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

4 Abstract

5 Presently over 3 million people, mostly living in the dry zone of Sri Lanka, experiencing acute water stress due to 6 excess salinity which results in palatability problems. In many parts of the world, reverse osmosis (RO) and 7 nanofiltration (NF) technologies are successfully used for water desalination. However, in Sri Lanka, these 8 methods show limited success due to inappropriate or over technologies adapted. Selection of the membranes 9 depends on the source water salinity variations. We judiciously selected a groundwater source that requires 10 desalination. The geochemical evolution of the groundwater source was determined by the 1D inverse modelling 11 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 12 13 cation) NDC-HCO₃⁻ (discharge zone) to Ca-HCO₃ (recharge zone) water type is observed along subsurface flow 14 paths. After regulating the water turbidity (below 0.1 NTU), appropriate RO and NF membrane configuration was 15 chosen for desalination. No external chemicals were added to maintain electrolytes balance in the treated water. 16 The wastewater generated by the membrane treatment is blended appropriately for other community water needs. 17 The chemical quality of treated water was optimized by a homogeneous diffusion-solution modelling method. The 18 laboratory water plant is automated enabling remote operation and user-end maintenance via a mobile phone 19 application. This step is vital to minimize community participation in plant maintenance. By our method, over 95% 20 of the feed water was utilized for community use in compliance with the UNESCO Water, Sanitation and Hygiene (WASH) program. 21

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23 Keywords: UNSDG 6, inverse modelling, reverse osmosis, nanofiltration, mobile app

25 1. Introduction

- 26 The United Nations declares to provide safe drinking water and sanitation to the entire globe by 2030 (UN 27 Sustainable Development Goals 6) (United Nations, 2015). The Government of Sri Lanka states that safe water for 28 Sri Lanka must be provided by 2025 (Ministry of Finance-Government of Sri Lanka, 2020). In Sri Lanka, over 3 29 million people, mostly from the North and North Central Provinces, suffer water stress due to a lack of access to 30 safe drinking water within 200 m of their residence (Fan, 2015). However, most of the water sources in the dry 31 zone has excess salinity (e.g., high total dissolved solids, TDS) renders them unpalatable—most of the saline water 32 experiences high hardness and fluoride levels, which further complicates its direct consumption. The TDS is a 33 secondary contaminant in drinking water with 300 mg/L permissible limits (World Health Organization, 1996). 34 Water salinity, hardness and fluoride problems are control by geogenic factors (Jayasena et al., 2008) When the 35 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 solution automatically adjust charge balance via
 energetically feasible pathways (Fayer, 2011). Therefore, water desalination is first recommended to improve palatability, and then assess residual solutes for additional treatments, if needed (Porada *et al.*, 2013).
- 39 Nowadays pressure driven membrane technologies such as ultrafiltration (molecular weight cut off, MWCO 1 to 40 500 kDa, 0.01 to 0.1 µm pore size), nanofiltration (MWCO 100 to 300 kDa; 1 to 10 nm pore) and reverse osmosis 41 (MWCO < 200 Da; < 1 nm pore) are widely used in water industry(Elimelech and Philip, 2011; Hankins and Singh, 42 2016). In reverse osmosis (RO) treated water, almost all ions and some neutral molecules are removed whereas 43 the nanofiltration (NF) membranes only remove di-and trivalent ions by solution-diffusion and molecular sieving mechanisms (Hannesschlaeger et al., 2019; Stevens et al., 2017)...The ultrafiltration (UF) can remove 90% turbidity 44 45 which requires a lower water footprint, less space in installation, and compact module configuration than sand 46 filtration. In global scale, RO membranes are successfully used in seawater desalination (Sedlak, 2019). Except 47 in the Northern Sector of Sri Lanka (TDS > 8000 mg/L), in the other parts of the island the water TDS content is 48 always less than 3000 mg/L (Dissanayake and Weerasooriya, 1985a). However, in Sri Lanka we observed that the 49 seawater RO membranes (SWRO) are used for freshwater desalination (Imbulana et al., 2020) The SWRO 50 membranes require high energy (1.1 kWh.m³⁻, TDS level 35 000 mg. L⁻¹) and they desalinate fresh water 51 excessively which results solutes deficient water (Davenport et al., 2018; Elimelech and Phillip, 2011). In some 52 cases, artificial salts were added to maintain water electrolyte balance that often results peculiar taste (Bragg, 1993; 53 Kozisek, 2005). Moreover, to regulate solute levels at desired concentrations, recently tuneable membranes are 54 also developed (Liu et al., 2021; Stevens et al., 2017; di Vincenzo et al., 2021). However, such technologies are 55 presently at experimental scale. Pseudo-tunability of the membranes to reach desired water quality can also be 56 attained by selecting appropriate NF and RO configurations (Taylor and Jacobs, 1996; Bergmann, 2005).
- Water is a universal solvent that dissolve natural materials even in minute concentrations to form natural water(Bragg and Brag, 1993; Stumm and Morgan, 1996). Therefore, the artificial synthesis of natural water from the RO treated water is a challenge. The wastes generated by RO and NF are prone to soil salination. In case of sea water desalination, the wastes are returned to the sea (however, in fresh water desalination, wastes cannot be returned to the source). These problems require addressing or the membrane-based technologies show a limited success in Sri Lanka (Cooray *et al.*, 2019; Sobsey et al, 2008)

- 63 Presently we proposed a water desalination method with minimal waste generation without adding external
- 64 chemicals to restore solutes levels. First, we used geological and geophysical data to determine geochemical origin
- 65 and the water availability of the selected groundwater source. This step is very important in the selection of
- 66 appropriate membranes and ensure water sustainability. After assessing source water quality, the appropriate NF
- 67 and RO configuration was chosen to regulate salinity (TDS). The wastes generated by the treatment was blended
- 68 with the source water to reach desired water quality for other needs. Further the laborious operational and routine
- 69 maintenance steps of the treatment plant was automated by developing a mobile phone application.

70 2. Methodology

71 2.1Research area and hydrogeochemical survey

72 Nettiyagama (Anuradhapura) is an agricultural village in the dry climatic region, Sri Lanka. The mean elevation 73 of the area is 125 m from the mean sea level. Approximately 90 families live in the village (513 males and 557 74 females) (Department of Census and Statistics-Sri Lanka, 2012). From geological viewpoint, Nettiyagama village 75 is located in the Wanni Complex under amphibolite facies metamorphism (Cooray, 1984). The regional geological 76 map is available at 1:100 000 scale (Geological Survey & Mines Bureau, 1999). However, the map resolution is 77 not adequate to identify local geological structures and lithogenic units. Therefore, a detailed geological map was 78 prepared covering a 20 km² area to receive fine geological and micro-structural details. A small-scale syncline runs 79 on the middle of the Nettiyagama, aligning north to east striking direction. The major fractures in the region lie N-80 S and E-W (Cooray, 1984; Geological Survey & Mines Bureau, 1999). The reddish-brown earth soils are common 81 of duplex nature. Small-scale irrigation tanks are abundant. For the Digital Elevation Model (DEM) development, 82 Q-GIS and MATLAB derived LEFA codes were used with the images in Nettiyagama downloaded from the Earth 83 Explorer site (https://earthexplorer.usgs.gov/). A regional geochemical survey covering 20 km² was also conducted 84 to evaluate trends in physicochemical water quality parameters. Groundwater and surface water samples were

85 collected into 500 mL bottles without leaving a headspace for chemical analysis.

86 2.2Water analysis

87 pH EC, TDS, and turbidity were determined using a multiparameter with a calibrated probe (HANNA h19811-5,

- 88 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.
- 90 One portion was acidified with spectroscopic grade HCl and preserved for cations analysis by ICP-OES (Thermo
- 91 iCAP TM 7400, USA). The unacidified portion for anions analysis was stored at 4 ^oC to minimize biological
- growth. Anions of water samples were determined by ion chromatography (Shimadzu 6A, Japan).
- 93 **2.3 Inverse geochemical modelling**

94 Inverse modeling method is used to reconstruct the geochemical evolution of a given water source as detailed in

95 (Zhu and Anderson, 2002). According to DEM data the source groundwater seems to recharge by two nearby water

96 sources (W1-182380.8N 346118.562E and W2-182140.3N 346817.679E). We chose the geochemical composition

- 97 of these water bodies in reconstructing the well water composition (Table 1). The primary and secondary mineral
- 98 phases were identified from field observations and petrography data (details not shown). We used public domain
- 99 code PHREEQC (USGS, 2021) to develop an inverse model to determine geochemical provenance of the source

well water found at the Nettiyagama Primary Vidyalaya (NPV, 456103N 920962E). PHREEQC built-in

WATEQ4f.data database was used in calculations. The minerals not found in the database were added externally. 101

102 2.4 Fabrication of the laboratory plant

103 A laboratory-scale membrane treatment plant was fabricated using the following unit processes; pre-filtration, 104 reverse osmosis (RO TW30-1812 DOW USA; active area 0.40 m³, flow rate 0.3 m³/day, max. P 2.07 mPa), and nanomembrane (NF 1812 Origin, China, active area, 0.39 m² flow rate 0.40 m³/day, salt rejection % 30 -50, T 25 105 - 40 °C, max P 2.07 MPa). Ultrafiltration membrane was used at pre-filtration (NF-UF-90, Hinda, China, 106 107 membrane area 4.68 m², flow rate 7.2 – 14.4 m³/day, Max, P 0.15 – 0.30 MPa, inlet NTC < 50 NTU). Diaphragm 108 RO booster pumps (RoHS, China, max. pressure 120 to 140 psi) were used to supply feed water. Pressure switches 109 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 0.01M NaOH ((Dupont, 2021)). When 110 membranes are in operation, intermittent flushing was carried out with the rainwater due to its aggressiveness (e.g., 111 112 $pH \sim 5.6$ at ambient conditions). The wastes were blended with the source water for other uses. A schematic design 113 diagram of the water treatment plant is shown in Figure 2. A. A scaled-up water treatment plant was carried out 114 with RO (LPT21-40 x 40 Vontron, Korea, active area 7.7 m², Max. P 4.14 MPa, inlet flow 3.6 m³/h, temperature 25 to 45 °C, pH 3 to 10) and NF (KeenSen, China, active area 7.9 m², inlet flow 35 m³/h, pH 1 to 14, temperature 115 25 to 45 °C. The water of the NPV well location is accessible readily to the village community. The water usage 116 distribution can be coordinated by the Nettiyagama School Development Society. Therefore, a community water 117 118 treatment plant was installed at the NPV well location.

119 2.5 Membrane treated water quality modelling

120 The chemical quality, flux, rejection, and water recovery of the water by RO/NF membrane treatment were 121 calculated along the flow network using solution-diffusion and thin-film models (Hannesschlaeger et al., 2019; 122 Wijmans and Baker, 1995; Ncube and Inambao, 2020) Table 2 shows relevant mathematical expressions used for 123 such calculations of a single membrane element. In most cases, more than one membrane element is used to yield 124 desired water quality. For multi-array membrane systems, relevant expressions (Table 2: equations 15 to 18) can 125 be extended after invoking interstage membrane transfer effects (Taylor and Jacobs, 1996). The information shown 126 in Table 2 was used in the integrated membrane system design public domain code (Hydranautics, 2021). The code 127 calculates the water quality along with the network when feeding water chemistry and design parameters, e.g., 128 permeate recovery, flux, feed flow, reject flow is given as input parameters (Table 2 for details).

129 2.6 Smartphone application

A SMART phone application has automated the functioning of the treatment plant and real-time monitoring of 130 the following water quality parameters; TDS/ EC/ hardness (NF-ZSX-1 sensor, China, 1-50 g.L⁻¹ \pm 1 mg. L⁻¹) 131 132 and pH (NF-ZSC-1, China, 0.14 ± 0.01). The centralized components of the clock generation and management 133 system are implemented in the following modules (Figure 1 for details): (1) CCM (clock control module) provides 134 a control for primary (source level) and secondary (root level) clock generation, division, allocation, 135 synchronization, and rough gating. (2) LPCG (low power clock gating) module distributes the clock to all blocks 136 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 (Table 1- S and Figure 1-S, Support documentation). The detailed technical
description, system's codes, viz., control, and communication segments are shown in support documentation

(Figure1 -S and Table 1-S). Further technical details can be provided upon request.

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141 **3. Results and Discussion**

142 3.1 Source selection

As shown in Figure 2. A, 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 2. E). The porous aquifer occurs in the weathered zone, and the hard rock aquifer occurs along with NE-SW fractures (Figure 2. C). The soil cover where a porous medium aquifer is located is thin, typically less than two meters; hence, it is prone to contamination (Figure 2. B). As in Figure 2.D, the digital elevation model (DEM) shows that the NPV well and the Mahakanadarawa tank are located

in two watersheds divided by a flat and undulated mountain range (average height ~120 m against MSL).

150 **3.2** Geochemical evolution

151 To determine the geochemical provenance of the NPV water, a regional hydrogeochemical survey was conducted. 152 The water quality variations between ground and surface water are shown in Table 3. The pH of surface and 153 groundwater samples does not vary significantly. However, turbidity, TDS, hardness, and alkalinity do vary between 154 surface and groundwaters. Compared to surface water, the TDS is enriched by about ten folds due to the long 155 residence time of the groundwater. When compared to carbonate rocks, the chemical weathering of silicate rocks is 156 less discerned (Appelo and Postma, 2004). However, in silicate rock terrains, about 40 % of TDS in water is 157 accounted for by rock-water interactions (Appelo and Postma, 2004; Stumm and Wollast, 1990). Gibb's diagram is 158 constructed to elucidate hydrogeochemical processes in determining the water composition (Gibbs, 1970; Marandi 159 and Shand, 2018). Rock-water interactions primarily dominate in determining groundwater composition (Figure 3. B). At mid TDS range, unlike most surface waters - $\left(\frac{Na^+}{Na^++Ca^{2+}}\right)$ in groundwater spans the entire range (i.e., from < 160 0.1 to > 0.9). When silicate rocks are dominant in the aquifer $\left(\frac{Na^+}{Na^++Ca^{2+}}\right)$ ratios are high (typically > 0.9), depending 161 162 on the properties of soils and aquifers that signify intense rock-water interactions (Marandi and Shand, 2018). 163 Accordingly, inverse modelling based on mass balance calculations was used to reconstruct the chemical evolution 164 of groundwater at the NPV well. As shown in Figure 2-C, the two water bodies in the recharge zones are determined 165 by the fracture patterns spanning from NE to SW direction. When water flows underground through these fractures, 166 it reacts with rocks and minerals in the vicinity. The chemical composition of the NPV well water can be 167 reconstructed using the wells in recharge zones. However inverse modelling technique has the following limitations. 168 No unique solution to a geochemical problem can be achieved by mass balance calculations solely. If the initial 169 reactions were not chosen judiciously and the kinetic constraints were not addressed, the relevant mass balance 170 calculations may be unrealistic. Aquifers are inherently heterogeneous. Therefore, assumptions based on 171 homogeneity reactions may sometimes yield inconsistent results (Zhu and Anderson, 2002).

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

180
$$2Na (AlSi_3) O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 + 2HCO_3$$
 (1)

181
$$KMg_3AlSi_3O_{10}(OH)_2 + 7CO_2 + 7.5H_2O \rightarrow 0.5Al_2Si_2O_5(OH)_4 + K^+ + 3Mg^{2+} + 4H_4SiO_4 + HCO_3^-$$
 (2)

182
$$Ca (Al_2Si_2) O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^{-1}$$
 (3)

183
$$2K (AlSi_3)O_8 + 2H^+ + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4H_4SiO_4$$
 (4)

184
$$3Na (AlSi_3) O_8 + Mg^{2+} + 4H_2O \rightarrow 2Na_{0.5}(Al_{1.5} Mg_{0.5}) Si_4O_{10}(OH)_2 + 2Na^+ + H_4SiO_4$$
 (5)

The hydrogeological facies of the W1 and W2 sources are non-dominant cations (NDC) – HCO₃. The facies evolved as Ca-HCO₃ at NN along the flow path. The conversion of kaolinite to Ca-montmorillonite is favoured by releasing {Na⁺} and {K⁺} into water (Appelo and Postma, 2004). The Ca-montmorillonite (CaX₂) seems to undergo reverse ion exchange producing Ca²⁺ into aqueous phase.

189 <u>Ion exchange</u>

190
$$CaX_2 + 2Na^+ \rightarrow 2NaX + Ca^{2+}$$
(6)

191
$$CaX_2 + 2K^+ \rightarrow 2KX + Ca^{2+}$$
(7)

Interestingly, at both W1 and W2 locations, the SO4²⁻ concentration is not high (Table 1). Compared to W1 and
 W2 locations, the SO4²⁻ concentration has increased by 200 folds. However, no sulfate-rich mineral phases can be
 seen. Hence high SO4²⁻ in NPV well water can be accounted for biogenic processes (Appelo and Postma, 2004;
 Bethke, 2007).

196 3.3 Configuration of the water treatment plant

197 The source groundwater selected (location NPV well) requires treating excess turbidity (0.22 NTU), hardness, and 198 TDS to improve palatability. The water type is Ca-HCO₃ (Dissanayake and Weerasooriya, 1985b) therefore, 199 flushing with rainwater or permeate is required to avoid membrane scaling. Ultrafiltration (UF) membranes are used 200 to remove water turbidity (DOC and microorganisms as well). Over 90 % turbidity is removed by ultra-filtration 201 (UF) under cross-flow or dead-end mode. Extended stay of raw water in the membrane compartment promotes 202 membrane fouling. Therefore, daily flushing of the membrane compartment with treated water or rainwater is 203 recommended. The concentrate and flushed water by UF treatment can be used for gardening or other purposes. 204 However, returning it to the raw water source is not recommended due to excess concentrates with colloids. In both 205 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 compositionto NF membrane is as in Figure 4. A.

208 An optimized membrane configuration is critical to yield desired water quality. Figure 4. B used both nano and 209 reverse osmosis membranes to devise the required membrane topology. The concentrate generated from the 210 nanomembrane was used as the feed water to the RO membrane. The two permeates, viz. nanomembranes and RO 211 membrane, are combined to receive the desired water quality. The concentrate generated at 90 % water recovery is 212 mixed with raw water to minimize environmental damage due to salinity. The source water contains excess non-213 carbonate hardness (395 mg/L, CaCO₃) and TDS (669 mg/L). Therefore, we selected NF and RO membranes suited 214 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). 215 The feed water was first treated with NF to remove excess hardness. The NF concentrate contains TDS 1722 mg/L 216 and hardness 433 mg/L CaCO₃, which was used as the feed solution of the RO membrane. The permeate after RO 217 contains TDS 26.0 and hardness 2.97 mg/L CaCO3 and F 0.78 mg/L. The concentrates after RO treatment contains 218 (2174 mg/L TDS) oversaturated conditions to calcite and gypsum mineral phases which can initiate membrane 219 scaling if kinetic conditions are favoured. The permeates are generated by RO and NF result in TDS 60.0 mg/L and 220 hardness 57.0 mg/L CaCO₃. The final concentrate yielded by the RO/NF membranes combination has TDS, 2174 221 mg/L and hardness 268 mg/L, CaCO₃. The concentrate is blended with raw water obtained at outlet reach TDS 1000 222 mg/L and 168 mg/L, CaCO₃. The agreement between modelled and observed water quality data at different points 223 is shown in Figure 5. As detailed elsewhere (Qian et al., 2020), the homogeneous solution model used for modelling 224 assumed water and solutes fluxes under pressure and concentration gradients, respectively.

225 **3.4 Smartphone applications**

The water purification plants are commonly used by the village community, where technical expertise is lacking 226 227 among them. Therefore, remote operation and user-level maintenance are achieved remotely by technically 228 competent personnel. Consequently, we developed a smartphone application using Java code. Java offers high 229 versatility in memory allocation, data transfer, run speed, and portability compared to other programming languages. 230 The smartphone application provides three functions in operating the laboratory-scale water treatment plant (Figure 231 5 for details). 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. 232 233 Water quality parameters such as TDS, EC, pH, hardness, and operate records can monitor runtime. They can be 234 transmitted to remote computer systems and saved in a database. The operator can monitor the process of the signal 235 lights on the platform from the video. The second function (F-2, Figure 5), the plant flushing management, provides 236 three flushing modes: (1) NF. — when only the NF is cleaning, (2) UF - when only the UF is cleaning, (3) NF. & 237 RO — during NF. & RO cleaning. When the water quality filter has been exhausted, the third function (F-3, Figure 238 5) automatically stops the filter. The operation of the water treatment plant occurs via a 4G signal transmit that can 239 be added to the cloud system to ensure versatility. Each function can be started independently. Finally, the display 240 on the right side of the filter result includes the working status display, the filter result data display, and the operation 241 log. In the future, the database poses big data, we will be able to optimize operation processing using the data 242 mining algorithm.

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246 **3.5** Community water treatment plant

Based on the concepts developed in this work, a water desalination treatment plant (scaled up to 5000 L/day) is 248 249 installed at the Nettiyagama Primary School to meet drinking and other water needs. The excess drinking water 250 produced is distributed among the village community under the preview of the School Development Society. The 251 water plant is in operation at permeate 95 % efficiency. The wastes generated are blended with the source water at a 252 1:9 ratio to be used in agriculture and sanitation. The annual variation of the TDS content of the source water is less 253 than 10 %. The total water production cost was calculated as 60.37 LKR/m³ after considering capital, power, 254 membrane replacement, and membrane costs. The mobile phone control developed for the laboratory module is not 255 yet available with the community scale plant. The water treatment method uses no chemicals, and the product is 256 named "Amaawatura".

257

258 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.

263 The scaled-up facility is now in operation at 5000 L/ day capacity in the village.

264

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- 269 formulations.
- 270

271 Declaration of conflicts of interest

272 All authors declared no conflicts of interest.

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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 are given in Figure 1-S and Table 1-S.



Figure 2: A: Geological map of 20 km² 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 1.D).



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



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

Е

0.202

60.0

57.0

6.25

0.101

0

438



Tuble 1. Geochemieur composition of water at reenarge (11 and 112) and discharge (11 v) points.	457	Table 1: Geochemical	composition of water	at recharge (W1 and	W2) and discharge	(NPV) points.
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Parameter		Location	
in mg/L except otherwise	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 CaCO3	31.7	32.6	740
Hardness, mg/L as CaCO3	55.4	74.5	390
Total Al	18.8	14.0	0.033
Ba ²⁺	0.02	0.06	ND
Br ⁻	0.420	0.000	0.075
Ca ²⁺	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
Mg^{2+}	7.23	10.4	37.1
NO ₃ -	0.12	0.61	26.7
Na ⁺	9.45	9.39	30.7
SO4 ²⁻	0.000	0.080	16.7
Sr^{2+}	0.168	0.199	0.492
Zn^{2+}	0.000	0.000	0.001

461 Table 2: Mathematical modelling of membrane water quality data (Hannesschlaeger <i>et al.</i> , 2019; Wijman	s and
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462 Baker, 1995); Taylor and Jacobs, 1996

Equation			Parameters
1)	Percentage rejection - Feed water cond	uctivity–Product water conductivity	1 utumotors
1)	100%	ed water conductivity	
2)	Percentage recovery $= \frac{Q_p}{Q_p + Q_c}$		Q_p - Water flow rate of permeate, m ³ /d Q_c - Water flow rate of rejection/concentrate, m ³ /d
3)	$J_w = A_w (\Delta P - \Delta \pi)$		J_W - Permeate flux, m/s A_W - Permeability coefficient, m/s, Pa ΔP - Pressure difference across the membrane, Pa $\Delta \pi$ - Osmotic pressure, Pa
4)	$J_{w} = \frac{Q_{p}}{A_{mem}}$		A_{mem} - Total membrane area, m ²
5)	$R_{s} = \left[1 + \frac{B_{s}}{A_{w}(\Delta P - \Delta \pi)}\right]^{-1}$		R_s - Salt rejection, % B_s - Solute transport parameter, m/s
6)	$R_s = 1 - \frac{TDS_P}{TDS_f}$		TDS_p -TDS values of permeate, ppm TDS_f -TDS values of feed water, ppm
7)	$\Delta \pi = RT \sum_{v}^{n} \frac{n}{v}$		<i>R</i> - Gas constant, J/mol K <i>T</i> - Temperature, K n – Number of moles, mole v – Volume, L
8)	$R = \frac{q_p}{q_f}$		<i>R</i> -Recovery ratio Q_f – Water flow rate of feed water, m ³ /d
9) Q _f C	Mass balance $f_f = Q_p C_p - Q_c C_c$		C_f -Solute concentration of feed water C_p -Solute concentration of permeate C_c -Solute concentration of concentrate
10)	$\Delta P = \frac{P_f + P_c}{2} - P_p$		P_f - Feed water pressure, Pa P_c -Concentrate pressure, Pa P_p - Permeate pressure, Pa
11)	$A_{mem} \approx \left(\frac{1000 \times Q_h}{\phi_1}\right) + z \left(\frac{1000 \times Q_h}{\phi_2}\right)$		ϕ - Average flux (l/h.m ²) z - Selection factor, one for a double pass system, or zero for a single-pass system
12)	$E_{other} \approx \left[\frac{Q_h \times P_f}{36 \times \eta}\right]$		E_{other} - Other additional energy η - Efficiency of other units
13)	$E_T = E_{desal} + E_{ERD} + E_{other}$		E_T -Total energy required for the entire RO process
14)	$J_i = k_i \Delta C = \frac{Q_p C_p}{A}$		$\begin{array}{l} J_i\text{-Solute flux, } M/L^2t \\ \Delta C\text{-Concentration gradient, } M/L^3\text{, } [(C_f+C_c)/2\text{-}C_p] \end{array}$
15)	$C_{p,i} = \frac{k_{i,i}C_{f,i}}{k_{w,i}\Delta P_i[(2-2r_i)/(2-r_i)] + k_{i,i}} = Z_i C_{i,j}$	Ĉf,i	K_{iv} - Solvent mass transfer coefficient, L ² t/M K_i - Solute mass transfer coefficient, L/t r- Recovery Z_i - modified mass transfer coefficient $\Delta P_i = \Delta P - \Delta \pi =$ Net average driving pressure including hydraulic losses <i>Subscript i</i> any stage in multistage membrane array

$$16) \quad C_{c,i} = \frac{Q_{f,i}C_{f,i}-Q_{p,i}C_{p,i}}{Q_{c,i}} = \frac{C_{f,i}-r_iC_{p,i}}{1-r_i}$$

$$17) \quad C_{c,i} = C_{f,i+1} = C_{f,i} \left(\frac{1-Z_ir_i}{1-r_i}\right)$$

$$18) \quad C_{c,i} = X_iC_{f,i} \quad , \quad X_i = \frac{1-Z_ir_i}{1-r_i} \quad \text{define } X_0 \equiv 1$$

$$19) \quad C_{p,system} = \frac{C_f \sum_{i=1}^n (A_ik_{w,i}\Delta P_i Z_{i,cp} \prod_{j=0}^{i-1} X_{j,cp})}{\sum_{i=1}^n A_ik_{w,i}\Delta P_i}$$

$$20) \quad C_{p,system} = \frac{C_f \sum_{i=1}^n (A_ik_{w,i}\Delta P_i Z_{i,cp} \prod_{j=0}^{i-1} X_{j,cp})}{L_{i=1}^n A_ik_{w,i}\Delta P_i} \prod_{j=0}^{1-\frac{k_{i,j}r_j}{1-r_j}} \frac{A_i \text{-}\text{Total membrane area}}{Z_{i,cp} \text{-}Modified film theory feed stream} \\ \frac{C_f \sum_{i=1}^n \left[A_ik_{i,i}\Delta P_i \frac{k_{i,i}}{k_{w,i}\Delta P_i[(2-2r_i)/(2-r_i)] + k_{i,i}} \prod_{j=0}^{1-\frac{k_{i,j}r_j}{1-r_j}} \frac{1-\frac{k_{i,j}r_j}{k_{w,j}\Delta P_j[(2-2r_j)/(2-r_j] + k_{i,j}]}}{\sum_{j=1}^n A_ik_{w,i}\Delta P_i} \right]}$$

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

467	Parameter	Groundwater	Surface water
468		Mean \pm s. d	Mean \pm s. d.
469		N = 67	N =10
470	рН	7.31 ± 0.34	7.60 ± 0.20
471	TDS (ppm)	455 ± 191	39.0 ± 11.0
472	Conductivity (μ S cm ⁻¹)	932 ± 376	94.0 ± 18.0
473	Turbidity (NTU)	2.79 ± 8.24	6.09 ± 1.66
474	Alkalinity (ppm CaCO ₃)	366 ± 87	65.6 ± 5.5
475	Total hardness (ppm CaCO ₃)	641 ± 305	39.5 ± 4.9
476	F ⁻ (ppm)	0.95 ± 0.58	0.14 ± 0.03