## **RESEARCH ARTICLE**

Sustainable pressure-driven membrane facility controlled by a smartphone application for groundwater desalination in the dry zone of Sri Lanka<sup>+</sup>

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## Highlights

- The geochemistry of the groundwater was reconstructed using the 1-D inverse modeling method.
- Reverse osmosis membrane and nanofiltration methods were used for water desalination with near-zero wastes.
- A smartphone application was developed for remote maintenance of the treatment facility.

## **RESEARCH ARTICLE**

# Sustainable pressure-driven membrane facility controlled by a smartphone application for groundwater desalination in the dry zone of Sri Lanka<sup>+</sup>

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Abstract: Presently over three million people, mostly living in the dry zone of Sri Lanka, experiencing acute water stress due to excess salinity which results in palatability problems. In many parts of the world, reverse osmosis (RO) and nanofiltration (NF) technologies are successfully used for water desalination. However, in Sri Lanka, these methods show limited success due to inappropriate or over technologies adapted. The selection of the membranes depends on the source water salinity variations. We judiciously selected a groundwater source that requires desalination. The geochemical evolution of the groundwater source was determined by the 1D inverse modelling method. The source water salinity is ascribed to the incongruent dissolution of silicate minerals into montmorillonite followed by an ion-exchange process. The transition of geochemical facies from (non-dominant cation) NDC-HCO<sub>3</sub><sup>-</sup> (discharge zone) to Ca-HCO<sub>3</sub> (recharge zone) water type is observed along subsurface flow paths. After regulating the water turbidity (below 0.1 NTU), appropriate RO and NF membrane configuration was chosen for desalination. No external chemicals were added to maintain electrolytes balance in the treated water. The wastewater generated by the membrane treatment is blended appropriately for other community water needs. The chemical quality of treated water was optimized by a homogeneous diffusion-solution modelling method. The laboratory water plant is automated enabling remote operation and user-end maintenance via a mobile phone application. This step is vital to minimize community participation in plant maintenance. By our method, over 95% of the feed water was utilized for community use in compliance with the UNESCO Water, Sanitation and Hygiene (WASH) program.

*Keywords*: UNSDG 6; inverse modelling; reverse osmosis; nanofiltration; mobile app.

## INTRODUCTION

The United Nations declares to provide safe drinking water and sanitation to the entire globe by 2030 (UN Sustainable Development Goals 6) (United Nations, 2015). The Government of Sri Lanka states that safe water for Sri Lanka must be provided by 2025 (Ministry of Finance-Government of Sri Lanka, 2020). In Sri Lanka, over three million people, mostly from the North and North Central Provinces, suffer water stress due to a lack of access to safe drinking water within 200 m of their residence (Fan, 2015). However, most of the water sources in the dry zone have excess salinity (e.g. high total dissolved solids, TDS) renders them unpalatable most of the saline water experiences high hardness and fluoride levels, which further complicates its direct consumption. The TDS is a secondary contaminant in drinking water with 300 mg/L permissible limits (World Health Organization, 1996). Water salinity, hardness, and fluoride problems in Sri Lanka are controlled largely by geogenic factors (Jayasena et al., 2008). Therefore when the water source is chosen in an appropriate geologic formation most of the salinity issues can be reduced. It is noted that when the excess salinity is removed, other ions present in the solution automatically adjust charge balance via energetically feasible pathways (Fayer, 2011). Therefore, water desalination is first desired to improve palatability, and then assess residual solutes for additional treatments, if needed (Porada et al., 2013).

Nowadays pressure-driven membrane technologies such as ultrafiltration (molecular weight cut off, MWCO 1 to 500 kDa, 0.01 to 0.1  $\mu$ m pore size), nanofiltration (MWCO 100 to 300 kDa; 1 to 10 nm pore) and reverse osmosis (MWCO < 200 Da; < 1 nm pore) are widely



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used in the water industry (Elimelech and Philip, 2011; Hankins and Singh, 2016). In treated water by reverse osmosis (RO), almost all ions and some neutral molecules are removed whereas the nanofiltration (NF) membranes only remove di-and trivalent ions by solution-diffusion and molecular sieving mechanisms (Stevens et al., 2017; Hannesschlaeger et al., 2019). The ultrafiltration (UF) can remove 90% turbidity which requires a lower water footprint, less space in installation, and compact module configuration than sand filtration. On a global scale, RO membranes are successfully used in seawater desalination (Sedlak, 2019). Except in the Northern Sector of Sri Lanka (TDS > 8000 mg/L), in the other parts of the island, the water TDS content is always less than 3000 mg/L (Dissanayake and Weerasooriya, 1985a). However, in Sri Lanka, we observed that the seawater RO membranes (SWRO) is used for freshwater desalination (Imbulana et al., 2020) The SWRO membranes require high energy  $(1.1 \text{ kWh.m}^{3-}, \text{ recommended water TDS} 35 000 \text{ mg L}^{-1})$ and, therefore they desalinate freshwater excessively which results in solutes deficient water (Elimelech and Phillip, 2011; Davenport et al., 2018). In some cases, artificial salts were added to maintain a water-electrolyte balance that often results in peculiar taste (Bragg, 1993; Kozisek, 2005). Moreover, to regulate solute levels at desired concentrations, recently tuneable membranes are also developed (Stevens et al., 2017; di Vincenzo et al., 2021; Liu et al., 2021). However, such technologies are presently at an experimental scale. Pseudo-tunability of the membranes to reach desired water quality can also be attained by selecting appropriate NF and RO configurations (Taylor and Jacobs, 1996; Bergmann, 2005).

Water is a universal solvent that dissolves natural materials even in minute concentrations to form natural water (Bragg and Brag, 1993; Stumm and Morgan, 1996). Therefore, the synthesis of natural water from RO-treated water is a challenge. The wastes generated by RO and NF are prone to soil salination. In the case of seawater desalination, the wastes are returned to the sea (however, in freshwater desalination, wastes cannot be returned to the source). These problems require addressing or the membrane-based technologies show limited success particularly in Sri Lanka (Sobsey *et al.*, 2008; Cooray *et al.*, 2019)

We proposed a desalination method with desired water salinity without adding external chemicals. To select appropriate membranes, the chemical composition and evolution of the source water were examined using geological and geophysical data. The wastewater generated by the treatment was blended with the source water to reach desired quality for other needs. Additionally, the laborious operational and routine maintenance steps involved in the treatment plant were automated by developing a mobile phone application.

## MATERIALS AND METHODS

## Research area and hydrogeochemical survey

Nettiyagama (Mihintale) is an agricultural village in the dry

climatic region, Sri Lanka. The mean elevation of the area is about 125 m from the mean sea level. Approximately 90 families live in the village (513 males and 557 females) (Department of Census and Statistics-Sri Lanka, 2012). From a geological viewpoint, Nettiyagama village is located in the Wanni Complex under amphibolite facies metamorphism (Cooray, 1984). The regional geological map is available at 1:100 000 scales (Geological Survey and Mines Bureau, 1999). However, the map resolution is not adequate to identify local geological structures and lithogenic units. Therefore, a detailed geological map was prepared covering a 20 km<sup>2</sup> area to receive fine geological and microstructural details. A small-scale syncline runs on the middle of the Nettiyagama, aligning north to east striking direction. The major fractures in the region lie N-S and E-W (Cooray, 1984; Geological Survey and Mines Bureau, 1999). The reddish-brown earth soils are common of duplex nature. Small-scale irrigation tanks are abundant. For the Digital Elevation Model (DEM) development, Q-GIS and MATLAB derived LEFA codes were used with the images in Nettiyagama downloaded from the Earth Explorer site (https://earthexplorer.usgs.gov/). A regional geochemical survey was also conducted in the same area to evaluate trends in water quality parameters. Groundwater and surface water samples were collected into 500 mL bottles without leaving headspace for chemical analysis.

## Water analysis

pH EC, TDS, and turbidity were determined using a multiparameter with a calibrated probe (HANNA h19811-5, USA). The alkalinity was determined by a potentiometric titrator (AT- 610, Japan). In both cases, unfiltered samples were used. The samples were then filtered by 0.22 um membrane filters and divided into two portions. One portion was acidified with spectroscopic grade HCl and preserved for cation analysis by ICP-OES (Thermo iCAP TM 7400, USA). The unacidified portion for anion analysis was stored at 4 °C to minimize biological growth. Anions in water samples were determined by ion chromatography (Shimadzu 6A, Japan).

## Inverse geochemical modelling

The inverse modeling method is used to reconstruct the geochemical evolution of a given water source as detailed in (Zhu and Anderson, 2002). According to DEM data, the source groundwater seems to recharge by two nearby water sources (W1 - 182380.8 N; 346118.562 E and W2 - 182140.3 N; 346817.679 E). We chose the geochemical composition of these water bodies in reconstructing the well water composition (Table 1).

The primary and secondary mineral phases were identified from field observations and petrography data (details not shown). We used public domain code PHREEQC (USGS, 2021) to develop an inverse model to determine the geochemical provenance of the source well water found at the Nettiyagama Primary Vidyalaya (NPV, 456103 N; 920962 E). PHREEQC built-in WATEQ4f.data database was used in calculations. The mineral information not found in the database was added externally.

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	Table 1	: G	eochemica	l composition	of water	at recharge	(W1	and W2) and	discharge (NP	V) 1	points.
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Parameter in mg/L excent otherwise	Location           W1         W2           29         29           10.0         8.4           200         120           5.02         7.27           31.7         32.6           55.4         74.5		
	W1	W2	NPV
Temperature, °C	29	29	29
pH	10.0	8.4	7.2
TDS, mg/L	200	120	740
Turbidity, NTU	5.02	7.27	0.370
Alkalinity, mg/L as CaCO <sub>3</sub>	31.7	32.6	740
Hardness, mg/L as CaCO <sub>3</sub>	55.4	74.5	390
Total Al	18.8	14.0	0.033
Ba <sup>2+</sup>	0.02	0.06	ND
Br-	0.420	0.000	0.075
Ca <sup>2+</sup>	10.3	12.6	97.6
Cl-	61.0	19.8	28.4
F-	0.000	0.07	0.30
Total Fe	0.09	0.06	ND
$K^+$	2.64	4.90	3.92
$\mathrm{Mg}^{\scriptscriptstyle 2+}$	7.23	10.4	37.1
NO <sup>3-</sup>	0.12	0.61	26.7
$Na^+$	9.45	9.39	30.7
SO <sub>4</sub> <sup>2-</sup>	0.000	0.080	16.7
$\mathrm{Sr}^{2+}$	0.168	0.199	0.492
Zn^{2+	0.000	0.000	0.001

#### Fabrication of the laboratory plant

A laboratory-scale membrane treatment plant was fabricated using the following unit processes; pre-filtration, reverse osmosis (RO TW30-1812 DOW USA; active area 0.40 m<sup>3</sup>, flow rate 0.3 m<sup>3</sup>/day, max. P 2.07 mPa), and nanomembrane (NF 1812 Origin, China, active area, 0.39 m<sup>2</sup> flow rate 0.40 m<sup>3</sup>/day, salt rejection % 30 - 50, T 25 - 40 °C, max P 2.07 MPa). Ultrafiltration membrane was used at pre-filtration (NF-UF-90, Hinda, China, membrane area 4.68 m<sup>2</sup>, flow rate 7.2 - 14.4 m<sup>3</sup>/day. Max. P 0.15 - 0.30 MPa, inlet NTC < 50 NTU). Diaphragm RO booster pumps (RoHS, China, max. pressure 0.82 to 0.97 MPa) were used to supply feed water. Pressure switches were used as sensors, and solenoid valves were used to control the water flow. As recommended by the manufacturers, the membranes were first cleaned with 0.01 M HCl and 0.01 M NaOH ((DOW, 2021)). When membranes are in operation, intermittent flushing was carried out with the rainwater due to its aggressiveness (e.g. pH  $\sim$  5.6 at ambient conditions). The wastes were blended with the source water for other uses. A schematic design diagram of the water treatment plant is shown later.

A scaled-up water treatment plant was carried out with RO (LPT21-40 x 40 Vontron, Korea, active area

7.7 m<sup>2</sup>, Max. P 4.14 MPa, inlet flow 3.6 m<sup>3</sup>/h, temperature 25 to 45 °C, pH 3 to 10) and NF (KeenSen, China, active area 7.9 m<sup>2</sup>, inlet flow 35 m<sup>3</sup>/h, pH 1 to 14, temperature 25 to 45 °C. The water of the NPV well location is accessible readily to the village community. The water usage distribution can be coordinated by the Nettiyagama School Development Society. Therefore, the community water treatment plant was installed at the NPV well location.

#### Membrane treated water quality modelling

The chemical quality, flux, rejection, and water recovery of the water by RO/NF membrane treatment were calculated along the flow network using solution-diffusion and thinfilm models (Wijmans and Baker, 1995; Hannesschlaeger *et al.*, 2019; Ncube and Inambao, 2020) Table 2 shows relevant mathematical expressions used for such calculations of a single membrane element.

In most cases, more than one membrane element is used to yield desired water quality. For multi-array membrane systems, relevant expressions (Table 2: equations 15 to 18) can be extended after invoking interstage membrane transfer effects (Taylor and Jacobs, 1996). The information shown in Table 2 was used in the integrated membrane system design public domain code (Hydranautics, 2021). The code calculates the water quality

	Equation	Parameters			
(1)	Percentage rejection = <u>Feed water conductivity</u> – Product water conductivity Feed water conductivity × 100%				
	$Q_p$	$Q_p$ - Water flow rate of permeate, m <sup>3</sup> /d			
(2)	$Percentage recovery = \frac{1}{Q_p + Q_c}$	$Q_c$ - Water flow rate of rejection/concentrate, m <sup>3</sup> /d			
		$J_w$ - Permeate flux, m/s			
(3)	$I = A (\Lambda P - \Lambda \pi)$	$A_w$ - Permeability coefficient, m/s, Pa			
(3)	$f_W = H_W(\Delta I - \Delta R)$	$\Delta P$ - Pressure difference across the membrane, Pa			
		$\Delta \pi$ - Osmotic pressure, Pa			
(4)	$J_w = \frac{Q_p}{A_{mem}}$	$A_{mem}$ - Total membrane area, m2			
	[ p ] <sup>-1</sup>	$R_s$ - Salt rejection, %			
(5)	$R_{s} = \left[1 + \frac{D_{s}}{A_{w}(\Delta P - \Delta \pi)}\right]$	$B_s$ - Solute transport parameter, m/s			
(6)	$R_s = 1 - \frac{TDS_p}{TDS_f}$	$TDS_p$ -TDS values of permeate, ppm			
(6)		<i>TDS<sub>f</sub></i> -TDS values of feed water, ppm			
		<i>R</i> - Gas constant, J/mol K			
	$A = - p \pi \sum_{n=1}^{n} p \pi$	T - Temperature, K			
(7)	$\Delta \pi = RI \sum \frac{1}{v}$	n – Number of moles, mole			
		v – Volume, L			
(8)	0	R-Recovery ratio			
	$R = \frac{q_p}{Q_f}$	$Q_f$ – Water flow rate of feed water, m <sup>3</sup> /d			
		$C_f$ -Solute concentration of feed water			
	Mass Balance	C -Solute concentration of			
(9)	$Q_f C_f = Q_p C_p - Q_c C_c$	permeate			
		$C_c$ -Solute concentration of concentrate			
	$\Delta P = \frac{P_f + P_c}{2} - P_p$	$P_f$ -Feed water pressure, Pa			
(10)		$P_c$ -Concentrate pressure, Pa			
		$P_p$ - Permeate pressure, Pa			
(11)	$A_{mem} \approx \left(\frac{1000 \times Q_h}{\emptyset_1}\right) + z \left(\frac{1000 \times Q_h}{\emptyset_2}\right)$	$\phi$ - Average flux (l/h.m <sup>2</sup> )			
		z - Selection factor, one for a double pass system, or zero for a single-pass system			
(12)	$[Q_h \times P_f]$	$E_{other}$ - Other additional energy			
(12)	$E_{other} \approx \left[ \frac{36 \times 1}{36 \times 1} \right]$	$\eta$ - Efficiency of other units			

Table 2: Mathematical modelling of membrane water quality data (Wijmans and Baker, 1995; Taylor and Jacobs, 1996; Hannesschlaeger et al., 2019).

(13)	$E_T = E_{desal} + E_{ERD} + E_{other}$	$E_T$ -Total energy required for the entire RO process
(14)	$J_i = k_i \Delta C = \frac{Q_p C_p}{A}$	Ji-Solute flux, $M/L^2t$ $\Delta C$ -Concentration gradient, $M/L^3$ , $[(C_c + C_c)/2 - C_n]$
(15)	$C_{p,i} = \frac{k_{i,i}C_{f,i}}{k_{w,i}\Delta P_i[(2-2r_i)/(2-r_i)] + k_{i,i}} = Z_i C_{f,i}$	$K_w$ - Solvent mass transfer coefficient, L <sup>2</sup> t/M $K_i$ - Solute mass transfer coefficient, L/t r- Recovery $Z_i$ - modified mass transfer coefficient $\Delta P_i = \Delta P - \Delta \pi = \text{Net average}$ driving pressure including hydraulic losses Subscript <i>i</i> any stage in multistage membrane array
(16)	$C_{c,i} = \frac{Q_{f,i}C_{f,i} - Q_{p,i}C_{p,i}}{Q_{c,i}} = \frac{C_{f,i} - r_iC_{p,i}}{1 - r_i}$	
(17)	$C_{c,i} = C_{f,i+1} = C_{f,i} \left( \frac{1 - Z_i r_i}{1 - r_i} \right)$	
(18)	$C_{c,i} = X_i C_{f,i} \qquad X_i = \frac{1 - Z_i r_i}{1 - r_i} \qquad \text{define } X_0 \equiv 1$	
(19)	$C_{p,system} = \frac{C_f \sum_{i=1}^n (A_i k_{w,i} \Delta P_i Z_{i,cp} \prod_{j=0}^{i-1} X_{j,cp})}{\sum_{i=1}^n A_i k_{w,i} \Delta P_i}$	$A_t$ -Total membrane area $Z_{i,cp}$ - Modified film theory feed stream mass transfer coefficient
(20)	$\begin{split} C_{p,system} &= \\ \underbrace{C_{f} \sum_{i=1}^{n} \left[ A_{i} k_{i,i} \Delta P_{i} \frac{k_{i,i}}{k_{w,i} \Delta P_{i} [(2-2r_{i})/(2-r_{i})] + k_{i,i}} \prod_{j=0}^{i-1} \frac{1 - \frac{k_{i,j} r_{j}}{k_{w,j} \Delta P_{j} [(2-2r_{j})/(2-r_{j}] + k_{i,j}]}}{1 - r_{j}} \right]}_{\sum_{j=1}^{n} A_{i} k_{w,i} \Delta P_{i}} \end{split}$	$X_{j,cp}$ -Modified film theory concentrate stream concentration factor Subscript <i>i</i> & <i>j</i> -any stage in multistage membrane array

along with the network when feeding water chemistry and design parameters, *e.g.* permeate recovery, flux, feed flow, reject flow is given as input parameters (Table 2 for details).

## **Smartphone application**

A SMART phone application has automated the functioning of the treatment plant and real-time monitoring of the following water quality parameters; TDS/ EC/ hardness (NF-ZSX-1 sensor, China, 1 - 50 g  $L^{-1} \pm 1$  mg  $L^{-1}$ ) and pH (NF-ZSC-1, China, 0 - 14  $\pm$  0.01).

The centralized components of the clock generation and management system are implemented in the following modules (Figure 1 for details): (1) CCM (clock control module) provides a control for primary (source level) and secondary (root level) clock generation, division, allocation, synchronization, and rough gating. (2) LPCG (low power clock gating) module distributes the clock to all blocks in the SoC and handles block-level software controllable and automatic clock gating (Figure 1). The I/0 ports were used to turn on and off the pumps. The detailed technical description, system's codes, viz., control, and communication segments and further technical details can be provided upon request.

## **RESULTS AND DISCUSSION**

#### **Source selection**

As shown in Figure 2A, Nettiyagama village is underlined by migmatites, hornblende-biotite, granitic, Augen, garnet-cordierite gneisses, quartzites, charnockites, and calc-silicate rocks. The resistivity maps show two types of aquifers *e.g.* porous medium and fractured rock (Figure 2E). The porous aquifer occurs in the weathered zone, and the hard rock aquifer occurs along with NE-SW fractures (Figure 2C). The soil cover where a porous medium aquifer is located is thin, typically less than two meters; hence, it is prone to contamination (Figure 2B). As in Figure 2D, the digital elevation model (DEM) shows that the NPV well and the Mahakanadarawa tank are located in



SNVS-Secure Non-Volatile Storage, SJC-System JTAG Controller, SRC-System Reset Controller, CCM-Clock Control Module, LPCG-Low Power Clock Gating

Figure 1: Power, clock, and voltage domain layout of the SMART phone application controller. Interfacing, data processing, and communication codes will be provided upon request.

two watersheds divided by a flat and undulated mountain range (average height  $\sim 120$  m against MSL).

#### **Geochemical evolution**

To determine the geochemical provenance of the NPV water, a regional hydrogeochemical survey was conducted. The water quality variations between ground and surface water are shown in Table 3.

The pH of surface and groundwater samples does not vary significantly. However, turbidity, TDS, hardness, and alkalinity do vary between surface and groundwaters. Compared to surface water, the TDS is enriched by about ten folds due to the long residence time of the groundwater. When compared to carbonate rocks, the chemical weathering of silicate rocks is less discerned (Appelo and Postma, 2004; Jayasena *et al.*, 2008).

However, in silicate rock terrains, about 40% of TDS in water is accounted for by rock-water interactions (Stumm and Wollast, 1990; Appelo and Postma, 2004). Gibb's diagram is constructed to elucidate hydrogeochemical processes in determining the water composition (Gibbs, 1970; Marandi and Shand, 2018). Rock-water interactions primarily dominate in determining groundwater composition (Figure 3B). At mid TDS range, unlike most surface waters -  $[Na^+ / (Na^+ + Ca^{2+})]$  in groundwater spans the entire range (*i.e.* from < 0.1 to > 0.9). When silicate rocks are dominant in the aquifer  $[Na^+ / (Na^+ + Ca^{2+})]$  ratios are high (typically > 0.9), depending on the properties of soils and aquifers that signify intense rock-water interactions (Marandi and Shand, 2018). Accordingly, inverse modelling

based on mass balance calculations was used to reconstruct the chemical evolution of groundwater at the NPV well. As shown in Figure 2C, the two water bodies in the recharge zones are determined by the fracture patterns spanning from NE to SW direction. When water flows underground through these fractures, it reacts with rocks and minerals in the vicinity. The chemical composition of the NPV well water can be reconstructed using the wells in recharge zones. However inverse modelling technique has the following limitations. No unique solution to a geochemical problem can be achieved by mass balance calculations solely. If the initial reactions were not chosen judiciously and the kinetic constraints were not addressed, the relevant mass balance calculations may be unrealistic. Aquifers are inherently heterogeneous. Therefore, assumptions based on homogeneity reactions may sometimes yield inconsistent results (Zhu and Anderson, 2002).

As shown in Figure 3A, in Nettiyagama village, hornblende, biotite, anorthite, K-felspars, and albite phases are found in hornblende biotite and pegmatitic granitoid gneisses are oversaturated in groundwater (saturation index, SI > 0). The common secondary minerals are montmorillonite and illite. Kaolinite has also occurred in small proportions. Secondary minerals, namely kaolinite, montmorillonite, and Ca-montmorillonite, show unsaturated conditions (SI < 0). However, the carbonate phase minerals are not discerned. Therefore, incongruent dissolution of silicate minerals coupled with reverse ion exchange reactions are used to reconstruct the chemical evolution of groundwater at NPV well-using reaction stoichiometries shown below:

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Incongruent dissolution

$$2Na(AlSi_{3})O_{8} + 2CO_{2} + 11H_{2}O \rightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + 2Na^{+} + 4H_{4}SiO_{4} + 2HCO_{3}^{-} (1)$$

$$2KMg_{3}AlSi_{3}O_{10}(OH)_{2} + 138CO_{2} + 131H_{2}O \rightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + 2K^{+} + 6Mg^{2+} + 4SiO_{2} + 138HCO_{3}^{-} + 124H^{+} (2)$$

$$Ca(Al_{2}Si_{2})O_{8} + 2CO_{2} + 3H_{2}O \rightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + Ca^{2+} + 2HCO_{3}^{-} (3)$$

$$2K(AlSi_{3})O_{8} + 2H^{+} + 9H_{2}O \rightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + 2K^{+} + 4H_{4}SiO_{4} \quad (4)$$

$$3Na(AlSi_{2})O_{8} + Mg^{2+} + 4H_{2}O \rightarrow 2Na_{6}S(Al_{1,5}Mg_{6,5})Si_{4}O_{10}(OH)_{2} + 2Na^{+} + H_{4}SiO_{4} \quad (5)$$



**Figure 2:** A.Geological map of 20 km<sup>2</sup> area B. Soil profile data with aquifer types C. Rose diagram of fracture patterns. B. The digital elevation map of Nettiyagama. The red dot indicates the source water location. C. Resistivity profile of Nettiyagama well (L1 line. Figure 1D).

The hydrogeological facies of the W1 and W2 sources are non-dominant cations (NDC)–HCO<sub>3</sub>. The facies evolved as Ca-HCO<sub>3</sub> at NN along the flow path. The conversion of kaolinite to Ca-montmorillonite is favoured by releasing {Na<sup>+</sup>} and {K<sup>+</sup>} into water (Appelo and Postma, 2004). The Ca-montmorillonite (CaX<sub>2</sub>) seems to undergo reverse ion exchange producing Ca<sup>2+</sup> into aqueous phase.

Ion exchange

$$CaX_{2} + 2Na^{+} \rightarrow 2NaX + Ca^{2+}$$
(6)

$$CaX_{2} + 2K^{+} \rightarrow 2KX + Ca^{2+}$$
<sup>(7)</sup>

Interestingly, at both W1 and W2 locations, the  $SO_4^{2-}$  concentration is not high (Table 1). Compared to W1 and W2 locations, the  $SO_4^{2-}$  concentration has increased by 200 folds. However, no sulfate-rich mineral phases can be seen. Hence high  $SO_4^{2-}$  in NPV well water can be accounted for biogenic processes (Appelo and Postma, 2004; Bethke, 2007).

## Configuration of the water treatment plant

The source groundwater selected (location NPV well) requires treating excess turbidity (0.22 NTU), hardness, and TDS to improve palatability. The water type is Ca-HCO, (Dissanayake and Weerasooriya, 1985b) therefore, flushing with rainwater or permeate is required to avoid membrane scaling. Ultrafiltration (UF) membranes are used to remove water turbidity (DOC and microorganisms as well). Over 90% turbidity is removed by ultra-filtration (UF) under cross-flow or dead-end mode. Extended stay of raw water in the membrane compartment promotes membrane fouling. Therefore, daily flushing of the membrane compartment with treated water or rainwater is recommended. The concentrated and flushed water by UF treatment can be used for gardening or other purposes. However, returning it to the raw water source is not recommended due to excess concentrates with colloids. In both methods flushing of the UF membrane to minimize fouling is recommended before use. At this stage, the other parameters, TDS, pH, and hardness of the UF treated water, showed no variation, and the feed water composition to NF membrane is as in Figure 4A.

Table 3: Chemical composition of surface and groundwater in Nettiyagama village.

Parameter	Groundwater	Surface water		
i arameter	$Mean \pm s. d N = 67$	Mean ± s. d. N = 10		
рН	$7.31\pm 0.34$	$7.60\pm0.20$		
TDS (ppm)	$455\pm191$	$39.0 \pm 11.0$		
Conductivity (µS cm <sup>-1</sup> )	$932\pm376$	$94.0\pm18.0$		
Turbidity (NTU)	$2.79\pm8.24$	$6.09 \pm 1.66$		
Alkalinity (ppm CaCO <sub>3</sub> )	$366\pm87$	$65.6\pm5.5$		
Total hardness (ppm CaCO <sub>3</sub> )	$641\pm305$	$39.5\pm4.9$		
F <sup>-</sup> (ppm)	$0.95\pm0.58$	$0.14\pm0.03$		



Figure 3: A. Possible mineral phases of precipitation and dissolution used for geochemical evolution of water. B. Gibbs diagrams showing different physicochemical processes.



Figure 4: A. Schematics of water treatment plant B. Topological configuration of membrane network. Modelled water quality data are also shown. M. modelled data, E: experimental data.

An optimized membrane configuration is critical to yield desired water quality. Figure 4B used both nano and reverse osmosis membranes to devise the required membrane topology. The concentrate generated from the nanomembrane was used as the feed water to the RO membrane. The two permeates, *viz.* nanomembranes and RO membrane, are combined to receive the desired water quality. The concentrate generated at 90% water recovery is mixed with raw water to minimize environmental damage due to salinity. The source water contains excess non-carbonate hardness (395 mg/L, CaCO<sub>3</sub>) and TDS (669 mg/L). Therefore, we selected NF and RO membranes suited at low TDS that yield low-pressure gradient, viz. RO 0.86 to 2.07 kPa and NF 0.34 to 1.03 kPa) (Bergmann, 2005). The feed water was first treated with NF to remove excess hardness. The NF concentrate contains TDS 1722 mg/L and hardness 433 mg/L CaCO<sub>3</sub>, which was used as the feed solution of the RO membrane. The permeate after RO contains TDS 26.0 and hardness 2.97 mg/L CaCO, and F 0.78 mg/L. The concentrates after RO treatment contains (2174 mg/L TDS) oversaturated conditions to calcite and gypsum mineral phases which can initiate membrane scaling if kinetic conditions are favoured. The permeates are generated by RO and NF result in TDS 60.0 mg/L and hardness 57.0 mg/L CaCO<sub>2</sub>. The final concentrate yielded by the RO/NF membranes combination has TDS, 2174 mg/L and hardness 268 mg/L, CaCO<sub>2</sub>. The concentrate is blended with raw water obtained at outlet reach TDS 1000 mg/L and 168 mg/L, CaCO<sub>2</sub>. The agreement between modelled and observed water quality data at different points is shown in Figure 5. As detailed elsewhere (Qian et al., 2020), the homogeneous solution model used for modelling assumed water and solutes fluxes under pressure and concentration gradients, respectively.

## **Smartphone applications**

The water purification plants are commonly used by the village community, where technical expertise is lacking among them. Therefore, remote operation and user-level maintenance are achieved remotely by technically competent personnel. Consequently, we developed a smartphone application using Java code. Java offers high versatility in memory allocation, data transfer, run speed, and portability compared to other programming languages. The smartphone application provides three functions in operating the laboratory-scale water treatment plant (Figure 5). In the first function (F-1, Figure 5), through the switch operation of the button on the platform side, the water pump could start pumping water, start the filter operation,

pause the filter operation, turn off the pump. Water quality parameters such as TDS, EC, pH, hardness, and operate records can monitor runtime. They can be transmitted to remote computer systems and saved in a database. The operator can monitor the process of the signal lights on the platform from the video.

The second function (F-2, Figure 5), the plant flushing management, provides three flushing modes: (1) NF. - when only the NF is cleaning, (2) UF - when only the UF is cleaning, (3) NF and RO - during NF and RO cleaning. When the water quality filter has been exhausted, the third function (F-3, Figure 5) automatically stops the filter. The operation of the water treatment plant occurs via a 4G signal transmit that can be added to the cloud system to ensure versatility. Each function can be started independently. Finally, the display on the right side of the filter result includes the working status display, the filter result data display, and the operation log. In the future, the database poses big data, we will be able to optimize operation processing using the data mining algorithm.

## Community water treatment plant

Based on the concepts developed in this work, a water desalination treatment plant (scaled up to 5000 L/day) is installed at the Nettiyagama Primary School to meet drinking and other water needs. The excess drinking water produced is distributed among the village community under the preview of the School Development Society. The water plant is in operation at permeate 95% efficiency. The wastes generated are blended with the source water at a 1:9 ratio to be used in agriculture and sanitation. The annual variation of the TDS content of the source water is less than 10 %. The total water production cost was calculated as 60.37 LKR/m<sup>3</sup> after considering capital, power, membrane replacement, and membrane costs. The



Figure 5: Flowchart of mobile phone application set up.

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mobile phone control developed for the laboratory module is not yet available with the community scale plant. The water treatment method uses no chemicals, and the product is named "*Amaawatura*".

## CONCLUSIONS

The geochemical evolution of the groundwater (Nettiyagama Vidyalaya) was reconstructed by the inverse modelling method. The nanofiltration and reverse osmosis membrane technology were used to generate water with 60 mg/L TDS without chemicals addition. The salinity of the wastewater was matched to source water quality before releasing to the environment. Routine maintenance and operation of the water treatment are achieved via a mobile application. The scaled-up facility is now in operation at 5000 L/ day capacity in the village.

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## DECLARATION OF CONFLICT OF INTEREST

All authors declared no conflicts of interest.

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