Aquifer Segmentation as a Tool for Sustainable Drinking Water Supply and Reverse-Osmosis Waste Management in the Dry Zone of Sri Lanka's North Central Province

Inoka M. S. Peiris[2]*, Tom Brikowski[1]

[1]Department of Geosciences, The University of Texas at Dallas, 800 W. Campbell Rd., Richardson, TX75080-3021, USA

[2]Faculty of Computing and Technology, University of Kelaniya, Kelaniya, Sri Lanka

***Corresponding Author**

DOI: https://doi.org/10.51584/IJRIAS.2026.11013SP0035

Received: 16 September 2026; Accepted: 21 September 2026; Published: 09 October 2026

ABSTRACT

Rural communities in Sri Lanka's North Central Province (NCP) Dry Zone face a drinking water security problem with two linked dimensions: physical scarcity, driven by low rainfall, high evapotranspiration and near total dependence on a thin, fractured bedrock aquifer; and poor water quality, with widespread hardness and elevated fluoride closely associated with an epidemic of Chronic Kidney Disease of unknown etiology (CKDu). The principal response over the last two to three decades has been the installation of several hundred small, community operated reverse osmosis (RO) treatment stations. These stations reliably remove hardness, salinity and fluoride from feed groundwater, but recover only 19–50% of the water they treat, and a large majority discharge their concentrated reject brine directly onto open soil, creating a second, comparatively unstudied threat to shallow groundwater and soil quality. This study asks whether subsurface structural information makes both problems more tractable. We monitored water chemistry at nine tube wells, one hand dug well and one seasonal tank in the Rambewa and Medawachchiya divisional secretariat divisions over approximately two years (July 2016–February 2018), and constructed a three dimensional groundwater flow model from 384 well logs. Piper diagram classification identified two distinct hydrochemical facies within close proximity: a dilute, meteoric Ca-Mg-HCO_3 facies at two locations and a more evolved, higher TDS Na-HCO_3 facies elsewhere, with no evidence of mixing during the study period. Cross sections through the flow model show a bedrock topographic high coincident with the facies boundary, consistent with compartmentalisation of the aquifer into discrete isolated segments rather than a single well-mixed system. Groundwater model is presented as a supporting hydrogeological interpretation rather than as quantitative proof of hydraulic separation. We propose that mapping this kind of segmentation at the scale of individual RO stations offers two low-cost management tools: siting supply wells within lower TDS compartments to reduce the volume of brine generated, and directing that brine toward already higher TDS, isolated compartments. Both proposals require on site testing: including a site specific risk assessment of the proposed disposal compartment before either is adopted operationally.

Keywords: aquifer segmentation; groundwater quality; reverse osmosis reject water; Dry Zone of Sri Lanka; chronic kidney disease of unknown etiology

INTRODUCTION

Groundwater is the primary drinking water source for roughly half of the world's population, and an estimated four billion people already experience severe water scarcity for at least one month each year [17]. Sri Lanka'sDry Zone covering roughly two thirds of the island and including the North Central Province (Fig. 1) is a regional example of this global pattern: low and highly seasonal precipitation combined with high year-round evapotranspiration severely limits the availability of surface water (yellow area, Fig. 1), so that rural

communities depend almost entirely on shallow regolith and deeper fractured bedrock groundwater for domestic supply [11, 18]. This physical scarcity is compounded by a water quality problem: Dry Zone groundwater is frequently hard and elevated in fluoride and other major ion constituents as a result of long residence times and water rock interaction with the underlying crystalline basement, so much of the region's available groundwater is unpalatable or unsuitable for drinking without treatment [5, 11].

The clearest public health consequence of this water quality problem is Chronic Kidney Disease of unknown etiology (CKDu), a distinct clinical entity [25] that has killed an estimated 20,000 rural Dry Zone residents over the last two decades [24] and remains the leading cause of hospital death in the NCP. A registry based analysis of 30,566 CKD/CKDu patients diagnosed at eleven North Central Province hospitals between 2003 and 2017 confirms that the disease burden has continued to rise, with roughly one in four registered patients dying and more than two thirds of those deaths occurring within three years of diagnosis [21]. Household survey based estimates across the ten most affected districts similarly confirm a strong association between historical reliance on groundwater and CKD prevalence [14].

Since the emergence of CKDu in the 1990s, no single causative factor has been identified [20], but primary environmental contributors are believed to be dissolved components in groundwater [24]; two literature reviews synthesizing the CKDu literature conclude that fluoride, magnesium dominated hardness and other major ion constituents are consistently implicated, though no single geochemical factor fully explains the disease's distribution [8, 15]. CKDu's etiology remains unresolved; it is, however, a consequence of a broader and betterdefined problem, namely the scarcity and variable quality of drinking water available to Dry Zone communities.

The dominant policy and community response to this water quality problem over roughly the last two to three decades has been the rapid, largely uncoordinated deployment of small scale, low pressure reverse osmosis (RO) treatment stations across the NCP: several hundred community based organisation (CBO), Sri Lankan Navy, government and privately operated units are now in service, treating raw groundwater to remove excess hardness, salinity and fluoride before distribution as drinking water [10, 11]. Evaluations of operating RO stations confirm that they are effective at this core task: essentially all sampled RO permeate met national and WHO drinking water guideline values for the constituents evaluated, even where feed groundwater badly exceeded them [5, 9, 10], and RO deployment has been associated with subsequent declines in newly diagnosed CKD/CKDu cases in some areas [1]. Community based RO treatment is therefore best understood as a genuine, if partial and interim, solution to the region's drinking water quality problem.

That solution, however, has created a second and comparatively unstudied environmental problem. Because feed groundwater in the NCP is unusually mineralised, RO systems here typically recover only 19–50% of the water fed into them as usable permeate, rejecting the remainder as a concentrated brine loaded with the same hardness, salinity and fluoride removed from the product water [9, 10]. Surveys of station operators report that the majority of this reject water on the order of 80% of stations surveyed in one study is discharged directly onto open ground with no treatment, in part because no regulatory framework or disposal guidance has been established for CBO scale RO systems [10].

Field studies at several NCP and Northern Province sites document the resulting impact: elevated Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and F^{-}in soils at reject water disposal points relative to nearby reference soils [13], and comparable water quality and environmental impact concerns at reject disposal sites specifically within the Medawachchiya divisional secretariat area studied here [19]. Proposed remedies constructed wetlands, irrigation reuse or engineered infiltration have so far been tested only at pilot scale [22], and none directly addresses the underlying siting question of where, hydrogeologically, reject water can safely be released. A treatment technology deployed specifically to protect drinking water quality is thus, at many sites, discharging a comparably mineral rich waste stream back onto the land surface immediately above the same shallow aquifer system.

Locating the least mineralised groundwater for direct or lightly treated supply, and safely disposing of RO reject brine, can be treated as structural, hydrogeological problems as much as water treatment problems, and

both could benefit from knowledge of aquifer segmentation, that is, the boundaries between distinct compartments of the fractured bedrock aquifer. Locally heterogeneous water quality over short distances is well documented in the NCP: an epidemiological study of CKDu distribution reported low disease prevalence in villages using natural springs alongside high prevalence in neighbouring villages relying on shallow dug wells

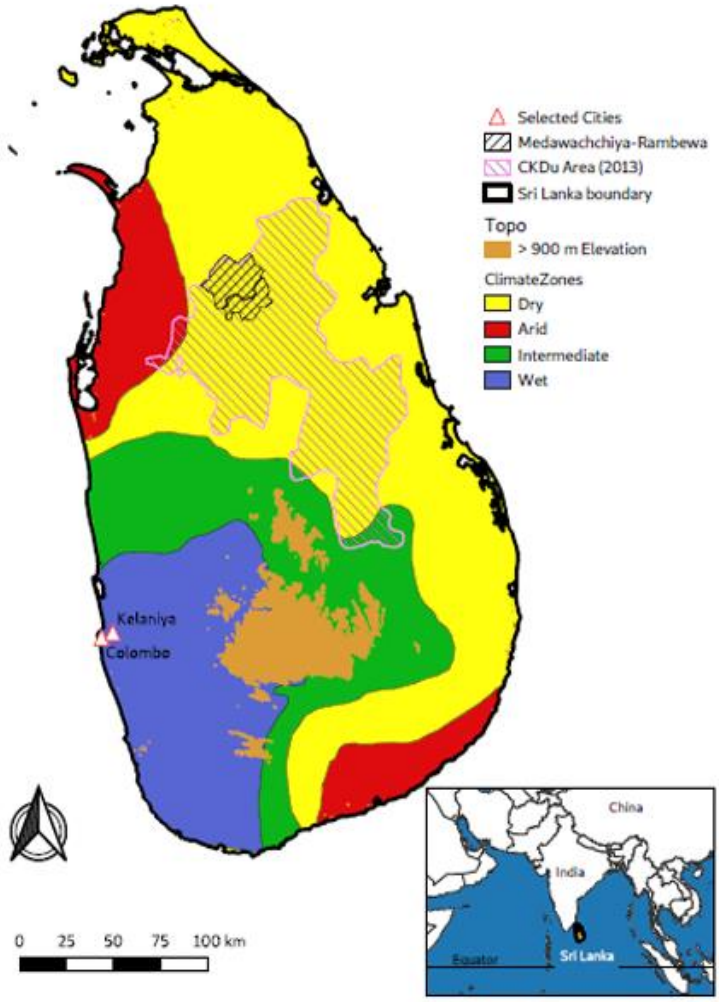


Figure 1: Study area within the North Central Province of Sri Lanka.

(Fig. 2, after Jayasekara et al. [12]), and site specific hydrogeochemical studies at other Dry Zone locations including household wells in the neighbouring Medawachchiya area [16] and the Ginnoruwa region [2] report comparably sharp local contrasts in groundwater facies. A 2025 systematic review of food and water quality studies in CKDu affected areas similarly concludes that nephrotoxic heavy metals and fluoride contamination remain the most consistently implicated water quality risk factors, while emphasising that the evidence base remains heterogeneous across studies and sampling designs [23]. This heterogeneity is usually discussed only as a complication for identifying CKDu's cause. If the aquifer beneath a given RO station's service area is segmented into discrete compartments with limited communication, then those compartments can in principle be characterised and put to differential use: better quality compartments prioritised for supply wells, poorer quality or already saline compartments designated to receive reject water disposal after proper site specific evaluations. Results presented below show that the aquifer beneath our study area is segmented, with little or no communication between segments during the two year study period supported by low precipitation and high evapotranspiration, consistent with the fine scale water quality heterogeneity documented in these earlier studies, and directly relevant to both applications proposed: locating the better quality segment(s) for supply, and identifying the isolated, more mineralised segment(s) as candidate reject water disposal zones after proper evaluations.

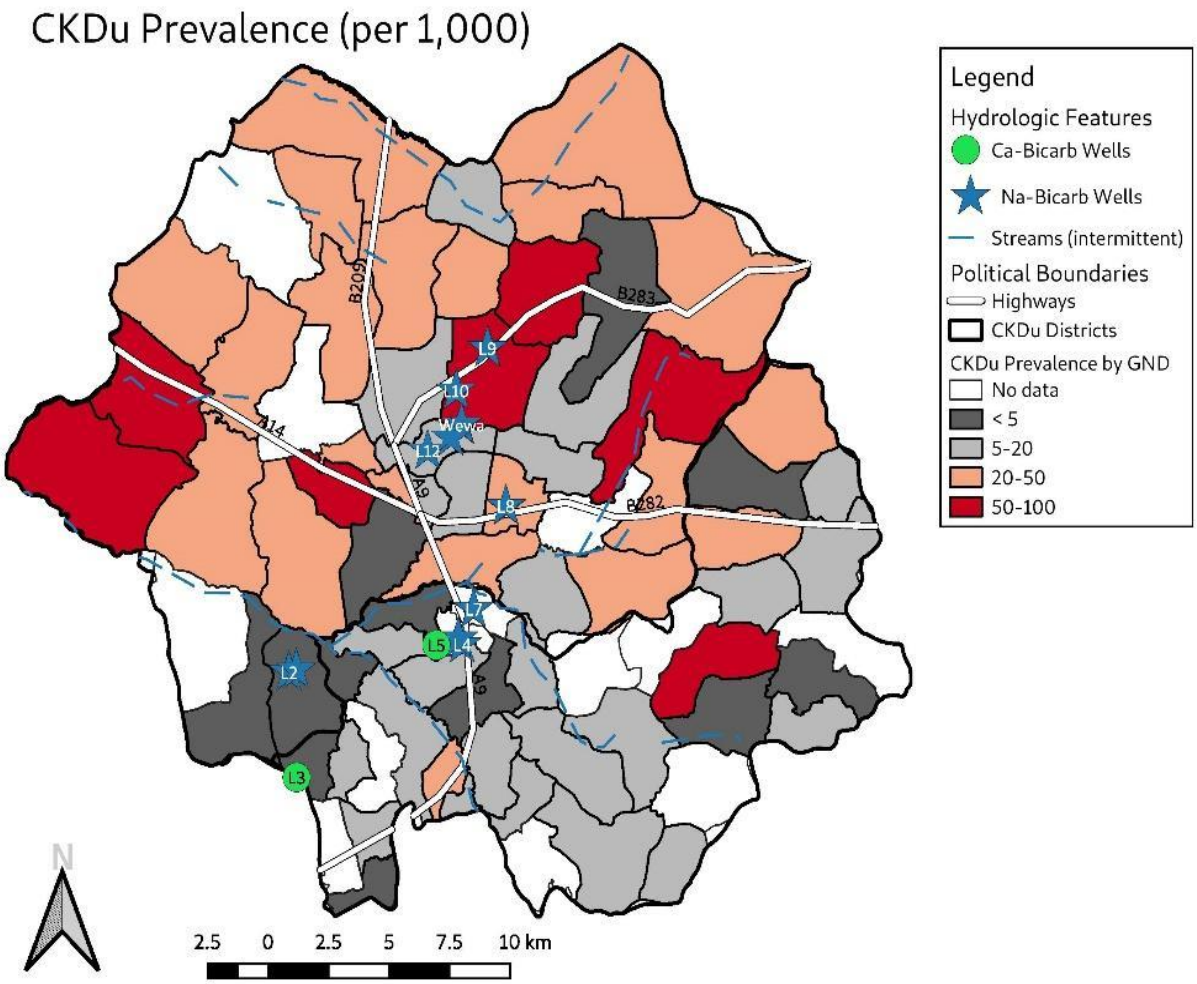


Figure 2. Distribution of incidences of chronic kidney disease of unknown origin in North Central Sri Lanka, used here as a proxy for local groundwater quality variation. Disease prevalence is not homogeneous: some areas of high prevalence lie immediately adjacent to areas where no incidents were reported. Redrawn from Jayasekara et al. [12]

Study Area and Hydrogeological Setting

Bedrock Geology

Aquifers in the Dry Zone are almost exclusively weathered regolith and altered, fractured metamorphic basement rocks; the bedrock is therefore the primary influence on groundwater composition. The Precambrian basement of Sri Lanka consists of three major geological divisions: the Wanni, Highland and Vijayan Complexes [4] and we retain the traditional three-fold nomenclature of Cooray [4] as it remains the terminology in general hydrogeological use for this study region. Under that nomenclature, the study area within the Rambewa and Medawachchiya divisional secretariat divisions lies within the Wanni Complex. The nature and exact position of the contact between the Wanni and Highland Complexes are not well known [4]. Wanni Complex rocks consist of amphibolite to granulite facies high grade metamorphic rocks, primarily charnockite (orthopyroxene rich gneiss), containing isolated elongate bodies of quartzite, granitic gneiss and some carbonate/dolomite. Quartzite commonly forms prominent ridges, while the other lithologies rarely outcrop (Fig. 3). No accessible fresh rock outcrops were found in the study area except one exposed road cut and dry stream bed, where prominent spheroidal weathering was observed. In that outcrop, extensively fractured bedrock was capped by a thin regolith/soil overburden layer, demonstrating the importance of the fractured rock as the primary aquifer.

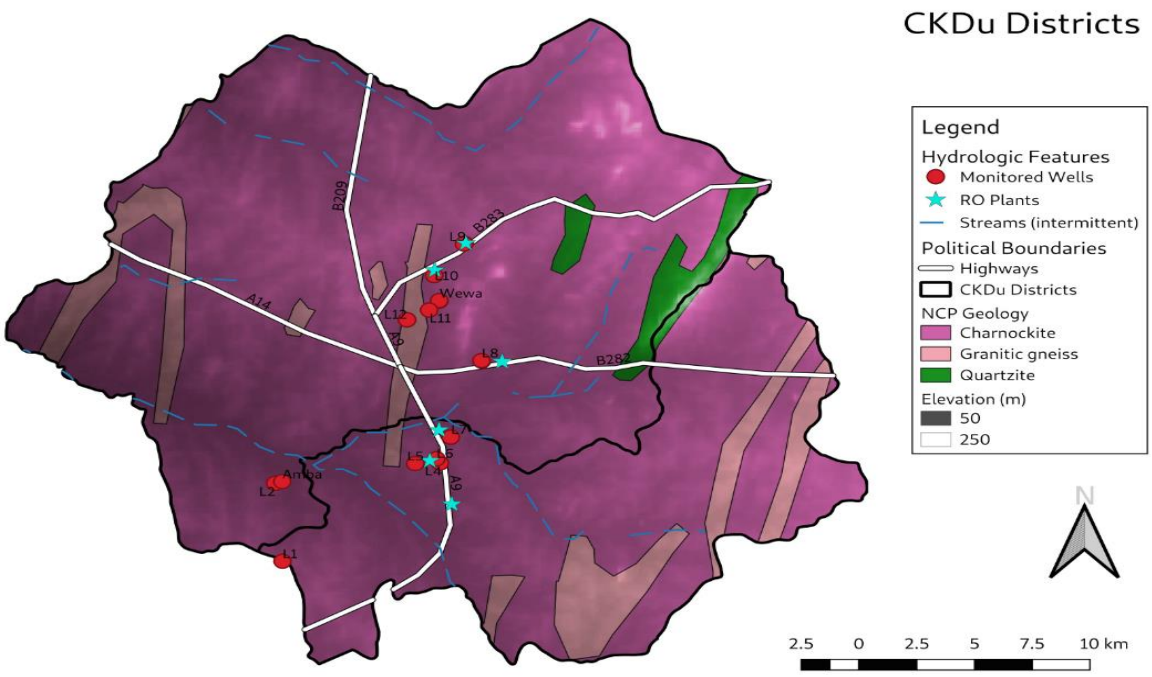


Figure 3. Bedrock geology and sample sites. Geology approximately located from the national geologic map of the International Water Management Institute (IWMI).

Aquifer Structure

Groundwater in the study area occurs both in weathered residual overburden and in fractured bedrock [18]. According to the available literature, shallow regolith aquifers reach a maximum of 10–12 m thickness, and the water table typically lies near the base of the regolith (5–10 m depth). Domestic open dug wells are located within the regolith aquifer. The deep fracture zone aquifer occurs in unweathered rock at depths beyond 30–40 m; the average depth of wells in the deep fracture zone is 40 m [18]. Dissanayake and Chandrajith [6] describe the nature of the aquifer similarly, noting that the high density of the metamorphic rocks causes the aquifer to persist as isolated pockets fed by rainwater infiltrating through cracks and fissures in the hard rock.

Climate and Hydrochemical Controls

Surface processes strongly influence the regolith groundwater. The study area receives close to 1450 mm/year of precipitation, primarily during two monsoon seasons (southwest monsoon, May–September; northeast monsoon, December–February). Monsoonal precipitation is collected and stored in man-made cascade tanks for agricultural purposes. Considering the low rainfall, high evapotranspiration and the nature of the aquifer, the primary hydrochemical controls in the study area are semi-annual fresh monsoon recharge, evaporation during semi-annual extended dry periods, and water rock interaction at depth. Most drinking water in the area is currently extracted from the deeper fractured rock aquifer, suggesting that water rock interaction plays a very important role in drinking water chemistry. Recent reviews conclude that groundwater consumed in CKDu endemic areas is disproportionately shaped by evaporative concentration and water rock interaction relative to non endemic areas [7, 8].

Spatial and temporal groundwater compositional variation occurs for a number of reasons. Important factors controlling groundwater chemistry include the rate of precipitation (which in turn is related to the recharge rate), the chemical composition of recharge water, evapotranspiration, the geology of the aquifer (which controls water rock interaction) and human activities. Groundwater originates as rain and infiltrates through soil overburden into the underlying geologic materials. As groundwater moves from recharge areas to discharge areas through the subsurface, its chemistry is altered by a variety of geochemical processes. According to the

classic hydrochemical evolution model of Chebotarev [3], the chemical relationship of water to rock is determined by several factors, including the type of geological formation, structural features of the area, water temperature, salinity, the abundance of particular ions and compounds in the water, and the volume and velocity of water movement through the system. In general, only a few major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (HCO_3^-, CO_3^{2-}, Cl^-, SO_4^{2-})are considered in determining the major facies or geochemical groups of water. These major elements appear to be the best indicators of groundwater compositional variability in the Dry Zone.

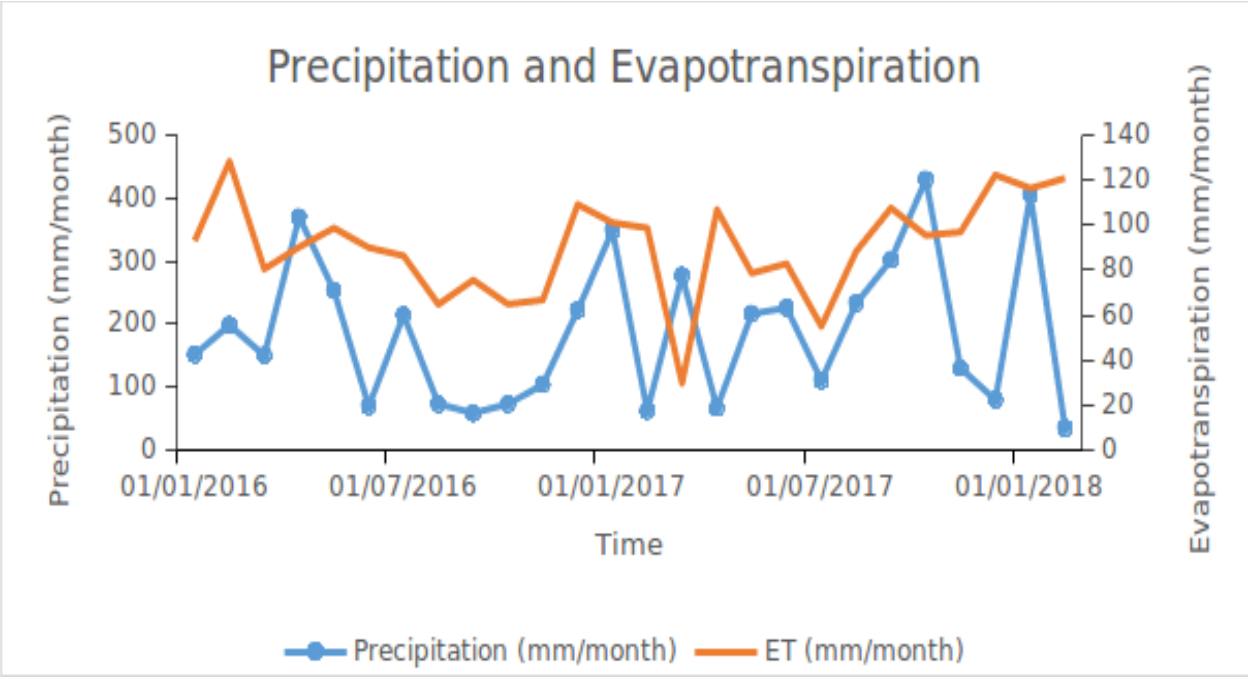


Figure 4: Precipitation and estimated evapotranspiration of the study area during study time period.

METHODOLOGY

Site Selection and Sampling

The selected study area in the NCP includes the region with the highest prevalence of CKDu in Sri Lanka, and more than 360 public groundwater wells were available for sampling. Selection of the study area and of sampling wells was carried out after reviewing the available literature and with the assistance of local government officials. A subset of these wells was selected for regular monitoring over a period of approximately two years. Water samples were collected from nine tube wells, one hand-dug well and one tank during the period July 2016 to February 2018 (Fig. 5), to include an anticipated total of four wet and four dry seasons. The tank dried up during the first dry season (by August 2016) and was only intermittently sampled during the study.

General water-well sampling protocols from the USGS and EPA were followed. For each sampling, the hand pump at the well was operated for a few minutes to purge the well prior to sampling. Field measurements were taken during sampling for pH, temperature, total dissolved solids (TDS), dissolved oxygen, oxidation reduction potential (ORP) and turbidity, using appropriate meters calibrated in the laboratory prior to each field excursion. A field bacteria test was conducted using test strips. Sampling was conducted according to guidelines specified for drinking water sampling for trace metal analysis. Samples were collected in 250 ml high-density polyethylene (HDPE) bottles. New filters and syringes were used for each sample. From each location, one filtered–acidified, one unfiltered–acidified and one unfiltered, non-acidified sample were collected into HDPE bottles. Trace metal grade ultrapure nitric acid was used to acidify samples to pH 2, and a 0.45µm filter was used to filter samples in the field. All samples were stored at 4°C. Field blanks were collected during sampling.

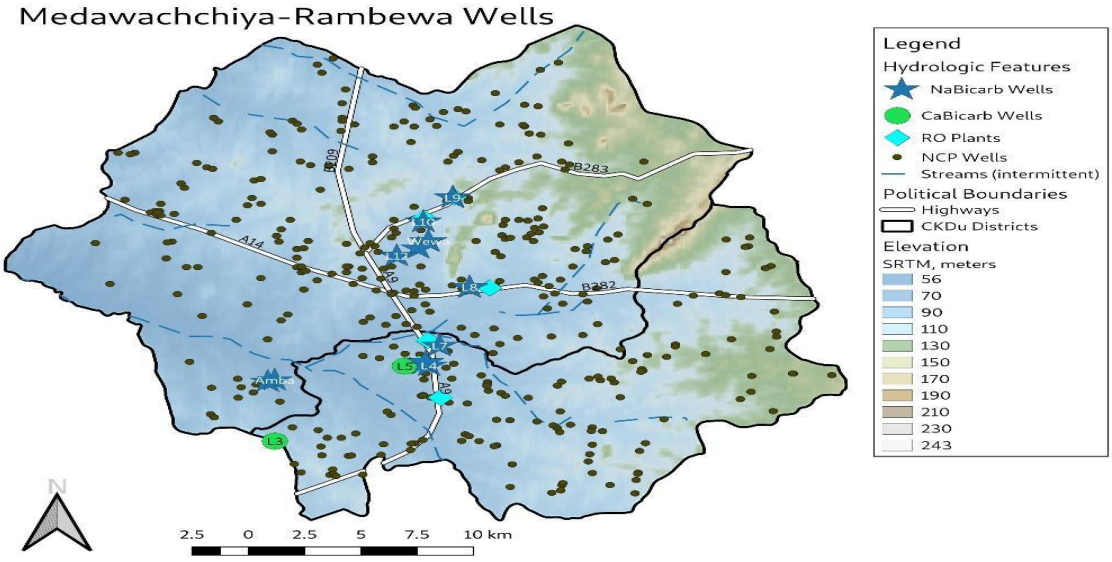


Figure 5. Sampling locations within the Rambewa and Medawachchiya divisional secretariat area, together with the locations of community-based RO stations operating in the same area at the time of sampling.

Analytical Methods

Water analyses were conducted using inductively coupled plasma mass spectrometry (ICP-MS) at the University of Texas at Dallas and Kansas State University, atomic absorption spectrometry (AAS) at the Institute of Chemistry Ceylon, and spectrophotometry and titration for selected species was also conducted. Fluoride concentrations were measured using a Hach high-range fluoride meter. Samples were analysed both undiluted and after 1:100 dilution, owing to the high concentrations of Na and Si. Duplicate sample analyses and laboratory blanks were included to identify any instrumental or procedural errors during analysis.

Groundwater Flow Modelling

A groundwater flow model was developed in GMS 10.1.4 using MODFLOW-2000 with the Layer Property Flow (LPF) package and the Preconditioned Conjugate Gradient (PCG) solver. Tube-well borehole logs for 384 wells from the Rambewa and Medawachchiya divisional secretariats were used to construct the model, with aquifer thickness inferred from these well logs. The model consists of five layers, with 178 rows and 139 columns with approximately 123,710 grid cells. The model uses a steady-state stress period, with time units of days and length units of metres. The grid is spatially variable, with column widths ranging from approximately 32.5 to 293.2 m and row widths ranging from approximately 35.0 to 297.4 m, giving a model domain of approximately 24.38 km × 27.71 km.

Hydraulic conductivity (K) was spatially distributed among the model layers. The model K values range from 0.00864 to 8.64 m/day in Layers 1–4 and 0.000864 m/day in Layer 5 to represent regional groundwater system comprising a relatively permeable upper aquifer (layer 1 to layer 3), an underlying low-permeability confining unit (layer 4), and a deeper very-low-permeability unit (layer 5). These values provide a relatively broad range of hydraulic conductivity and are consistent with representing a heterogeneous subsurface comprising lower-permeability overburden materials together with more permeable zones associated with weathered and/or fractured bedrock. Published groundwater-flow modelling studies likewise use substantially different hydraulic-conductivity values for contrasting unconsolidated materials and fractured or weathered bedrock units.

Recharge was represented spatially in the model, with a recharge value of 0.000678 m/day (approximately 247.5 mm/year) assigned to recharge-active cells and zero recharge assigned elsewhere. Given the seasonal rainfall regime/ low precipitation and high evapotranspiration characteristic of the Sri Lankan Dry Zone, the value is considered a plausible modelling assumption;

Surface-water interaction was represented using the MODFLOW SFR2 package, which contains 380 stream reaches grouped into seven stream segments. An inverse modeling framework was configured in GMS/MODFLOW for parameter estimation. In this study we present the numerical model as supporting hydrogeological interpretation rather than as quantitative proof of hydraulic separation.

RESULTS

The study was originally designed to monitor temporal variability of groundwater chemistry, seeking transient spikes in inorganic nephrotoxins that might explain the general prevalence of CKDu in the Dry Zone. These spikes proved to be minimal, but in the process, very localised spatial variability of groundwater chemistry was revealed that is directly relevant to both drinking-water supply planning and RO reject-water management.

Variation of Total Dissolved Solids (TDS)

TDS variation is one of the best general indicators of evaporation versus fresh recharge effects, and potentially of water–rock interaction. TDS is the sum of the concentrations of inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulfates) and small amounts of organic matter dissolved in water. The United States Environmental Protection Agency (EPA) has established primary and secondary standards for drinking water: primary standards are based on health considerations, and secondary standards on taste, odour, colour, corrosivity, foaming and staining properties. There is no US primary drinking-water standard for TDS; the commonly cited palatability classification treats less than 300 mg/l as good, 300–600 mg/l as fair and 600–900 mg/l as poor. Within our study area, TDS varies strongly both spatially and temporally, ranging between 50 - 1300 mg/l during the sampling period, with a mean of 600 mg/l (Fig. 6).

An evaporative signal is clear in the TDS of tanks and hand-dug wells. Tanks and hand-dug wells are open directly to surface conditions and respond to them quickly. Tanks show extreme variation in TDS, since they dry up completely between monsoons and are refilled by direct runoff of fresh precipitation. Hand-dug wells tend to show high average TDS, varying directly with precipitation. TDS in the hand-dug well varies in synchrony with precipitation and evapotranspiration, indicating a relatively short recharge time. Tube wells tend to show little variation, but two wells in our study show high variability: Locations 3 and 5 show a comparatively wide range in TDS relative to the other locations of the study area.

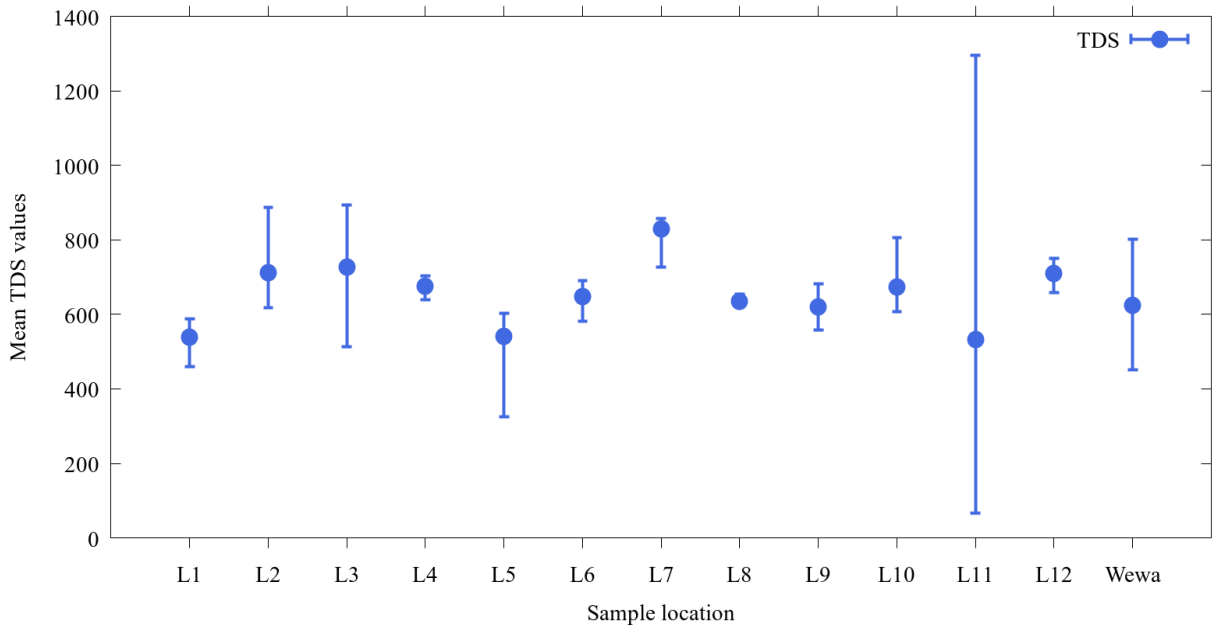


Figure 6. Spatial and temporal variation of TDS. Open water bodies show higher variation in TDS. TDS below 600 mg/l is considered good to fair quality water for consumption

Major Ion Chemistry

Major cations Na^+, K^+, Ca^{2+} and Mg^{2+} and anions SO_4^{2-}, Cl^-, CO_3^{2-} and HCO_3^- can be used to classify water into different facies. Concentrations of these major ions may vary from 1 mg/l to several hundred mg/l. Minor ion concentrations can be close to 1 mg/l, and trace-metal concentrations can be as low as 0.1–0.01 mg/l. Analysis of major cations in the study area shows a high concentration of Na, with a mean of 326.98±357.34 mg/l. Na concentration also shows the highest variation (0.005–2044.226 mg/l) during the study period compared with Mg, Ca and K. No health-based guideline value is recommended for Na by WHO; however, sodium may affect the taste of drinking water at levels above 200 mg/l. Mg concentration varies between 0.02 and 76.08 mg/l, with an average of 27.16±12.87 mg/l. Ca concentration in the study period lies within 0.003–20.981 mg/l, with an average of 11.665±5.134 mg/l. K concentration in the water samples shows the lowest variation, ranging from 0.02 to 50.73 mg/l with an average of 2.005±5.477 mg/l. Average concentrations of the major cations follow the order Na >Mg >Ca >K (Fig. 7). High Na levels in the water can be due to weathering of Na-bearing silicate minerals. The absence of a 1:1 ratio between Na and Cl rules out halite dissolution as an explanation for the high levels of Na in the water samples.

Bicarbonate is the dominant anion in the groundwater within the study area, followed by carbonate, chloride and sulfate respectively (Fig. 8). Excessive concentrations of sulfate and chloride can make water unpleasant to drink. EPA secondary drinking-water regulations recommend a maximum concentration of 250 mg/l for both sulfate and chloride. Sulfate in our samples varies between 1 and 85 mg/l with an average of 23.60±15.89 mg/l, which falls below the recommended limit. Chloride concentration in samples varies between 6.75 and 460 mg/l with an average of 53.016±108.517 mg/l. Chloride levels in the hand-dug well exceeded the secondary limit in September 2016 (370 mg/l), December 2016 (320 mg/l), March 2017 (340 mg/l) and January 2018 (460 mg/l).

Chloride can naturally enter solution through water–rock interaction or through deposition of marine aerosols in precipitation. Natural high spikes of chloride concentration can occur during dry periods, especially when evapotranspiration exceeds precipitation. The high chloride concentration in the September 2016 samples may be due to low precipitation or the prevailing dry climate during that period. Anthropogenic causes such as contamination by sewage or by potassium-based fertiliser can also increase chloride concentration. Since hand-dug wells are shallow, the increased chloride concentration may be due to contamination by fertilizer.

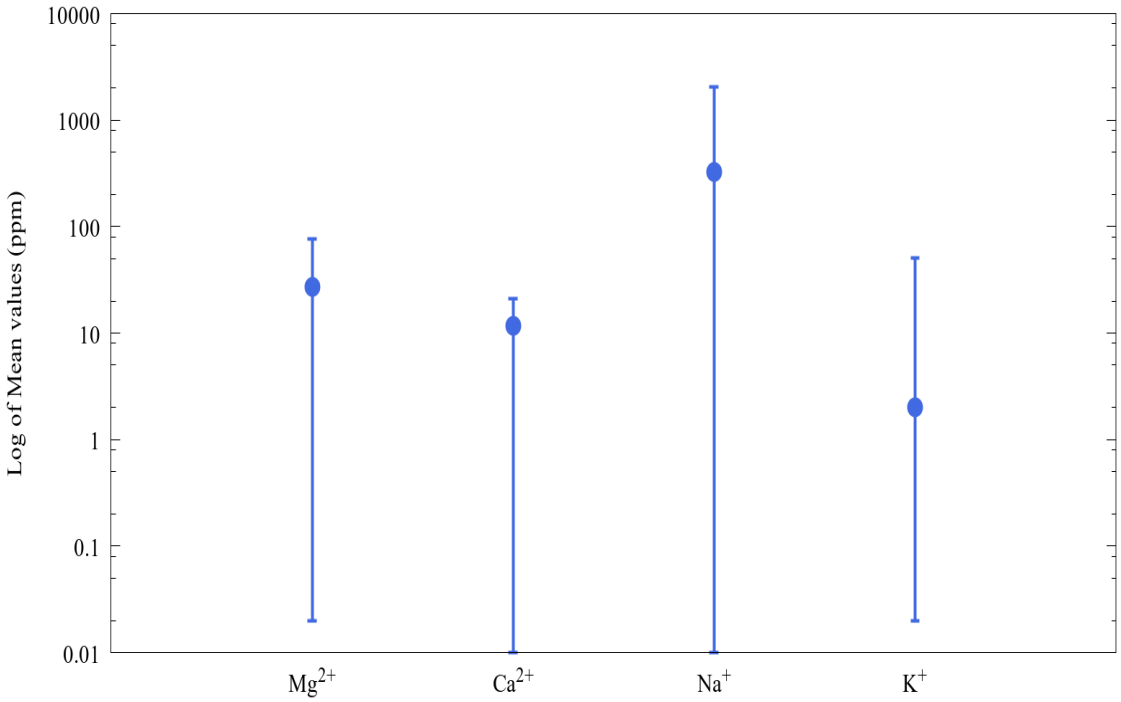


Figure 7. Variation of major cations in the water samples during the study period.

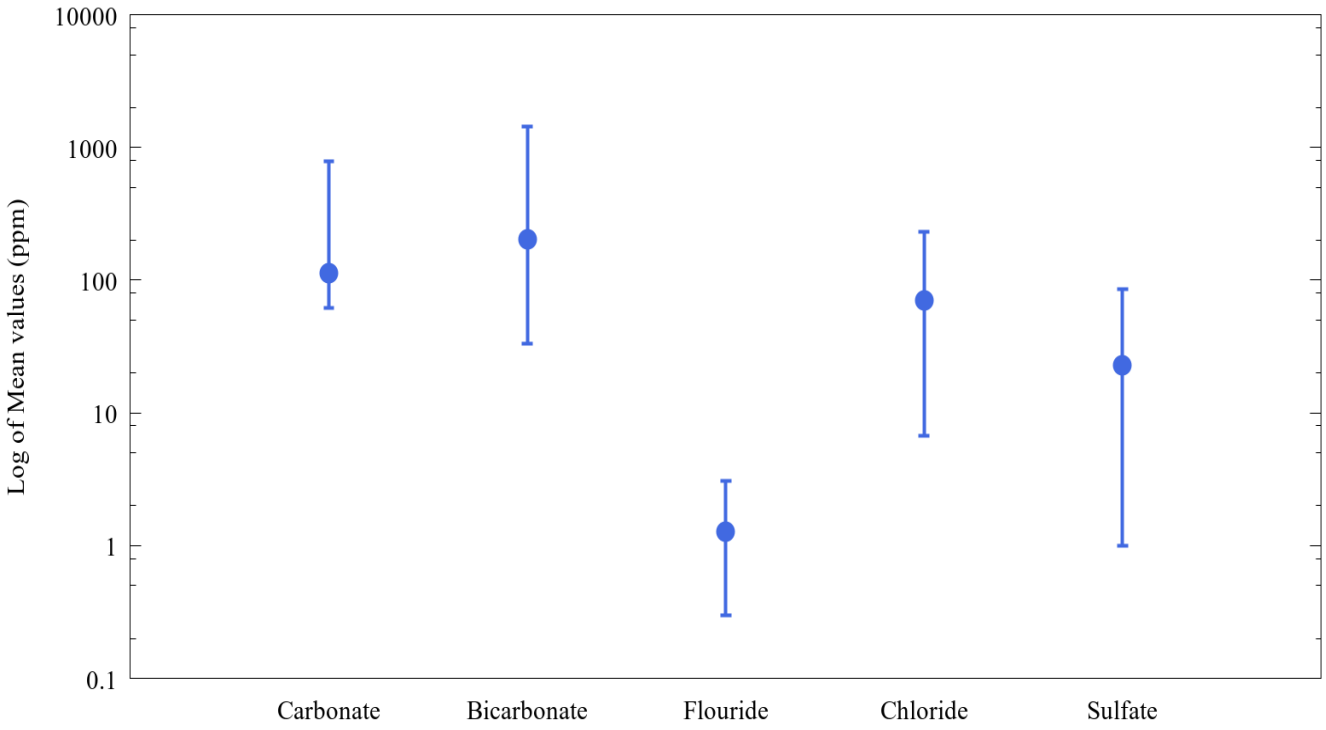


Figure 8. Major anions in the samples during the study period.

Chemical Classification of Water

When meteoric water comes into contact with soil or geologic material, chemical alteration occurs because meteoric water is extremely dilute, slightly acidic and oxidising. Soil overburden usually undergoes a loss of mineral matter to infiltrating water. As water travels through geologic material and the age of the water increases, groundwater tends to evolve chemically towards the composition of sea water, passing through several facies.

The general expectation is therefore that waters trend from Ca-HCO_3 type (meteoric) to NaCl type (formation) with increasing water–rock interaction. Between these two end-member facies, Ca(Mg)–HCO_3, mixed cation, Na–HCO_3, Na–$HCO_3(SO_4)$ and Na–SO_4 type waters can be present, depending on the available geological material. Hydrochemical facies are used to categorise water according to major ionic composition.

Major elemental analysis of water samples using a Piper diagram reveals that samples plot in two distinct groups, Na-HCO_3 type and Ca-HCO_3 type (Fig. 9) among samples collected from the two closely located wells during the two-year study period. Despite their close spatial proximity, the samples consistently occupied different regions of the Piper diagram, indicating differences in their major-ion composition. The presence of two types of water within a very short distance, without mixing, suggests the segmented nature of the aquifer.

Low precipitation and high evapotranspiration in the study region could also help prevent mixing of water between separate aquifer segments. Locations 3 and 5 have meteoric-type Ca(Mg)-HCO_3 facies water together with relatively low TDS (Fig. 8), indicating a meteoric origin and little water–rock interaction. Other locations exhibit Na-HCO_3 facies, which may indicate chemically evolved groundwater influenced by cation exchange and/or longer residence time along the groundwater flow path.

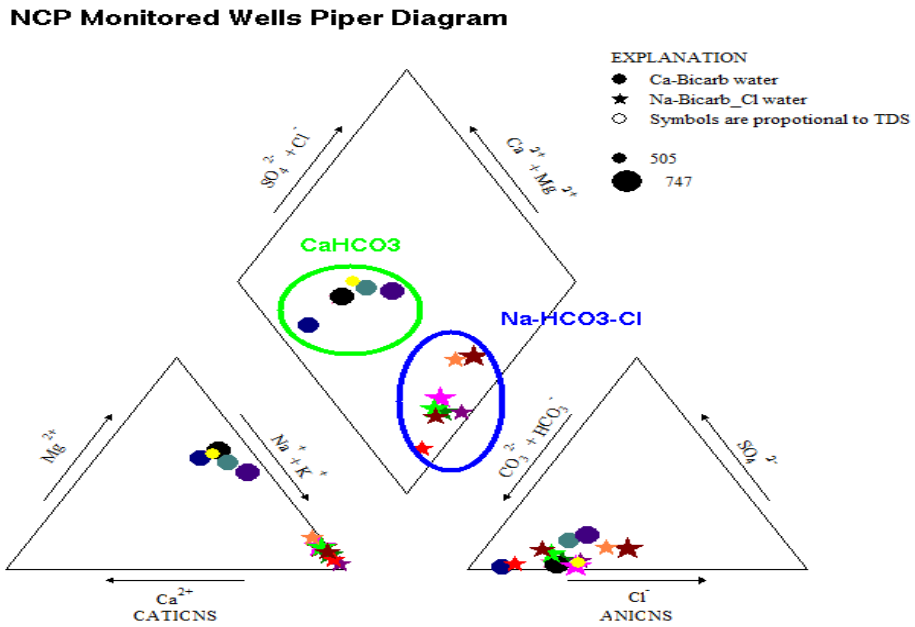


Figure 9. Piper diagram showing two distinct hydrochemical groups among samples collected from the two closely located wells during the two-year study period. Despite their close spatial proximity, the samples consistently occupied different regions of the Piper diagram.

Physical Origin of Aquifer Segmentation

Fence diagrams and cross sections through the groundwater flow model (Fig. 10) show distinct highs and lows in the depth to solid bedrock, that is, the base of the aquifer. Fractured bedrock is treated as the aquifer in the study area, and the model shows a prominent bedrock topographic high that coincides with the boundary between the two hydrochemical facies identified from major-ion analysis. We interpret this high as a low-permeability structural barrier that limits communication between fracture networks on either side, effectively acting as a groundwater divide rather than a divide defined purely by water-table geometry. The Ca(Mg)-HCO_3 type water-bearing wells (Locations 3 and 5) lie west of this prominent bedrock high, consistent with their distinct chemical facies relative to the other sampled locations.

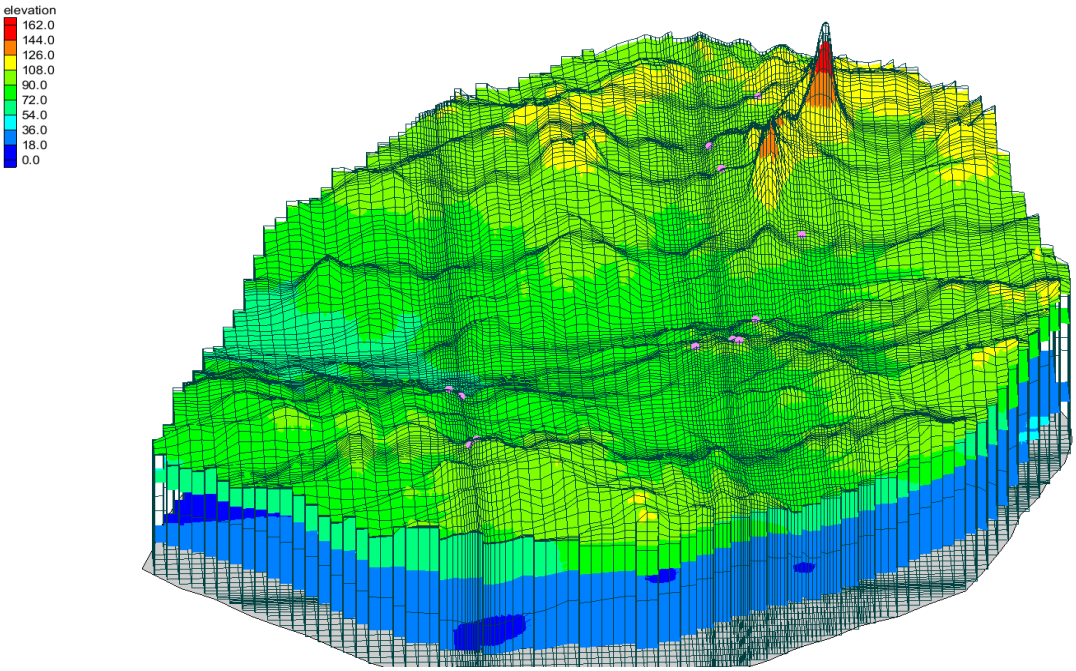


Figure 10.a: Study area with the refined grid around observation wells with vertical exaggeration.

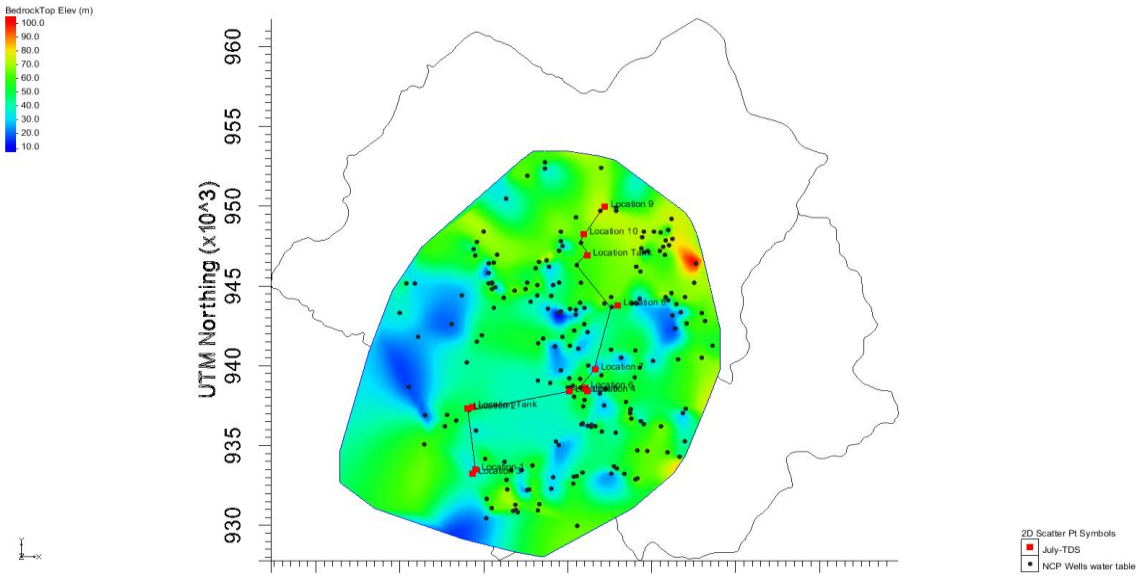


Figure10.b: Boundaries of the groundwater model within Rambewa and Medawachchiya divisional secretariat area.

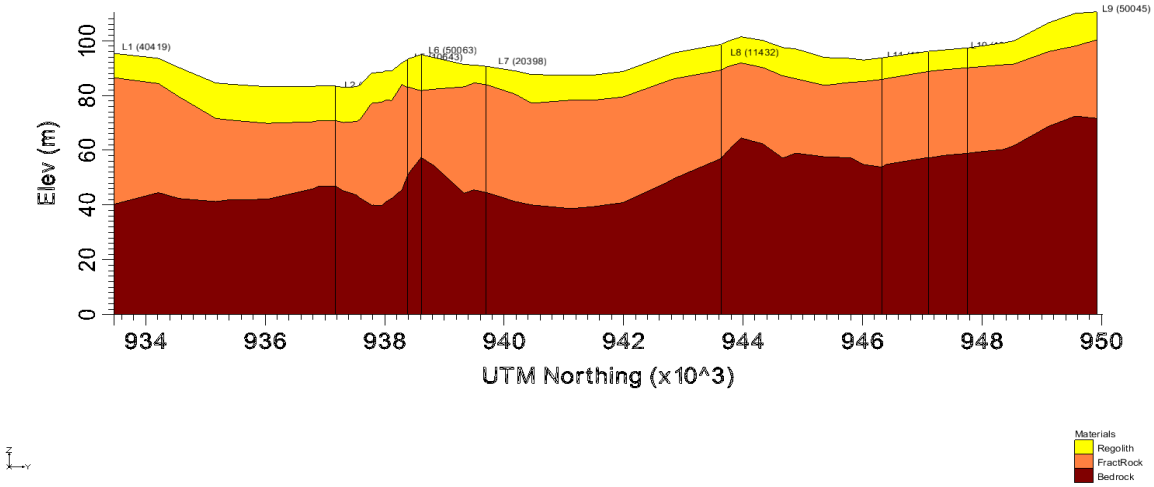


Figure 10.c: Cross section of the groundwater model for the study area..

DISCUSSION

Trace-Element Correlations and Water–Rock Interaction

Chemical results strongly suggest a water–rock interaction origin for the differing hydrochemical types of groundwater found in close proximity. Trace-element correlation analysis, performed using the Spearman rank correlation coefficient, is consistent with distinct water–rock interaction pathways in the two hydrochemical groups, evidenced by differing element-pair correlations between them. The Spearman coefficient is a non-parametric statistic for detecting monotonic trends between two variables (here, chemical concentrations across sampling locations); its associated p-value was used to help identify possible common sources or parent-rock associations for the correlated elements. A coefficient of +1 denotes a perfect positive (monotonic) correlation and −1 a perfect negative correlation. Correlations between 0.00 and 0.39 are considered very weak to weak, 0.40–0.59 moderate, 0.60–0.79 strong, and 0.80–1.00 very strong. Heat plots use shades of red and blue to denote positive and negative correlations respectively, with darker shades indicating stronger correlations and lighter shades weaker ones.

Locations 3 and 5 have Ca-Mg-HCO_3-type water, while other locations have Na-HCO_3 facies water. Heat plots for Location 3 (Fig. 12) and Location 5 (Fig. 13) show a strong correlation (Spearmanρ=0.83) between Mg and Mn at both locations. A good-to-excellent Mg–Sr correlation for these Mg-HCO_3 waters (Location 3:ρ=0.71; Location 5:ρ=1.00) suggests a common source for these ions, consistent with a dolomite contribution to water chemistry; carbonate and dolomite bodies are documented within the Wanni Complex host rock, making this the most plausible mineralogical explanation. Given that these two locations have higher combined Ca + Mg than Na, dolomite weathering is the most likely source of these ions.

Table 1. Top ten feature pairs by Spearman correlation coefficient, with associated p-values, for Location 3

Feature 1	Feature 2	Correlation (R)	p-value
Cd	Ba	1.000000	0.000000
Co	Ni	1.000000	0.000000
Mg	Ni	1.000000	0.000000
Mg	Co	1.000000	0.000000
Cd	T	0.985611	0.000309
V	T	0.985611	0.000309
Ba	T	0.985611	0.000309
Zn	Ba	0.942857	0.004805
Zn	Cd	0.942857	0.004805
K	Ba	0.942857	0.004805

Implications For Water-Supply Siting and RO Reject-Water Management

The physical and chemical results above: two hydrochemical facies separated by a bedrock topographic high that behaves as a structural groundwater divide paired with low precipitation and high evapotranspiration of the area can be used as low-cost applications for managing drinking water supply and RO reject water in the study area with a proper site specific evaluations.

Targeting Supply Wells toward Better-Quality Segments

Locations 3 and 5, on the dilute Ca-Mg-HCO_3 side of the bedrock high, have consistently lower TDS throughout the study period than the Na-HCO_3 segment that dominates the rest of the study area (Fig. 6). Where new tube

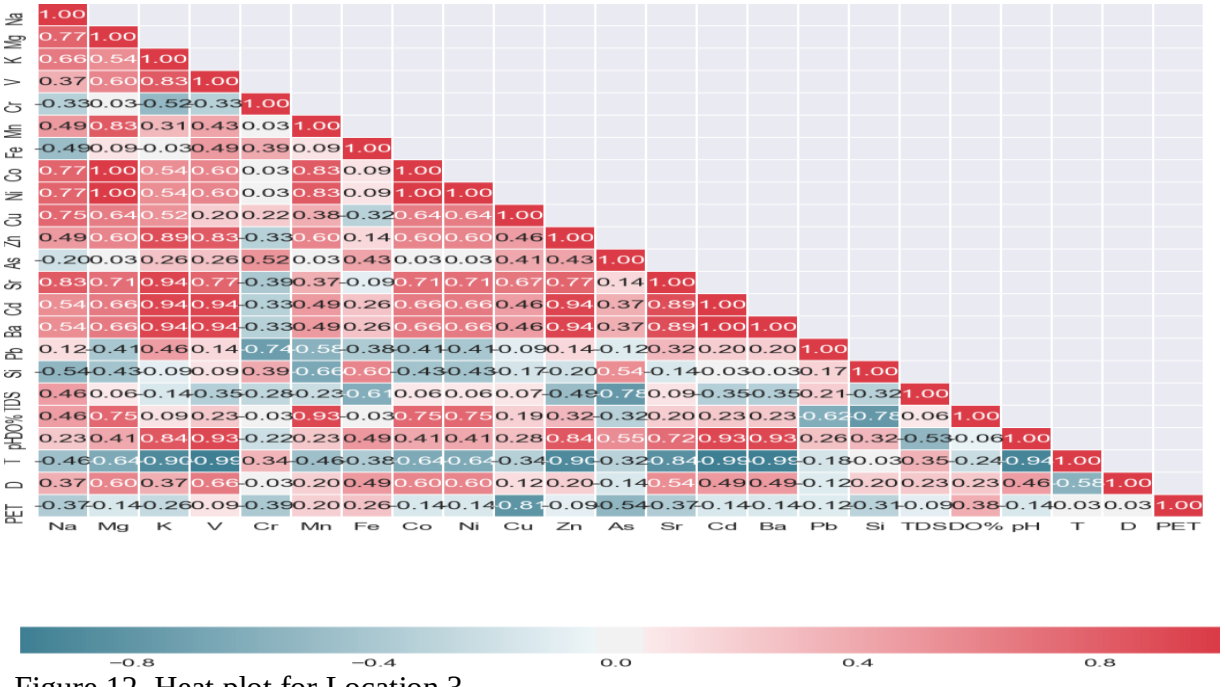


Figure 12. Heat plot for Location 3

Table 2. Top ten feature pairs by Spearman correlation coefficient, with associated p-values, for Location 5

Feature 1	Feature 2	Correlation (R)	p-value
Mg	Sr	1.000000	0.000000
Co	Ba	0.942857	0.004805
Mg	V	0.942857	0.004805
V	Mn	0.942857	0.004805
Fe	Zn	0.942857	0.004805
Mn	Ni	0.942857	0.004805
V	Sr	0.942857	0.004805
TDS	DO%	0.941176	0.005089
Fe	TDS	0.927634	0.007666
Cr	Pb	0.898027	0.015068

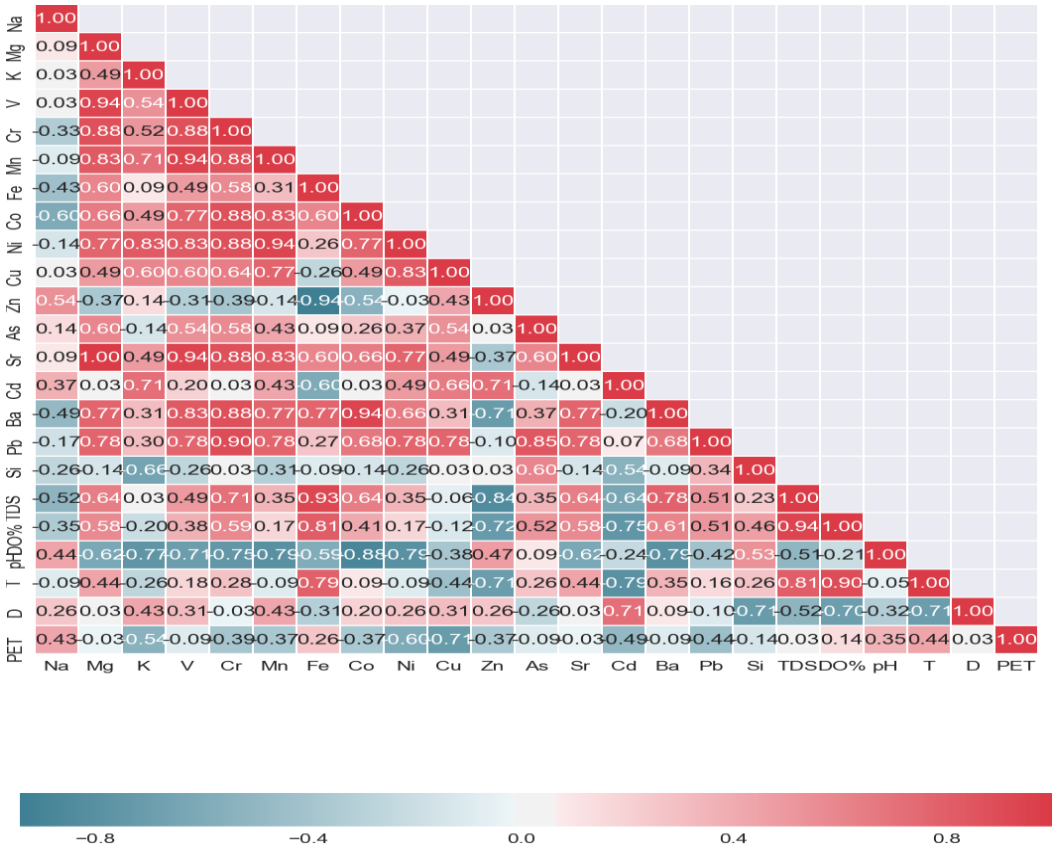


Figure 13. Heat plot for Location 5

wells are drilled, or existing wells rehabilitated, to serve as raw-water sources for community RO stations or for direct supply, the segmentation matters operationally as well as for water quality: RO recovery and reject-water volume are both sensitive to feedwater TDS, so drawing feed from a lower-TDS segment should modestly improve recovery and reduce the volume of reject brine generated per unit of potable water produced, compared with drawing from an adjacent higher-TDS segment purely because it happens to be closer to a given place.

Siting RO Reject-Water Disposal within Isolated, Already-Mineralised Segments

Independent surveys of NCP RO stations report that a large majority discharge concentrated reject brine directly onto open soil with no treatment [10], and site specific studies including one conducted within the Medawachchiya divisional secretariat area document elevated Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} and F^{-}in soils and shallow water at these disposal points [13, 19]. The segmentation identified here suggests a specific, low-cost

mitigation. Because the Na-HCO_3 segment is both more mineralised to begin with and, per the flow model cross sections (Fig. 10), separated from the dilute Ca-Mg-HCO_3 segment by a low-permeability bedrock, engineered reject water disposal (lined evaporation ponds, soakage pits or constructed wetlands of the kind piloted by Ranathunga et al. [22]) sited within the already higher TDS segment, and away from the boundary with the dilute segment, should pose comparatively less risk of degrading a currently usable freshwater resource than uncontrolled surface discharge sited without regard to aquifer structure. This is explicitly a containment strategy, not a treatment technology: it does not reduce the mineral load of the reject water, and it does not substitute for developing regulatory guidance and engineered disposal infrastructure for CBO scale RO systems, an absence repeatedly flagged in the RO performance literature [9, 10].

CONCLUSION

Rural communities in the NCP Dry Zone face a two part drinking-water security problem: physical scarcity of usable surface water, forcing near total reliance on a thin, geochemically variable fractured bedrock aquifer; and widespread hardness and fluoride in that same groundwater. The dominant current response, community scale RO treatment, addresses the quality problem effectively but at the cost of a second, largely unmanaged problem: low water recovery (19–50%) and, at a majority of surveyed stations, untreated discharge of the resulting mineral rich reject brine directly onto open soil above the same shallow aquifer system.

We have shown, for a representative section of the Rambewa and Medawachchiya divisional secretariat area, that the underlying fractured rock aquifer is segmented into at least two hydrochemically distinct compartments, separated by a bedrock topographic high that behaves as a structural groundwater divide, rather than behaving as a single well mixed system. This segmentation was previously framed primarily as a complication for identifying CKDu's environmental cause. We propose instead that it is a directly usable planning tool: the hydrochemical characterisation used here to delineate aquifer segments can, in principle, be extended across other RO station service areas in the NCP to prioritise drilling or rehabilitating supply wells within lower TDS segments, reducing both raw water hardness and the volume of reject brine generated per unit of treated water, and to identify isolated, already higher TDS segments as preferred locations for engineered RO reject water disposal, reducing the risk that untreated brine discharge degrades an adjacent, currently usable freshwater compartment in the long run.

This is a containment and siting strategy, not a substitute for the engineered disposal infrastructure, treatment technology or regulatory framework that RO reject water in the NCP still largely lacks [10].

ACKNOWLEDGEMENTS

This work was supported by the UTD Graduate Research Fund and the GSA Student Research Fund. We thank the National Water Resources and Drainage Board for providing borehole logs, and local government officials in the Rambewa and Medawachchiya divisional secretariats for assistance with site access.

Ethical Approval

This study did not involve human participants or animal subjects. Groundwater samples were collected from public wells with the permission of the relevant divisional secretariat authorities, and no ethical approval was therefore required.

Conflict of 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 Statement

The hydrochemical dataset generated and analysed during this study is available from the corresponding author on

reasonable request. The tube-well borehole logs used to construct the groundwater flow model were obtained from the National Water Resources and Drainage Board of Sri Lanka

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