isotopic compositions, but overall seasonal differences in shallow groundwater isotopes are insignificant ($p > 0.05$). The presence or absence of TCSs emerges as a pivotal factor influencing regional water dynamics.

PCA results reveal a negative correlation between the depth to the shallow groundwater table and stable isotope composition in both basins (Fig. S5a, b), indicating depleted levels at lower depths in the dry season. Dissolved mineral levels (EC) show no clear relationship with stable isotopes, indicating independence from regional contaminants. While the MK basin exhibits a negative relationship between elevation and stable isotopes in the shallow GW, the KW basin shows no such correlation (Fig. S5a, b). Cluster plots based on isotope compositions and seasonal changes in shallow groundwater indicate spatial deviations in the KW basin's hydrology, contrasting with the MK basin's cascade regions that lack clear isotopic signature deviations (Fig. S5c, d). This suggests that regions without TCSs (KW basin) experience regional deviations in groundwater hydrology. The presence of TCSs in the MK basin regularizes the regional groundwater system, maintaining spatially homogeneous hydrological patterns.

In the wet season, higher elevation tanks display enriched stable isotopes, positively correlated with elevation and negatively correlated with d-excess (Fig. S5e). Conversely, dry-season tank water shows no significant elevation correlation. The negative correlation of EC with elevation indicates increased mineral content downstream. Higher elevations experience dilution in tank water during the wet season. Deep groundwater exhibits a strong negative correlation between elevation and stable isotopes, signifying depletion in high elevations, possibly recharged by precipitation from mountain areas and independent of dissolved mineral content (EC) (Fig. S5f).

4. Discussions

4.1. Isotopic interpretation of SW-GW interactions

4.1.1. Stable isotope mass balance model for mixing water bodies

Stable isotope compositions of the natural waters can be used to estimate fractions of source water (tank water and surrounding groundwater) that have been mixed during the flow of the groundwater by a two-component mixing model derived based on the simple mass balance equations for deuterium (δ^2H ‰) and oxygen-18 (δ^{18}O ‰) in the water (Clark, 2015).

Results revealed that the fraction of tank water (f_T) mixed into the

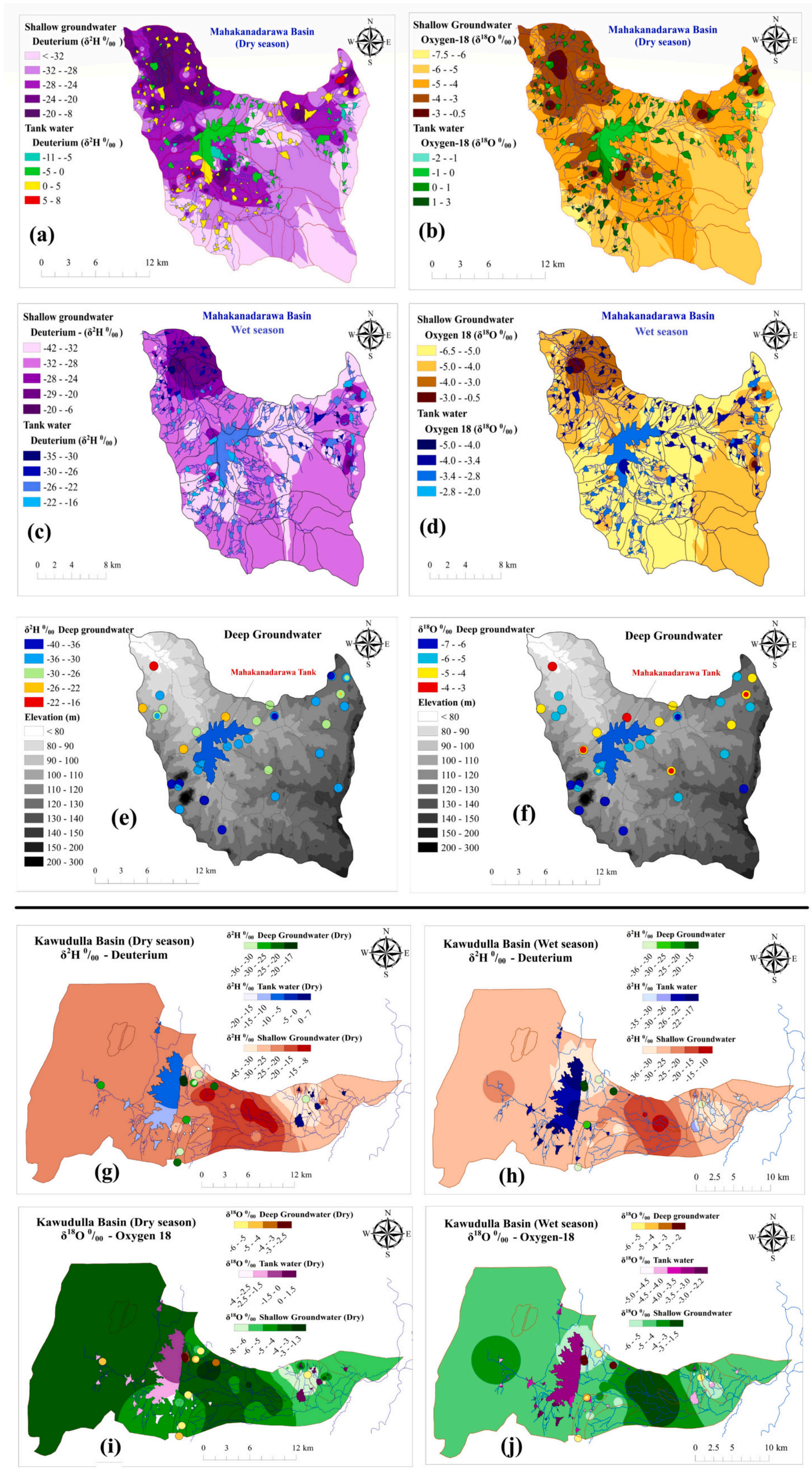

Fig. 5. Spatial variation of stable isotope ratios in natural waters in the MK (a-f) and KW (g-j) basins within dry and wet seasons.

flowing groundwater from the catchment ranged from 0.9 % to 77.8 % depending on the different locations of the basin (Table 1). This huge variation of interactions could be due to the deviation of geo-hydrological and climatic settings throughout the basin. Due to the higher tank water levels and continuous water table within the wet season, a comparatively higher level (>39.9 %) of tank water discharge on the shallow groundwater was observed. In this season, downstream cascades showed the highest tank water influence (53.9 %) on the groundwater. This might be attributed to the presence of a highly permeable soil layer in the region and the alluvial sediments that can hold much groundwater which are not dominant upstream. Hence, groundwater in the downstream cascades showed a higher possibility of anthropogenic contamination like agricultural runoff, especially in the wet season.

Shallow groundwater in downstream cascades minimally interacts (1 %) with tank waters in the dry season, possibly due to aquifer-tank disconnection, aligning with correlation analysis compared to interactions (>28 %) in the upper-end tanks of upstream and middle-stream cascades (Section 4.1.2, Table 1). During the dry season, tank water interactions were minimal (<24.7 %) in intermediate tanks of upstream and middle stream cascades, intensifying in the wet season. Similarly, in the dry season, lower tanks in most TCSs exhibited the highest tank water mixing with groundwater, while in the wet season, middle and upper tanks showed the highest mixing.

4.1.2. Cascade-wise assessment of interactions between SW and GW

For the investigation of the SW-GW interactions in the MK basin using stable isotopes, three major TCSs were selected based on their location as represent the upstream, middle-stream and downstream compared to the location of the main reservoir (MK Tank) in the MK basin.

1. Upstream Cascades (Cascade 1: Kokmaduwa cascade)

In this TCS, over 16 operational village tanks provide year-round irrigation to paddy fields (Fig. 1a). Located at a significantly higher elevation in the basin, it receives the most depleted rainfall runoff during the monsoon. In the dry season, elevated level of stable isotopes in the shallow groundwater under the two upper tanks (Kahatagasdigiliya tank and Kokmaduwa tank) and one lower tank (Ranpathwila tank) of the basin was observed. This could be due to the higher evaporation rates in the dry season (Fig. 6a, b, c).

Fig. S6a, b, c, d illustrates interpolated shallow groundwater isotope ratios correlated with tank water. Strong positive correlations (Pearson correlation) were found in both dry (δ^2H ‰: $r = +0.68$; δ^{18}O ‰: $r = +0.78$) and wet seasons (δ^2H ‰: $r = +0.70$; δ^{18}O ‰: $r = +0.71$). The noted interaction underscores a substantial hydraulic connection between tank water and shallow groundwater in regolith aquifers year-round (refer to Section S4.1 for further insights into isotopic characteristics in this cascade).

2. Middile stream cascades (Cascade 3: Mahakirindegama cascade)

Mahakirindegama cascade is located adjacent to the Mahakanadarawa Tank with operational 14 village tanks. (See Section S4.2 in Supporting information for more basic isotopic analysis).

Correlation analysis of the isotopes in the shallow groundwater and the tank water in this region showed a significant negative correlation in both Deuterium and Oxygen-18 (δ^2H ‰: $r = -0.66$; δ^{18}O ‰: $r = -0.63$) (Fig. S6e, f). This negative correlation was stronger in the wet season (δ^2H ‰: $r = -0.99$; δ^{18}O ‰: $r = -0.95$) (Fig. S6g, h). This trend was the opposite in the upstream tank cascades (Cascade 1). Upper region groundwater may lack hydrological connection to nearby tanks due to the shallow soil layer and discrete water table. Hence, higher tank water enrichment doesn't impact depleted dry-season groundwater (Fig. 6g, h). In the lower section of the cascade, groundwaters were notably enriched, likely due to interaction and mixing processes with a continuous groundwater table connected to the MK tank water body. Long-term siltation and infrequent de-siltation have significantly reduced the capacity of upper-end tanks, leading to higher evaporation rates and enriched tank waters in the dry season.

3. Downstream cascades (Cascade 5: Nikawewa cascade)

The basin's lowest elevation, coupled with a gentle slope, results in slower water drainage. Over 60 % of the cascade's middle section comprises undulating Reddish brown earth, known for higher water-holding capacity. (Moorman and Panabokke, 1961). The lower section of the cascade features alluvial sediment-based soil and an aquifer from the Lower Weli Oya floodplain. In contrast, the uppermost section, with a shallow soil layer on a quartz-rich rock knob plain, may have lower availability of shallow groundwater.

Higher stable isotope ratios (δ^2H ‰ > 2; δ^{18}O ‰ > 0.5) in upper-end tanks result from increased evaporation due to lower tank capacity and shallowness (Fig. 6a, b). Highly permeable, shallow soil layer (Moorman and Panabokke, 1961; Panabokke, 2000) contributes to reduced upper tank capacity, weakening groundwater recharge and causing a drastic water table drop (Fig. 6m, n). In the dry season, the lack of groundwater discharge into the upper-end tanks raises their stable isotope levels.

Lower-end tanks exhibited depleted isotopes, indicating groundwater discharge even in the dry season (Fig. 6m, n). Positioned in the lower valley, these tanks benefit from higher groundwater availability due to their position in the lower valley and the alluvial aquifer region with high water-holding capacity. This results in significant interconnectivity between tanks and the shallow groundwater as well as elevated groundwater table. This mixing phenomenon is further

Table 1
Results from the mass balance calculations of stable isotope in the TCS region of the MK basin.

Zone	Cascade	Section of the Cascade	Wet season			Dry season			Seasonal change in (f_T)%
			GW fraction (f_g)%	Tank water fraction (f_T)%	Tank water fraction (Whole Cascade) %	GW fraction (f_g)%	Tank water fraction (f_T)%	Tank water fraction (Whole Cascade) %	
Up-stream	Cascade 1	Down	78.4	21.6	48.2	68.0	32.0	25.6	+10.5
		Middle	43.4	56.6		75.3	24.7		−31.9
		Upper	55.4	44.6		71.5	28.5		−16.1
	Cascade 2	Down	35.0	65.0	39.9				
		Middle	57.6	42.4					
		Upper	75.2	24.8					
Middle-stream	Cascade 3	Down	72.0	28.0		49.8	50.2		+22.2
		Middle	68.3	31.7	44.7	89.8	10.2	33.4	−21.6
		Upper	25.7	74.3		59.1	40.9		−33.4
Down-stream	Cascade 5	Down	81.5	18.5		58.3	41.7		+23.2
		Middle	32.5	67.5	53.9	61.9	38.1	30.1	−29.4
		Upper	48.6	51.4		99.1	0.9		−50.5

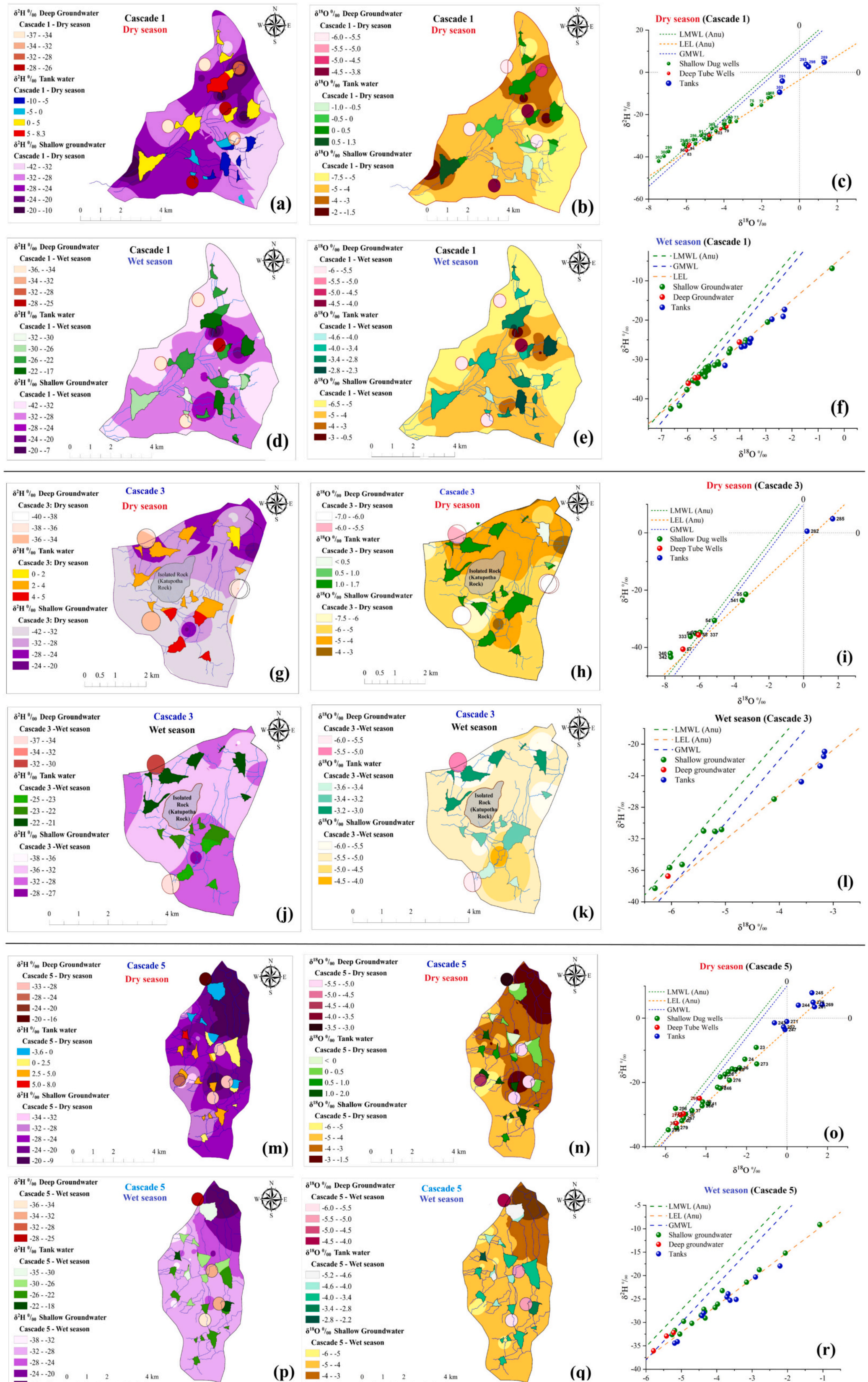

Fig. 6. Spatial variations of stable isotopic ratios of the natural waters in Cascade 1 (a, b, d, e), Casade 3 (g, h, j, k) and Cascade 5 (m, n, p, q) in Dry and wet seasons with Dual isotope charts (c, f, i, l, o, r).

confirmed by having enriched shallow groundwater which is closely similar to tank water compositions in the lower region (δ^2H ‰ > −20; δ^{18}O ‰ > −2) compared to the upper areas (δ^2H ‰ < −28; δ^{18}O ‰ < −4) (Fig. 6m, n) in the dry season. (See Section S4.3 in Supporting information for more basic isotopic analysis).

4.1.3. Groundwater dynamics in regions without TCSs (KW basin)

Based on the spatial and seasonal deviations of stable isotopes, groundwater flow and geology deviations, three distinct regions (Region 1, Region 2, and Region 3) could be identified within the KW basin (Fig. 1d and Section S2.2).

In Region 1, TCSs are rare, except for the Diwulankadawala cascade in the southern basin. During the dry season, shallow groundwater in this area exhibits significantly higher isotope ratios (δ^2H > −25; δ^{18}O > −5) than Region 3 due to distinct recharge sources. Shallow groundwaters are significantly aligned with the LEL, highlighting the increased evaporation effect which indicates the major recharge source is the KW main tank (δ^2H ‰ > −8; δ^{18}O ‰ > −1) (Fig. S7a). However, in the wet season, these groundwaters lie on the LMWL while showing a reduction in isotopic ratios (δ^2H ‰ < −27; δ^{18}O ‰ < −4.5) which also coincide with the isotopic depletion of water in KW tank in the wet season (δ^2H ‰ < −19; δ^{18}O ‰ < −3; Fig. 5g, i). Hence, the KW tank seems to be the primary recharge source of groundwater in this section and a direct hydrologic connection between shallow groundwater and the KW tank is clear. Depletion within the wet season could also be a result of the direct infiltration of rainwater.

In Region 2, the shallow groundwater line shifts left from the LMWL, indicating notable rock-water interaction in the dry season (Fig. S7b). Dissolution of regional silicate minerals during groundwater infiltration, particularly quartz, biotite, and feldspars, has significantly impacted groundwater chemistry (Cooray et al., 2019b; Indika et al., 2023). This region also lacks permanent surface water bodies like village tanks. During the wet season, shallow groundwater isotopic ratios align with the LEL, with significant enrichment (δ^2H > −20; δ^{18}O > −3) (Fig. S7c). This indicates persistent groundwater flow, which is exerted by rising KW tank water level and the groundwater table from Region 1 to Region 2. Enriched groundwater stored in Region 1 during the dry season, moves down words in the wet season (Section S2), giving enriched isotope nature to shallow groundwater in Region 2. This is a sign of comparatively lower percolation rates of rainwater compared to tank water seepage rates into the regional water table.

Region 3 which consists of a shallow TCS (Aluthwewa cascade), exhibits the most depleted stable isotope ratios within the basin (δ^{18}O ‰: <−5; δ^2H ‰: <−25) in shallow groundwater in both wet and dry seasons, suggesting recent precipitation recharge (Fig. 5h, j). The dry season sees a lower slope (6.02 ± 0.27) in the groundwater line than LMWL (~7.9), indicating increased evaporation due to higher ambient temperatures (Fig. S7b). In the wet season, slight isotopic changes in Region 3 are observed, with all samples along the LMWL (Fig. S7c). The natural drainage system in this region is governed by the ephemeral streams which originate from a natural reservation forest area (Palliyagodella) located in the north. The shallow aquifer system around these cascade systems is primarily sourced from surface runoff originating from the Palliyagodella forest area. This runoff carries isotopically depleted rainwater. During the dry season, most tanks in this cascade reach their lowest water levels, and some upstream tanks dry out. Consequently, the remaining tanks (202, 215) exhibit highly enriched surface water with stable isotopes (δ^{18}O ‰: >+1; δ^2H ‰: >+5) due to substantial evaporation rates in this region (Fig. S7a). Siltation and neglect caused decreased dry season water storage in tanks, risking total abandonment of these TCSs within a few years.

4.2. SW-GW interactions based on chloride

The Chloride in the tank waters and surrounding shallow groundwater in TCSs were compared by linear regression lines and correlation analysis to identify the hydraulic and hydro-chemical interactions between them (Fig. 7).

4.2.1. Upstream cascades (Cascade 1, 2 and 8)

According to the stable isotope analysis (Sections 4.1 and 4.2), TCSs in the upstream region of the MK basin have considerably higher interactions between tank water and shallow groundwaters.

Cascade 1 (Kokmaduwa cascade) showed a positive moderate correlation of chlorides ($r = +0.65$) between the tank water and shallow groundwater in the dry season following almost close to the 1:1 line (Fig. 7a). This revealed that in the dry season, all the tanks and regional groundwaters undergo exchange processes (GW recharge and discharge). However, in the wet season, only upper-end tanks follow the 1:1 line, revealing their higher interactions with shallow groundwater due to the higher permeability of the regolith materials and infiltration of agricultural contaminants like chlorides (Fig. 7b). Thus, natural water bodies in the upper section of the cascade respond quickly to anthropogenic pollution reflecting the higher permeability of the regional thin soil layer with high proposition quartz on rock knob plain (Moorman and Panabokke, 1961; Panabokke, 2000).

In Cascade 2 (Ellewewa cascade) higher positive correlation between chlorides in tank waters and shallow groundwater was observed in both wet and dry seasons (wet: $r = +0.93$ and dry: $r = +0.81$) (Fig. 7c, d). The deviation of the regression line from the 1:1 line in the wet season indicates the comparatively high enrichment of chlorides in shallow groundwater. This could be due to the leached chlorides from the excess fertilizers which are trapped in the soil layers during the dry season, dissolves in the percolating rainwater and increases the groundwater chlorides (Indika et al., 2023). However, waters in the upper-end tanks are located in the 1:1 line in both seasons which reveals the higher permeability of the regolith layer in the upper season of the cascade. Hence, this is an indication of the higher buffering capacity of chloride contamination in larger reservoirs. Thus, tanks with larger surface areas have the capability of resisting agrochemicals that come through groundwater flow and surface runoff. But, smaller tanks always reflect the groundwater characteristics of the region and the impact from the agricultural practices is higher.

Cascade 8 (Weruppankulama) is located just above the Mahakandarawa tank. In the dry season, shallow groundwater and tank waters show almost similar chloride levels indicating the tank's water is mostly sustained by the discharged groundwater flow from the upper section of the cascade in the dry season (Fig. 7e). However, in the wet season tanks' waters become diluted and shallow groundwater becomes enriched in chlorides (Fig. 7f). It is clear that chloride in the whole water system originated in the wet season and enriched the shallow groundwater first. But in the dry season, chloride in the groundwater has diffused into the tank's water body due to the regular mixing processes while reducing the gap between concentrations in the tanks and shallow groundwater. The average value of chlorides in tanks and shallow groundwater in the wet season is similar to that of both water bodies in the dry season.

4.2.2. Middle stream cascades (Cascade 3)

Cascade 3 (Mahakirindegama cascade) is located in the south direction of the MK tank and tanks are positioned around an isolated mountain with rock outcrops called Katupothakanda Rock (Fig. 6). Thus, the source water of this cascade mainly originates from the monsoonal precipitation received by this elevated mountain landscape which is almost covered by a forest reserve.

In the dry season, tank water in this cascade does not show any clear correlation with the groundwater (Fig. 7g). However, in the wet season, the majority of the tanks and groundwaters nearly follow the 1:1 line indicating the mixing processes between tank and groundwater (Fig. 7h). This could be due to the groundwater table continuing after the wet season and functioning as a single system. However, the tank located at the lowermost end has always deviated from the 1:1 line

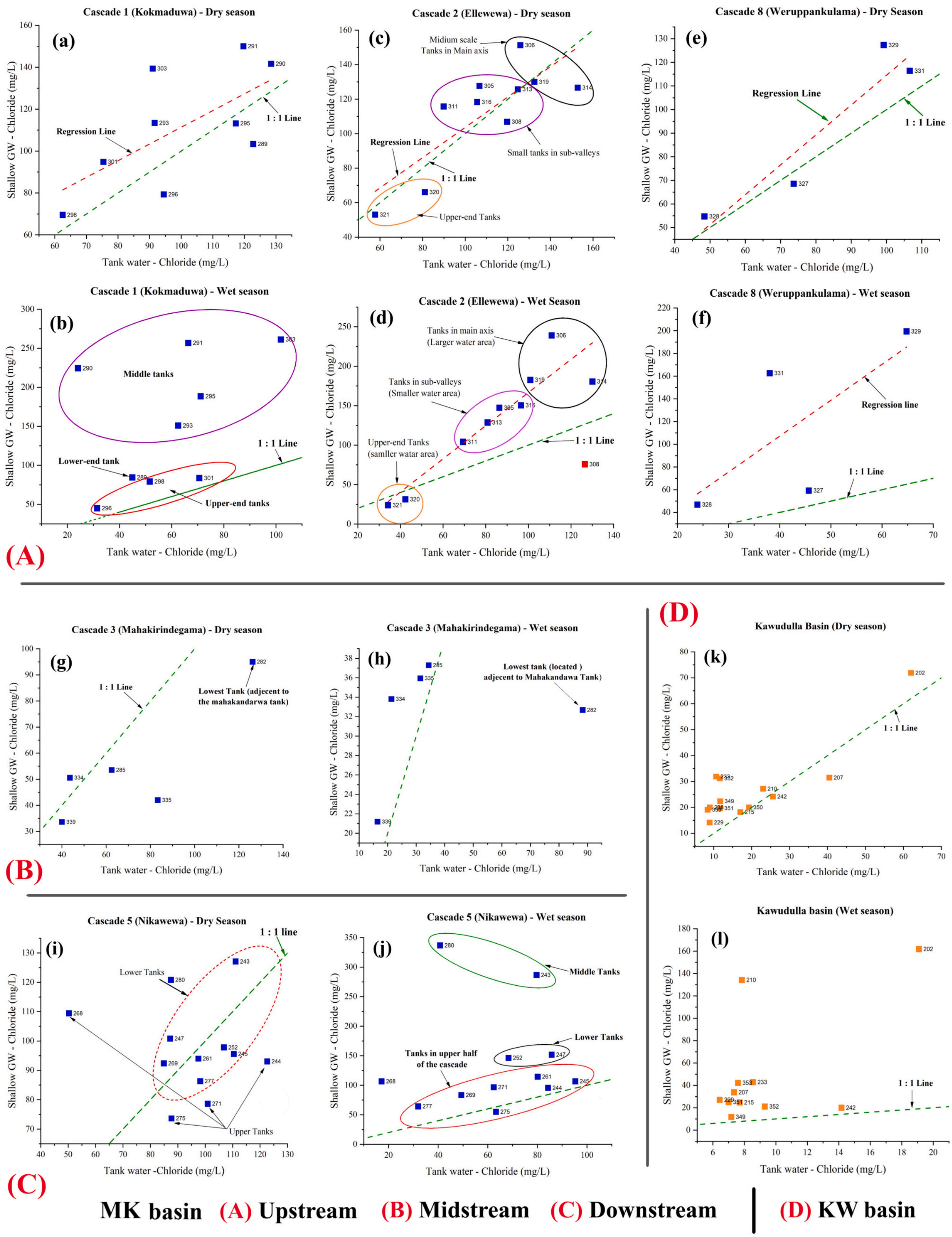

Fig. 7. Comparison of chloride levels in tanks and regional groundwaters in different cascade systems in the upstream of Mahakandarawa basin.

having a relatively higher chloride concentration (126 mg/L) in the tank water. During the dry season, shallow groundwater chloride levels in the lowest cascade section, are directly linked to the MK tank (Cl^-: 89–96 mg/L). Negligible groundwater flow was observed from the upper landscape. However, in the wet season, groundwater becomes more diluted than in the MK tank which could be due to the higher and diluted GW flow from the upper section. Thus, GW flow becomes spatially interconnected during the wet season. However, these lower tanks maintain higher chloride levels (88 mg/L) in the wet season as well. This could be due to the chlorides leached from inorganic fertilizers used in paddy lands in the upper and middle sections of the cascade.

4.2.3. Downstream cascades (Nikawewa cascade, Cascade 5)

Cascade systems located in the lower section of the basin show different degrees of interactions between water bodies in different seasons. In the dry season, the lower half of the cascade shows higher correction between tank waters and the shallow groundwater (Fig. 7i), which could be due to the higher availability of groundwater in the dry season in this lower section (Section S1). In the dry season, upper tanks are less connected to shallow groundwater due to a significantly lower surrounding water table. However, in the wet season (Section S1), a higher water table enables continuous interaction between tanks and groundwater, in the upper half (Fig. 7j). Then, tank waters become slightly diluted in chloride level, while shallow groundwater in the middle section reaches 275–350 mg/L (dry season: 120–130 mg/L), likely due to agricultural runoff percolation in extensive paddy lands.

4.2.4. Regions without TCSs (KW basin)

Dry season chloride levels align with a 1:1 line, indicating positive interaction between surface water bodies (tanks) (Fig. 7k). The main KW tank exhibits minimal seasonal chloride variation (dry: 11.6 mg/L; wet: 7.8 mg/L), likely attributed to its primary water source – diverted water from the Mahaveli River. However, below the KW tank, chloride is slightly lower in the wet season (10–25 mg/L) than in the dry season (20–35 mg/L). Hence, the KW tank water dominates in the regional shallow groundwater compared to the impact of fertilizer contamination.

A southward cascade from the KW tank sees a slight wet season increase in groundwater chloride (Fig. 7l). Another cascade (Aluth wewa) 14 km east exhibits elevated groundwater chloride levels (>130 mg/L) in the lower region but lower in the upper section (<45 mg/L) (Fig. S8b, d). Tank water chloride levels are comparatively lower than shallow groundwater. Therefore, regions with smaller tanks cannot effectively mitigate agricultural input effects like chlorides in shallow groundwater. The tank scale determines its buffering capacity for anthropogenic contamination in regional shallow groundwaters.

Chloride tracing in the KW basin reveals the same results from the isotope analysis. Below the KW tank, groundwater has the most diluted chloride concentrations (<20 mg/L) in both seasons due to tank seepage (Fig. S8b, d). Near the end of Region 1, closer to the underground geological rock barrier, chloride accumulates in groundwater due to dry season no-flow conditions across the geological belt separating Region 1 and Region 2 (Fig. 1d). In the wet season, the rise in groundwater level and active flow from Region 1 to Region 2 dilute shallow groundwaters at the edge of Region 1. The lower sections of Region 2 and Aluth Wewa cascade are greatly affected by chlorides (>120 mg/L), possibly from agricultural or paddy lands along the KW Oya floodplain (Fig. S8d). However, the lower section of the KW Oya floodplain has lower chloride levels (<60 mg/L) in both seasons. This aligns with isotope and water table analysis, indicating the presence of a large-scale alluvial aquifer system that can buffer anthropogenic contamination.

Chloride tracing results reveal that extensive use of inorganic fertilizer significantly alters shallow groundwater chemistry compared to tank waters (Indika et al., 2023). Excess fertilizers trapped in the lower soil profile during the dry season are more likely to dissolve in percolating rainwater runoff through agricultural lands, paddy fields, and rain-fed Chena land than surface runoff contaminants into the tanks in both basins.

4.3. Vulnerability and stability of the shallow groundwater bodies in the dry zone

Seasonal change in stable isotopes indicates groundwater stability and the scale of the water body. Regions with minimum variation suggest higher buffering capacity against isotope addition or removal. This signals larger, deeper, and more stable groundwater bodies, less vulnerable to external factors and anthropogenic pollution. This study identifies areas with minimal seasonal isotopic variation in groundwater within the study regions. (Fig. 8a, b).

Seasonal isotopic ratio changes in the MK basin highlight five regions with stable groundwater bodies, suggesting significant water storage (Fig. 8a, b). Region 1, the lower reach of Cascade 5, boasts stable, larger, or deeper shallow groundwater, supported by minimal water table changes (Fig. 8c). This region, rich in alluvial sediments, is less vulnerable to water quality deterioration, signifying substantial groundwater storage. Region 2, below the MK tank with vast rice fields, exhibits strong connectivity between tank water and shallow groundwater, ensuring stability against isotope and mineral changes (Fig. 8a, b). Minimal seasonal water table change (<1.25 m) confirms extensive groundwater supplied by tank water seepage, providing stable, safe drinking water unaffected by seasonal variations or pollution. Region 3 uppermost section of cascade 5, shows minimal isotopic changes, hinting at a larger but relatively deeply positioned shallow aquifer (Fig. 8a, b) which is confirmed by the significant drop of groundwater table (>3 m change) within the dry season. Even though, Region 4 experiences minimal isotopic changes, significant groundwater table depletion in the dry season (Fig. 8c) due to a thinner regolith layer and poor connectivity between shallow groundwater and tank water indicate the less capacity of the shallow aquifers. The dominant transpiration process from the forest cover reduces the seasonal changes in isotope composition in shallow groundwaters. In Region 5, located in the upstream cascades, minimal seasonal isotopic and water table changes are the results of the continuous groundwater flow maintained by the TCSs. However, the upper section of cascade 1 faces groundwater table depletion, signalling vulnerability to external factors.

In the downstream KW basin, three regions (A, B, C) with minimal seasonal water table changes are identified. Region A, below the KW tank, maintains a stable water table (<1 m) throughout the year due to tank seepage flow, influencing groundwater quality. However, regions farther away exhibit isotopic variations due to intense rock-water interactions. The presence of Village Tank Cascade Systems proves advantageous in minimizing geogenic contaminants in shallow groundwater.

4.4. Challenges and recommendations

Major challenges identified in these VTCSs are natural and anthropogenic water quality degradation, lower capacity of upper-end tanks, depletion of groundwater bodies in the upper section of the cascades, drastic seasonality in the GW table, insufficient maintenance of these TCSs, and abandonment of village tanks.

This study revealed the drastic hydro-chemical changes in tank water and shallow groundwater in the wet season due to the extensive agricultural practices, especially in the upper section of the cascades. A higher level of Chloride enrichment was observed in both shallow groundwater and tank waters. However, ancient water systems aren't designed for modern-scale fertilizer usage. Thus, it's important to implement advanced intermediate processes for recycling agricultural runoff and sediments such as wetland systems. Restoring the ancient "Thaulla" component which has been mostly destroyed by human encroachment is essential (Mahatantila et al., 2008). Promoting organic farming and developing sediment management technologies based on

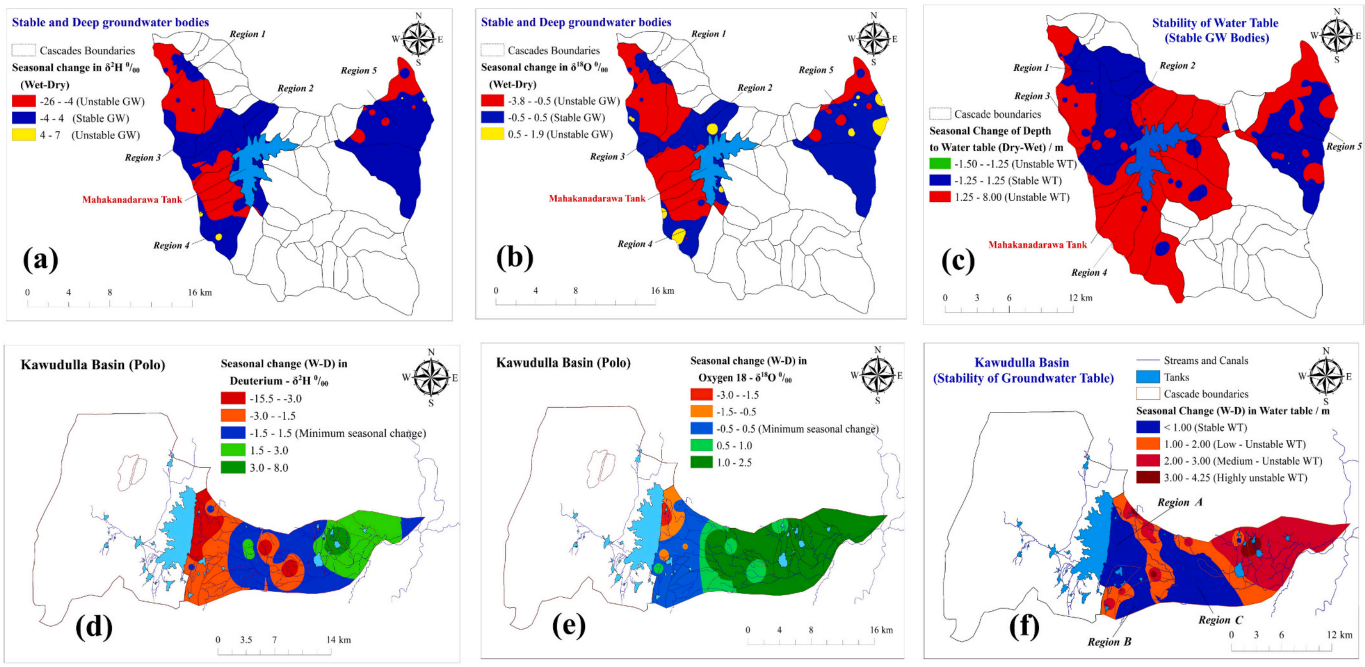

Fig. 8. Identified stable and large groundwater bodies in the MK and KW basins based on the seasonal change in (a) (d) Deuterium, (b) (e) ^{18}O, and (c) (f) Shallow GW table.

ancient TCS-related knowledge, such as using tank sediments as fertilizers, is crucial. Reintroducing the ancient "Mada sorowwa (Mud sluice)" component to release sediment during dry seasons can be beneficial. (Dharmasena, 2020, 1992, 1991).

The connectivity problem between tank water and shallow groundwater in the shallow soil regions was observed in this study. This problem leads to the depletion of the water table during the dry season, reducing the accessibility of safe drinking water sources to the community. Capacity reduction of upper tanks in TCSs due to the heavy siltation as the major reason for the reduction of interactions and recharge events of these groundwater bodies. Thus, policies should be established for the restoration of the groundwater table, enhancing the capacity of upper tanks by desiltations processes (Dharmasena, 2023, 2020; Sakthivadivel et al., 1997, 1996), restoring ancient Kulu Wewa tanks which could function as silts traps, protection of catchment areas, mitigation of deforestation and encouraging reforestation to improve the stability of irrigation and drinking water supply, as a major step for building a climate resilient water system in these vulnerable regions in Sri Lanka.

5. Conclusions

A dual stable isotope (^{2}H and ^{18}O) combined with the conservative chloride tracer was used in this study to explore the hydrogeochemical interconnections between surface water and groundwater in TCS regions of Sri Lanka. Understanding the interactions is beneficial for building climate resilience water management strategies for vulnerable regions.

This study highlights that water quality (TDS and Cl^-) in natural waters between the two basins was significantly different (ANOVA: $p < 0.05$) in both seasons. Differences in dominant hydro-chemical species in natural waters between the two basins reconfirm the significant differences. Statistically uniform dissolved mineral content in tanks and shallow groundwater in the MK basin contrasted with significant regional deviation in the KW basin. However, anthropogenic chloride, leached from excess inorganic fertilizer, poses a significant threat to changing the hydrochemistry of waters, particularly in upper-end tanks of many cascades and their surrounding groundwaters within the wet season.

Dual isotopic and chloride tracing results from this study reveal that TCSs (MK basin) sustain continuous groundwater flow with minimum seasonality, and the absence of village tanks (KW basin) results in significant deviations in groundwater flow. Thus, the presence or absence of TCSs emerges as a pivotal factor influencing regional water dynamics. ANOVA and Tukey tests showed significant seasonal differences ($p < 0.05$) in mean values of δ^2H and δ^{18}O compositions of shallow groundwaters and tank water within the MK basin, while non-significance in the KW basin. Isotopic mass balance calculations revealed that tank water mixing (f_T) in the shallow groundwater was considerable and ranged from 0.9 % to 77.8 % across the MK basin depending on the regional soil characteristics.

Lack of tank-aquifer interconnection in the shallow soil in rock knob plain causes groundwater depletion as well as a drastic drop in tank water level in the dry season. Enhanced interconnections within alluvial sediment regions result in stable and pollution-resistant shallow groundwater bodies. Regions proximal to large-scale water reservoirs (MK and KW main tanks) maintain an isotopically and hydrologically stable water table, emphasizing their resilience against pollution events.

The consistency of the groundwater flow system in TCS regions throughout the year ensures a stable water supply, highlighting the vital role of TCSs in the protection of regional groundwater in these arid regions. These findings shed insights for policymakers and water managers to implement effective conservation strategies for rehabilitation and restoring these ancient TCSs targeting the climate-resilient water management system for Sri Lanka.

CRediT authorship contribution statement

Suresh Indika: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dazhou Hu:** Investigation, Data curation. **Yuansong Wei:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Isuru Yapabandara:** Investigation. **Samadhi Athauda:** Investigation. **Ashen Randika:** Investigation. **Sangeeth Prasad:** Investigation. **Titus Cooray:** Resources, Investigation. **Madhubhashini Makehelwala:** Resources. **Hui Zhong:** Resources, Project administration. **Yawei Wang:** Resources, Project administration. **K.B.S.N. Jinadasa:** Validation. **Sujithra K. Weragoda:** Resources. **Rohan Weerasooriya:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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