A study of saltwater intrusion in the Kallada River, southwest coast of Kerala, India

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ABSTRACT

Munroe Island in Kollam District of Kerala is a typical backwater village situated at the confluence of the Ashtamudi backwater and the Kallada River system. It is an amalgamation of eight small islands with a total area of 13.4 km². Salinity intrusion has been a serious threat in the downstream areas of Kallada River for more than one and half decades, affecting the groundwater quality of Munroe Island. The present study focuses on the seasonal variation in physico-chemical characteristics of the underground water system of Munroe Island and Kallada River with special reference to saline water intrusion. Physico-chemical analysis of ground water revealed that samples were unsuitable for drinking due to higher content of Na, Ca, and K. Microbiological analysis of island groundwater showed the presence of coliform and E. coli bacteria above the permissible limit. Results indicated a significant correlation between salinity and major anions viz., Cl⁻ and SO₄²⁻ and cations viz., Mg, Na, Ca, and K of both river surface and island groundwater. In the present study it is clearly evident the occurrence of saltwater intrusion in Kallada River from Ashtamudy Lake and the its severity become higher during premonsoon season. The results also indicated that the salinity increase in Kallada River has a negative impact on island groundwater quality. The paper also suggests suitable management strategies for overcoming the saltwater intrusion thereby upgrading island sustainability.

Key words: groundwater, Kallada River, management, Munroe Island, saltwater intrusion, water quality

HIGHLIGHTS

• Identified saltwater intrusion in Kallada River.
• Impact of saltwater intrusion in island groundwater quality.
• Seasonal variation of physico-chemical parameters of river and island groundwater.
• Suggesting suitable management measures to prevent salt water intrusion.

INTRODUCTION

Water is essential for life. The amount of freshwater on the earth is limited, and its quality is under constant pressure. Water quality refers to the chemical, physical, biological, and radiological characteristics of water (UNDESA 2015). The lack of water quality adversely affect the health of living beings (Balwant et al. 2016). Environmental factors such as the occurrence of highly soluble or easily weathered minerals, distance to the marine environment, aridity, terrestrial primary productivity, ambient temperature, the weathering reaction kinetics, and quality of unpolluted waters influence the river water chemistry (Gibbs 1970).

In the coastal aquifer, seawater lies under freshwater as it is less dense, serving to push the seawater interface seaward. The zone of contact between freshwater and seawater is called brackish water (Werner et al. 2013). The seawater intrusion problem is one of the most important environmental issues that negatively affect groundwater resources since groundwater salinity leads to a reduction in freshwater availability and the degradation of groundwater quality (Nguyen et al. 2019). The process of saltwater intrusion is the phenomenon of the sea and river water mixing, and the estuarine stratification is the combination of small-scale turbulent diffusion and large-scale variation of the field of island constituting velocities, not constant either in time, space, and direction (Antony & Ignatius 2016).

Therefore, the study of seawater intrusion into coastal aquifers is highly needed to identify the affected zones where it should be able to prevent problems or remediate such areas efficiently.
During summer, the severity of saltwater intrusion increases with the decrease in groundwater recharge and increase in water demand (Al-Mikhlafi et al. 2003). Water management sectors such as agriculture, domestic, and industrial water supply may be affected by the salinization of groundwater systems (Kang & Jackson 2016). Increasing salinity from saltwater intrusion affects agriculture, aquaculture, infrastructure, coastal ecosystems, and the availability of freshwater for household and commercial use, which in turn create a negative impact on livelihoods and public health (Varol & Davraz 2016).

Kerala has a typical coastal aquifer system subjected to saltwater intrusion affecting groundwater sources including wells. Saltwater encroaches into wells when the sea levels rise or also when the groundwater table decreases, tides change, or when aquifers are fractured. Destruction of freshwater lakes and the conversion of wetlands contribute to the decrease in the water table (Brindha et al. 2014). Rising sea levels due to global climate change is only one of the reasons directly affecting this problem.

Munroe Island is an island group comprising of eight medium size and a few tiny islands located in the backwaters of the famous Ashtamudy Lake in Kerala, South India. The Munro Island with an area of 13.4 km² is situated at the confluence of the Ashtamudy Lake and the Kallada River. It is an artificial island built during the 18th century by reclamation of the Kallada River delta on the downstream side, where it debouches into the Arabian Sea. The individual islands of the Munro group, with an elevation of 3.3 m (approximately) above mean sea level.

The urgent concern for the present study is that recently the low-lying areas of the Munroe Island are facing a serious threat of water upwelling, salinity problems, poor drinking water quality and agricultural failure for more than one and half decades. The drinking water source for island inhabitants is private open wells. But due to colour change and taste differences of water in most of the wells, pure drinking water availability is scarce in the panchayat. Increased sea level rise and decreased flow rate of Kallada River due to the construction of Thenmala dam as a part of Kallada irrigational project are claimed as some of the reasons of water upwelling and saltwater intrusion in the island.

No systematic scientific studies were conducted so far to determine the occurrence of saltwater intrusion, this study aims to scientifically prove the severity and occurrence of saltwater intrusion occurring at various seasons, its impact on Munroe Island groundwater quality, and suggesting suitable management strategies for overcoming the current environmental degradation of island.

Study area

Munroe Island, locally known as Mundrothuruth, is an amalgamation of eight small islands in the archipelago of the Islands of Kollam. It has an area of 13.4 km². The island extends from 9 °00’0’’N to 76 °035’0’’E to 9 °00’0’’N to 76 °040’0’’E (Figure 1). Mundrothuruth Panchayat is under Chittumala Block division consisting of 12 wards. It has a total population of 9,599, consisting of 4,636 males and 4,963 females (District Census Hand Book 2011). The place is named in honour of Resident Colonel John Munroe of the farmer princely state of Travancore. During his tenure, Munroe oversaw the land reclamation efforts in the delta where one side of island is surrounded by Kallada River which originates from the western Ghats, travels 121 km with an average annual runoff of 2,152 million cubicmeters (MCM) of freshwater at the inlet of the basin and enters into the Ashtamudy Lake and then debouches to the Arabian Sea.

Ashtamudy Lake is the second largest lake, next to Vembanad lake in the state of Kerala, India. Ashtamudy wetland is an estuary filled with brackish water and sewage. This lake has eight arms and all the arms converge into a single outlet at Neendakara near Kollam, to enter the Arabian Sea. Ashtamudy is the deepest estuary in Kerala with a maximum depth of 6.4 m at the convergence zone.

Geology

The dominant lithology of the island constitutes the mainland composed of sedimentary rocks and low land of the deltaic region, near the banks of Kallada River and at the confluence of Ashtamudy Lake. The area surrounding the Munroe Island is a part of the Ashtamudy estuary which forms an important geological segment of the South Indian peninsular shield. Both crystalline rocks and tertiary sediments are the major components of the estuary. Sedimentary rocks belonging to the Warkalli and Quilon formation constitute the dominant lithology of the main island and nearby area (Kurian et al. 2001). The quaternary sediments are of marine and the fluvial origin are seen in the low lying area mostly by the side of Kallada River and to the western part in proximity with the Ashtamudy Lake are of numerous tidally active creeks.

The coastal configuration and land forms vary widely depending upon the intensity of wave action, tides, other currents, sediment load, stage of the rivers, wind action and the ever changing riverine regime. The shorelines can be straight or
irregular depending upon the structural features and wave energy. The delta formation along the river mouths has also an important role in the coastal hydro geologic scenario. The distribution of freshwater aquifers is controlled by the dynamic equilibrium between hydrostatic heads in the fresh and saline water zones, influx of sea water into the streams and lagoons and the relative amount of sea in respect to the land mass.

Objectives of study
To study the severity and occurrence of saltwater intrusion occurring at various seasons, its impact on Munroe Island groundwater quality, and suggesting suitable management strategies for overcoming the current environmental degradation of the island.

MATERIALS AND METHODS
Water samples from five different stations of the Kallada River basin were collected during pre-monsoon, monsoon, and post-monsoon seasons respectively. The samples were collected from five different stations 2 km apart from the downstream area of the river, near the confluence of Ashtamudy Lake towards the upstream area to the island proximal end covering a distance of 10 km (Table 1 & Figure 2). This method of sampling was done to understand the occurrence and severity of saltwater intrusion during various seasons with increasing distance from the river lake confluence. Groundwater samples from five different stations were collected in clusters but the network method was followed to determine the rate of saline water intrusion with increasing distance from the riverside to the mainland (Table 2 & Figure 3).

The study was conducted for a period of one year from December 2019 to November 2020 covering pre-monsoon, monsoon and post-monsoon seasons. For the assay of physico-chemical parameters, the following methods were adopted. pH was measured using pH meter, electrical conductivity (EC) using reference electrodes, total dissolved solids (TDS) was arrived at from calculation. The physico-chemical parameters are estimated by following the standard analytical procedures and techniques.
| Sl.No | Sampling station                         | Latitude          | Longitude         |
|------|-----------------------------------------|-------------------|------------------|
| 1    | Edachal bridge (RWS1)                    | N 8° 58’ 37.9596″ | E 76° 36’ 32.2848″ |
| 2    | Perungalamkadavu (RWS2)                  | N 8° 59’ 32.7984″ | E 76° 36’ 22.032″ |
| 3    | Pulimootilkadavu (RWS3)                  | N 8° 59’ 53.79″   | E 76° 36’ 23.7096″ |
| 4    | Karuthrakadavu (RWS4)                    | N 8° 59’ 59.6724″ | E 76° 37’ 6.8664″ |
| 5    | Ediyakadavu bridge (RWS5)                | N 9° 0’ 9.2736″   | E 76° 37’ 56.6976″ |

**Figure 2** | Location map of river water sampling station.
| Sl. No | Sampling station             | Latitude            | Longitude           |
|-------|-----------------------------|---------------------|---------------------|
| 1     | Kidapram (WWS1)             | N 9° 0’ 3.0658”     | E 76° 36’ 40.5256”  |
| 2     | Nenmeni kizhekku (WWS2)     | N 8° 59’ 44.3682”   | E 76° 36’ 43.1466”  |
| 3     | Pattamthuruth North (WWS3)  | N 8° 59’ 9.8665”    | E 76° 36’ 43.5227”  |
| 4     | Pattamthuruth East (WWS4)   | N 8° 58’ 54.9813”   | E 76° 36’ 36.3165”  |
| 5     | Edachal South (WWS5)        | N 8° 58’ 40.4043”   | E 76° 36’ 32.7825”  |

**Figure 3** | Location map of well water sampling station.
reported in the literature (APHA 2017). The salinity of river and groundwater samples were measured at the field itself with the help of a portable salinometer. The total viable count was performed on nutrient agar using the serial dilution agar plating method and total coliform count by most probable number (MPN) test to assess the domestic pollution level, using phenol red lactose broth (Ahmed et al. 2013).

RESULTS AND DISCUSSION

Physico-chemical characteristics of river water

The analytical results of the river water samples for pre-monsoon, monsoon, and post-monsoon and their corresponding results are shown in (Tables 3 and 4). Location names starting from RWS1 to RWS5 represent the river water samples collected from stations 1 to 5 respectively (Table 1).

pH of water summarizes the stability of the balance between different forms of carbonic acid and is linked to the system buffer developed by carbonates and bicarbonates (Joseph & Jacob 2010). In the present study, pH of the river water samples showed the highest value at RWS1 (7.85) during pre-monsoon and the lowest at RWS4 (6.15) during monsoon. According to Saravanakumar et al. 2008, pH values are inseparable from the values of temperature, salinity, and the rate of CO2, which are positively correlated with the acidity of water.

The conductivity of water is an indicator of changes in the composition of materials in water and proportional to the total dissolved salts. Increasing temperature, as well as salinity, affect the conductivity values to a great extent (Sujitha et al. 2012).

The results showed a marked seasonal variation in conductivity. The highest value of 20,140 µs/cm was recorded at RWS1 in pre-monsoon and the lowest value of 1,021 µs/cm at RWS5 in monsoon. Moreover, the conductivity values also revealed a

| Table 3 | Physico-chemical characteristics of river water during pre-monsoon and monsoon seasons |
|---------|-------------------------------------------------|
| Parameters                  | Pre-monsoon Sampling station | Monsoon Sampling station |
|                             | RWS1 | RWS2 | RWS3 | RWS4 | RWS5 | RWS1 | RWS2 | RWS3 | RWS4 | RWS5 |
| pH                          | 7.85 | 7.11 | 6.83 | 6.91 | 6.55 | 6.98 | 6.75 | 6.33 | 6.15 | 6.29 |
| EC (µs/cm)                  | 20,140 | 19,420 | 11,355 | 9,258 | 10,826 | 16,351 | 18,110 | 12,113 | 1,053 | 1,021 |
| TDS (mg/L)                  | 14,585 | 18,360 | 11,312 | 11,455 | 12,136 | 9,369 | 10,522 | 8,396 | 8,150 | 9,140 |
| Salinity (ppt)              | 10.25 | 9.86 | 9.34 | 6.88 | 6.15 | 10.25 | 9.86 | 9.34 | 6.88 | 6.15 |
| Turbidity (NTU)             | 2.21 | 2.33 | 0.95 | 1.33 | 0.81 | 2.96 | 2.55 | 1.35 | 0.85 | 0.99 |
| Total hardness (mg/L)       | 3,398 | 2,281 | 2,341 | 2,163 | 1,647 | 2,367 | 1,838 | 1,988 | 1,099 | 1,383 |
| Ca hardness (mg/L)          | 433.2 | 316.8 | 178.2 | 231.4 | 111.3 | 236.7 | 1,838 | 1,988 | 1,099 | 1,383 |
| Mg hardness (mg/L)          | 2,965 | 1,965.3 | 2,163 | 1,932 | 1,536.4 | 1,972.1 | 1,517.1 | 1,732.5 | 928.6 | 1,255.6 |
| Total alkalinity (mg/L)     | 43.12 | 45.43 | 38.33 | 35.26 | 36.45 | 39.45 | 321.2 | 256.5 | 171.1 | 128.2 |
| Chlorides (mg/L)            | 7,350 | 6,931.7 | 4,430 | 3,440 | 4,130.1 | 5,351.7 | 4,956.3 | 4,130.8 | 4,851.3 | 3,945.1 |
| Sulphate (mg/L)             | 1,396 | 936.3 | 751.5 | 710.3 | 733.6 | 831.2 | 715.8 | 759.9 | 813.2 | 732.4 |
| Nitrate (mg/L)              | 0.34 | 0.41 | 0.53 | 0.33 | 0.21 | 0.29 | 0.39 | 0.35 | 0.71 | 0.88 |
| Phosphates (mg/L)           | 0.13 | 0.23 | 0.15 | 0.29 | 0.15 | 0.25 | 0.22 | 0.31 | 0.29 | 0.15 |
| Calcium (mg/L)              | 185.2 | 190.33 | 121.3 | 95.67 | 73.15 | 120.31 | 115.26 | 79.26 | 95.44 | 106.36 |
| Magnesium (mg/L)            | 793.2 | 631.33 | 444.8 | 397.1 | 381.9 | 495.35 | 397.1 | 435.27 | 316.6 | 344.2 |
| Sodium (mg/L)               | 4,255 | 4,110 | 3,183 | 2,118 | 2,196 | 3,245 | 3,131 | 2,175 | 1,975 | 1,765 |
| Pottasium (mg/L)            | 110.1 | 75.6 | 89.5 | 39.5 | 35.5 | 75.15 | 81.23 | 55.31 | 31.65 | 42.41 |
| Iron (mg/L)                 | 0.09 | 0.17 | 0.08 | 0.33 | 0.95 | BDL | 0.31 | 0.29 | 0.15 |
| DO                          | 6.65 | 6.93 | 7.15 | 7.95 | 9.28 | 7.22 | 7.95 | 8.23 | 9.28 | 11.15 |
| BOD                         | 1.39 | 1.13 | 0.96 | 0.85 | 0.77 | 0.98 | 0.77 | 0.95 | 0.83 | 0.93 |
| COD                         | 460.9 | 276.6 | 135.5 | 85.5 | 106.5 | 125.5 | 98.8 | 133.1 | 96.3 | 89.3 |
gradient of decrease from downstream to upstream locations (RWS1 to RWS5). This may be explained by the far-off marine influences viz., tide and intrusion.

TDS comprise inorganic salts and small amounts of organic matter dissolved in water (WHO 1993). Concentrations exceeding the recommended value for drinking purposes (500 mg/L) give water an unpleasantly salty taste, making it unsuitable for drinking, irrigation, or other uses (Tiwari & Singh 2014). The highest TDS value was recorded at RWS2 (18,360 mg/L) and the lowest at RWS4 (8,150 mg/L) during pre-monsoon and monsoon seasons respectively. The maximum value during post-monsoon was recorded at RWS2 (13,175 mg/L). Climate affects concentrations of dissolved solids through precipitation, evaporation, and runoff. During pre- and post-monsoon seasons, as the precipitation is low and the evaporation rate is high, there is less water to dilute the dissolved salts and that may be the reason for the higher TDS values.

Salinity refers to the quantity of dissolved salt content in water. The salinity of surface and groundwater is determined by a combination of factors, including river flow, tidal surges, rainfall, and groundwater extraction, as well as the influence of sea level rise and other climatic variables (Khan et al. 2008). The salinity in the study area exhibited extreme values during various seasons with a pronounced descending gradient from downstream to the upstream part of the river (Figure 6). Similar spatial variation of salinity has also been studied elsewhere (Dipu & Josna 2020). Maximum salinity values were recorded from RWS1 (10.25 ppt) and RWS2 (10.15 ppt) during pre-monsoon and monsoon seasons respectively. The values decreased to 8.32 ppt for RWS1 (downstream) and 5.73 ppt for RWS5 (upstream) during monsoon. Here, increasing sea level, tidal surges, and decreased river flow rate played a vital role in rising salinity during pre- and post-monsoon, whereas dilution of water due to precipitation and increased river flow rate decreased salinity during monsoon.

Total hardness (TH) is a parameter of water quality used to describe the effect of dissolved minerals (Ca and Mg) that determine the solubility of water for domestic, industrial, and drinking purposes (Varol & Davraz 2016). A maximum value of

| Table 4 | Physico-chemical characteristics of river water during post-monsoon |
|---------|----------------------|
| Parameters | Post-monsoon |
|           | Sampling stations |
|           | RWS1 | RWS2 | RWS3 | RWS4 | RWS5 |
| pH       | 7.15 | 7.09 | 6.83 | 6.55 | 6.91 |
| EC (μs/cm) | 19,320 | 18,415 | 15,290 | 14,356 | 12,715 |
| TDS (mg/L) | 12,135 | 13,175 | 9,475 | 8,334 | 9,151 |
| Salinity (ppt) | 9.16 | 10.15 | 8.14 | 6.33 | 6.95 |
| Turbidity (NTU) | 1.95 | 2.03 | 1.15 | 0.961 | 0.765 |
| Total hardness (mg/L) | 2,293 | 1,991 | 1,669 | 1,934 | 1,552 |
| Calculated hardness (mg/L) | 358.13 | 259.22 | 138.22 | 198.3 | 121.2 |
| Magnesium hardness (mg/L) | 1,935.2 | 1,732.8 | 1,531.2 | 1,736.2 | 1,431.4 |
| Total alkalinity (mg/L) | 45.26 | 40.15 | 33.28 | 29.21 | 31.35 |
| Chlorides (mg/L) | 6,135.8 | 5,389.2 | 4,378.4 | 4,751.1 | 3,961.7 |
| Sulphate (mg/L) | 951.2 | 833.13 | 795.5 | 816.7 | 716.6 |
| Nitrate (mg/L) | 0.31 | 0.15 | 0.29 | 0.19 | 0.13 |
| Phosphate (mg/L) | 0.14 | 0.25 | 0.09 | 0.16 | 0.22 |
| Calcium (mg/L) | 125.6 | 133.4 | 151.31 | 106.3 | 99.36 |
| Magnesium (mg/L) | 596.3 | 493.6 | 396.6 | 414.4 | 386.4 |
| Sodium (mg/L) | 3,458.1 | 2,985.2 | 2,739.6 | 2,133.2 | 2,238.6 |
| Potassium (mg/L) | 42.56 | 39.45 | 26.22 | 45.21 | 31.42 |
| Iron (mg/L) | BDL | BDL | 0.65 | 0.31 | BDL |
| DO | 6.69 | 6.53 | 6.14 | 7.35 | 7.91 |
| BOD | 1.15 | 1.59 | 0.56 | 0.93 | 0.88 |
| COD | 322.3 | 265.3 | 161.2 | 105.5 | 99.81 |
3,398 mg/L was recorded at RWS1 in pre-monsoon, whereas its value reduced to 2,293 mg/L in post-monsoon. From the results, it is evident that the higher hardness value in the summer is mainly attributed to the rising temperature, facilitating the solubility of calcium and magnesium salts (Garg 2003). Moreover, these elevated values towards the downstream parts reveals sea water influences. Total alkalinity and hardness are related through common ions such as carbonates and bicarbonates of Ca and Mg in aquatic systems. So the total alkalinity values in the present investigation also showed similar spatial and temporal changes as that of total hardness (Figure 4).

Calcium and magnesium concentrations in ground and surface waters are governed by the dissolution of the bedrock containing their minerals. Calcium compounds occur naturally in surface water, and their concentrations are determined mainly by the carbonate balance (Khan et al. 2008). Ca and Mg concentration recorded maximum values during pre-monsoon at RWS1, and the corresponding values are 185.2 mg/L and 793.2 mg/L (Figure 5).

Figure 4 | Seasonal variation of total hardness and total alkalinity in river water.

Figure 5 | Seasonal variation of calcium, magnesium, sodium, and potassium in river water.
Sodium is one of the important naturally occurring cations and its concentration in freshwater is generally lower than that of calcium and magnesium (Tiwari & Singh 2014). But, in the present study, this order is reversed with an extremely higher concentration of Na. The highest content (4,255 mg/L) was observed at RWS1 during pre-monsoon and the lowest (1,765 mg/L) at RWS5 during monsoon. The post-monsoon sample recorded the highest value of 3,488 mg/L at RWS1. Saltwater intrusion attributed to such extreme values for Na in the study area (Figure 5). Potassium is usually found extensively in rock minerals and its concentration in natural waters is very low because of the resistance offered by potassium minerals to weathering and dissolution (Hem 1985). Potassium content registered a maximum value of 110.1 mg/L at RWS1 during pre-monsoon (Figure 5).

Chloride ions have a large migratory ability in connection with the very high solubility of chloride salts of sodium, magnesium, and calcium (Nikanorov & Brazhnikova 2009). Their concentration above 250 mg/L gives a noticeable salty taste to water (Sujitha et al. 2012). The chloride content of all the samples during the whole study period exceeded the permissible limit (Tables 2 and 3) for both drinking and irrigational purposes. Higher values of chloride towards the downstream direction indicate seawater intrusion (Figure 6).

Sulphate in natural water generally occurs as soluble salts of calcium, magnesium, and sodium (NAS 1977). Its content in the study area showed higher values near the downstream locations with a maximum value of 1,396 mg/L at RWS1. Higher contents indicate the influence of seawater. Nutrients such as nitrate and phosphate were detected at low concentrations in most of the sampling stations. Iron content in all the river water samples was very low or BDL and recorded a maximum value of 0.96 mg/L.

Dissolved oxygen (DO) is essential for the maintenance of healthy lakes and rivers, and a measure of the ability of water to sustain aquatic life. Its content varies with temperature, salinity, turbulence, and photosynthetic activity of algae. DO showed relatively higher values during monsoon with a maximum of 11.5 mg/L recorded at RWS5 near the upstream area (Figure 7). A low DO value of 6.61 was observed during post-monsoon at RWS1, near the downstream end. Biological oxygen demand (BOD) is used as the index of organic pollution of wastewater that decomposed by bacteria under anaerobic conditions (Garg 2003). All the river water samples showed BOD levels within the permissible limit with values ranging from 0.56 to 1.59 mg/L during all seasons. Chemical oxygen demand (COD) is widely used as a measure of the susceptibility to oxidation of the organic and inorganic materials present in water bodies and municipal and industrial wastes. Higher COD values indicate pollution from domestic sewage and industrial effluents (Tiwari & Singh 2014). COD varies from a minimum value of 85 mg/L at RWS4 to a maximum value of 460.9 mg/L at RWS1 near the river confluence (Figure 7). The increase in COD level near river mouth confluence shows the pollution status of the Ashtamudy Lake.
Physico-chemical characteristics of Island ground water

The results of the physicochemical analyses of the groundwater samples are presented in (Tables 5 and 6). For groundwater analysis, five different stations starting from GWS1 to GWS5 were fixed, and samples were collected in clusters in a network manner to determine the rate of saline water intrusion with increasing distance from the riverside.

The pH of groundwater samples showed values within the permissible limit (6.5–8.5) of the Bureau of Indian Standards (BIS 2012). The values ranged from 6.02 to 8.51 for different seasons. Turbidity of the groundwater samples exhibited relatively higher contents for all the seasons. The values ranged from 4.2 and 17.3 NTU in pre-monsoon, 11.8 and 19.5 NTU in monsoon and 11.3 and 21.6 NTU in post-monsoon respectively. Higher content of turbidity in water affects its portability. The permissible limit of turbidity for drinking purposes according to BIS (2012) is 5 NTU.

The EC ranged from 122.1 to 338.5 μS/cm during pre-monsoon, 139 to 295 μS/cm during monsoon, and 148 to 255 μS/cm during post-monsoon respectively. Higher values for EC were noticed at GWS1 and GWS2 (Tables 4 and 5), located near the riverside, for all the seasons. EC is an excellent indicator of TDS, which in turn is a measure of salinity that affects the taste of potable water (Weast 1968). Since EC is directly related to TDS, the samples showing higher contents of EC support higher TDS concentration (Anna 2017). During pre-monsoon, the TDS values ranged from 395 to 720 mg/L, comparatively lower values that ranged from 358 to 686 mg/L were detected during monsoon, and for post-monsoon the values ranged from 450 to 693 mg/L. Water resources with TDS values less than 300 mg/L are considered excellent, 300–600 mg/L good, 600–900 mg/L fair, and 900–1,200 mg/L poor (WHO 1993). Higher TDS of water have a heavier taste and a much more prominent ‘mouth feel’, which includes saltiness due to an appreciable sodium content in the water (Venketesan & Senthil 2018).

Salinity shows seasonal variation with relatively higher contents during pre-monsoon, ranging from 0.11 ppt to 1.02 ppt. Comparatively low values were detected during monsoon (0.16 ppt to 0.35 ppt) and post-monsoon (0.14 to 0.95 ppt). For all the seasons, the values, in general, showed a decreasing trend from GWS1 near the riverside towards GWS5, near the high land, except for GWS4 (Figure 10) as this area is affected by tidal upwelling. This reveals salinity intrusion from the river to the groundwater system. According to Holland et al. (2006) hydraulic connections with salty tidal waters occur in shallow, unconfined (water table) aquifers and less frequently in deeper, confined aquifers. When a saltwater intrusion occurs in confined aquifers, the saltwater intrudes through natural erosional channels in the overlying clay layers or leaky clay layers.

Figure 7 | Seasonal variation of COD, DO, and BOD in river water.
### Table 5 | Physico-chemical characteristics of island groundwater during pre-monsoon and monsoon

| Parameters       | Sampling stations | Sampling stations |
|------------------|-------------------|-------------------|
|                  | GWS1   | GWS2   | GWS3   | GWS4   | GWS5   | GWS1   | GWS2   | GWS3   | GWS4   | GWS5   |
| pH               | 6.75   | 6.02   | 6.11   | 6.8    | 5.25   | 7.02   | 6.85   | 7.11   | 8.1    | 8.5    |
| EC (μs/cm)       | 338.5  | 230.1  | 128.5  | 122.1  | 133.9  | 260    | 295    | 230    | 256    | 139    |
| TDS (mg/L)       | 598    | 726    | 698    | 405    | 395    | 670    | 686    | 525    | 489    | 358    |
| Salinity (ppt)   | 1.03   | 0.88   | 0.32   | 0.11   | 0.74   | 0.31   | 0.25   | 0.16   | 0.33   | 0.25   |
| Turbidity (NTU)  | 14.3   | 16.5   | 12.5   | 17.3   | 4.2    | 18.6   | 11.8   | 16.95  | 19.55  | 12.78  |
| Total hardness (mg/L) | 123.55 | 174.22 | 54.22  | 79.35  | 105.4  | 110.72 | 151.76 | 98.55  | 119.22 | 109.29 |
| Total alkalinity (mg/L) | 32.18  | 14.55  | 4.12   | 12.39  | 29.22  | 23.96  | 19.38  | 15.55  | 9.08   | 8.59   |
| Chlorides (mg/L) | 382.11 | 245.26 | 42.65  | 70.26  | 144.51 | 245.44 | 198.65 | 210.28 | 191.69 | 125.16 |
| Sulphate (mg/L)  | 17.12  | 28.15  | 49.22  | 31.45  | 19.25  | 51.59  | 48.66  | 20.36  | 75.19  | 79.11  |
| Nitrate (mg/L)   | 14.25  | 3.24   | 4.21   | 2.17   | 7.34   | 9.23   | 5.27   | 3.04   | 2.55   | 6.33   |
| Phosphate (mg/L) | 0.09   | 0.06   | 0.05   | 0.08   | 0.05   | 0.09   | 0.03   | 0.02   | 0.09   | 0.05   |
| Calcium (mg/L)   | 6.27   | 18.24  | 19.58  | 12.35  | 36.42  | 9.55   | 11.34  | 7.34   | 5.29   |        |
| Magnesium (mg/L) | 1.9    | 0.98   | 12.45  | 0.75   | 5.22   | 1.55   | 1.23   | 0.99   | 1.58   | 3.45   |
| Sodium (mg/L)    | 21.4   | 17.89  | 163.45 | 123.11 | 31.44  | 59.63  | 102.16 | 95.17  | 78.09  | 86.11  |
| Pottasium (mg/L) | 4.92   | 6.22   | 2.72   | 1.7    | 3.8    | 6.51   | 5.93   | 4.29   | 2.75   | 5.16   |
| Iron (mg/L)      | BDL    | BDL    | 0.12   | 0.19   | BDL    | BDL    | BDL    | BDL    | BDL    | BDL    |
| Total coliform (MPN/100 ml) | 50    | 120    | 80    | 30    | 90    | 30    | 70    | 155    | 50    | 20    |
| E. coli          | Absent | Absent | Absent | Absent | Present | Absent | Absent | Absent | Absent | Present |

### Table 6 | Physico-chemical characteristics of island groundwater during post monsoon

| Parameters       | Sampling stations |
|------------------|-------------------|
|                  | GWS1   | GWS2   | GWS3   | GWS4   | GWS5   |
| pH               | 6.89   | 6.55   | 6.33   | 7.31   | 6.99   |
| EC (μs/cm)       | 255    | 239    | 228    | 198    | 215    |
| TDS (mg/L)       | 693    | 655    | 450    | 518    | 515    |
| Salinity (ppt)   | 0.49   | 0.35   | 0.21   | 0.14   | 0.93   |
| Turbidity (NTU)  | 21.16  | 19.33  | 16.38  | 13.45  | 11.33  |
| Total hardness (mg/L) | 119.22 | 139.26 | 131.41 | 115.85 | 115.85 |
| Total alkalinity (mg/L) | 28.29  | 25.33  | 18.21  | 9.22   | 8.56   |
| Chlorides (mg/L) | 270.41 | 230.68 | 209.41 | 245.11 | 203.14 |
| Sulphate (mg/L)  | 62.04  | 58.42  | 39.55  | 46.33  | 71.99  |
| Nitrate (mg/L)   | 4.22   | 3.01   | 2.97   | 3.04   | 4.11   |
| Phosphate (mg/L) | 0.05   | 0.03   | 0.09   | 0.08   | 0.02   |
| Calcium (mg/L)   | 7.96   | 10.33  | 6.54   | 7.99   | 6.65   |
| Magnesium (mg/L) | 2.33   | 1.96   | 1.85   | 2.32   | 1.96   |
| Sodium (mg/L)    | 69.33  | 94.37  | 111.78 | 95.25  | 83.24  |
| Pottasium (mg/L) | 4.31   | 5.22   | 3.93   | 3.15   | 6.05   |
| Iron (mg/L)      | BDL    | BDL    | BDL    | BDL    | BDL    |
| Total coliform (MPN/100 ml) | 50    | 45    | 60    | 35    | 20    |
| E. coli          | Absent | Absent | Absent | Absent | Present |
Total hardness and total alkalinity values were within the permissible limits for all the samples throughout the investigation (Figure 8). The seasonal and temporal variations indicate maximum values in pre-monsoon season towards the downstream sampling stations.

The calcium concentration of open-well samples exhibited spatial and temporal variations. The content of Ca concentration ranged from 6.27 to 36.42 mg/L, 5.29 to 11.24 mg/L, and 6.55 to 10.32 mg/L during pre-monsoon, monsoon, and post-monsoon seasons, respectively (Figure 9). The calcium concentration of the entire open wells is less than 20 mg/L and also falls well within the highest desirable limit prescribed by BIS (2012) for drinking purposes. Magnesium in water derives from igneous rocks containing ferromagnesian minerals like olivine, pyroxenes, amphiboles, and various dark-
coloured micas (Hem 1985). Weathering of carbonates also contributes a greater percentage of Ca$^{2+}$ and Mg$^{2+}$ to both surface and groundwater (Al-Mikhlafi et al. 2003). The Mg content of open-well samples at different stations ranged from 0.75 to 12.45 mg/L during pre-monsoon, 0.99 to 3.45 mg/L during monsoon, and 1.96 to 2.33 mg/L during post-monsoon.

The seasonal sodium concentration of open-well samples ranged from 17.8 to 163.23 mg/L, 59.63 to 102 mg/L, and 69.33 to 111.32 mg/L during pre-monsoon, monsoon, and post-monsoon seasons respectively. Na concentration at various seasons comes under the desirable level as the maximum permissible limit of Na in drinking water is 200 mg/L (WHO 1984). The main source of Na in water is plagioclase feldspars and clay minerals (Hem 1985). The potassium content ranged from 1.6 to 6.2 mg/L, 2.71 to 5.26 mg/L, and 3.93 to 6.05 mg/L for pre-monsoon, monsoon, and during post-monsoon seasons respectively. Here all the values are higher than the permissible limit of 0.5 mg/L. Potassium toxicity has been studied with the use of high doses of salt substitutes. The symptoms have been chest tightness, nausea, vomiting, diarrhoea, shortness of breath, and heart failure (Divya & Manomani 2013).

The concentration of chloride ranged from 42.11 to 382.11 mg/L during pre-monsoon, 125.16 to 254.44 mg/L during monsoon, and 203.14 to 270.41 mg/L during post-monsoon seasons with maximum values recorded at the downstream sampling stations (Figure 10).

The content of SO$_4$ in the open well samples ranged from 19.25 to 49.14 mg/L during pre-monsoon, 20.36 to 51.59 mg/L during monsoon and in post-monsoon it ranged from 39.55 to 71.36 mg/L. The SO$_4$ concentration of entire open well samples, irrespective of seasons, was within the acceptable limit ($\leq 200$ mg/L) for drinking purposes (BIS 2012).

Nitrate was found in almost all the samples but all were below the drinking water guideline. However, the contents were relatively higher than the surface water samples in the study area. The sampling station GWS1 showed maximum values during the three seasons with a maximum of 14.25 mg/L in pre-monsoon. Usually, igneous rocks, plant, and animal debris are the natural sources of nitrate in water. Anthropogenic sources include seepage from septic tanks, the application of sewage and sludge to the land (Chattopadhyay et al. 2005). The concentration of phosphate in open-well samples collected from different stations at various intervals showed very low values ranging from 0.02 to 0.09 mg/L, and for iron too, the values were very low and below the detectable level. This indicates that no leaching or pollution of these ions is occurring in groundwater.

Microbiological analysis showed the presence of E. coli only in one sample (GWS5). The total MPN count was below the limit prescribed in drinking water standards (BIS 2012). The presence of E. coli bacteria in GWS5 during all the seasons indicates faecal contamination and its waterlogged condition. The presence of these bacteria seriously affects the health conditions and results in gastrointestinal illness (WHO 1993).
Correlation analysis
Correlation analysis of the physico-chemical parameters of the open well and river water samples were performed to understand the relationship between various parameters (Tables 7 and 8).

Correlation analysis of groundwater samples for various seasons
Significant correlation shown by various physico-chemical parameters of the open well samples is as follows:
1. pH, in general, showed positive correlation with TDS, turbidity, Mg\(^{2+}\), Cl\(^{-}\), and SO\(_4^{2-}\) during all the seasons.
2. TDS showed good correlation with EC and most of the anions and cations.
3. Salinity exhibited positive correlation with TDS, anions, and cations.
4. Total alkalinity was correlated well with Ca\(^{2+}\), Mg\(^{2+}\), Cl\(^{-}\)/C\(_0\), and NO\(_3^-\) during most of the seasons.
5. Mg\(^{2+}\) showed a significant correlation with SO\(_4^{2-}\) for all the seasons.

Correlation analysis of river water samples at various seasons
1. pH showed positive correlation with TH, salinity, Cl\(^{-}\), Ca\(^{2+}\), Mg\(^{2+}\), Na\(^{+}\), and K\(^{+}\) during all seasons.
2. EC exhibited significant correlation with TDS, TH, Salinity, TA, Cl\(^{-}\)/C\(_0\), Na\(^{+}\), SO\(_4^{2-}\), K\(^{+}\), and Mg\(^{2+}\).
3. Salinity was positively correlated with TDS, TH, pH, and EC during all seasons and moderately correlated with Na\(^{2+}\), Ca\(^{2+}\), and Mg\(^{2+}\).
4. Mg\(^{2+}\) showed good correlation with Ca\(^{2+}\), Cl\(^{-}\), K\(^{+}\) and SO\(_4^{2-}\).
5. Ca\(^{2+}\) with Cl\(^{-}\) and K\(^{+}\) during pre and post-monsoon season.
6. Cl\(^{-}\) with Ca\(^{2+}\), K\(^{+}\), Na\(^{2+}\) during all seasons and with TH and TA during monsoon season.

The correlation coefficient (r) between various pairs of the physico-chemical parameters of surface water samples of Kallada River and open wells of Munroe Island at various seasons reveals that salinity plays a vital role in controlling most of the anions and cations present in the ground and river water as an increase of TDS increases the salinity and total hardness of the water.

Management of saltwater intrusion and improving island water quality
• Construction of a check-dam at the downstream area near Bhagawati Temple to check the saltwater intrusion from Ashtamudy Lake, as the river has been observed running eastward in the opposite direction during high tide, especially in summer.
• Excessive sand mining should be banned in Kallada River, which lowered the river’s depth which created a positive way for trapping the saline water at depths that enter during high tide events.
• Island’s water development should be coupled with management of rain water harvesting and surface water. There should be proper water budgeting in the district. Artificial recharge schemes should be practiced in large scale along with rainwater harvesting. Rainwater in situ collection be practiced along the coastal region and artificial recharge to groundwater can be practiced in the midland regions.
• Planting mangroves near the island river side can check shore erosion that contribute to maintain water uptake and limit water loss to the soil and the atmosphere under saline conditions, from micro to macro scales.
• Mass awareness programmes should be carried out at Panchayat level to create awareness among the people on the importance of conservation and protection of groundwater.

CONCLUSION
Munroe Island is a typical backwater village peninsula and the quality of drinking water is a big concern. Recently the low-lying areas of the Munroe Island are facing a serious threat of water upwelling, salinity problems, poor drinking water quality and agricultural failure for more than one and half decades. The drinking water source for island inhabitants is private open wells. But due to colour change and taste differences of water in most of the wells, pure drinking water availability is scarce in the Panchayat.

The present study conducted at Munroe Island and Kallada River basin revealed significant saltwater intrusion into the Kallada River from Ashtamudy Lake during various seasons. Analysis of groundwater samples from five different stations reveals that as the distance from the riverside increases, the effect of saline intrusion decreases, and the same for related
Table 7 | Pearson correlation matrix of river water samples

| Parameters | pH | EC | TDS | Salinity | Turbidity | TH | Ca_Ha | Mg_Ha | TA | SO4 | NO3 | PO4 | Ca | Mg | Na | K | Fe | DO | BOD | COD |
|------------|----|----|-----|---------|-----------|----|-------|-------|----|-----|-----|-----|----|----|----|---|---|----|-----|-----|
| pH         | 1  |     |     |         |           |    |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| EC         | .772** | 1 |     |         |           |    |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| TDS        | .669** | .555* | 1 |         |           |    |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| Salinity   | .835** | .736** | .725** | 1 |           |    |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| Turbidity  | .572*  | .682** | .456 | .603*   | 1 |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| TH         | .853** | .681** | .567* | .710**  | .574* | 1 |       |       |    |     |     |     |    |    |    |   |   |    |     |     |
| Ca_Ha      | .673** | .674** | .447 | .621*   | .893* | .780** | 1 |     |     |     |     |    |    |    |   |   |    |     |     |
| Mg_Ha      | .843** | .642** | .561* | .687**  | .468  | .990** | .684** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| TA         | .547*  | .562*  | .766** | .658**  | .534* | .590* | .609* | .550* | 1 |     |     |     |    |    |    |   |   |    |     |     |
| Cl         | .702** | .651** | .697** | .762**  | .663** | .665** | .772** | .601* | .657** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| SO4        | .753** | .483  | .523* | .618*   | .417  | .770** | .671** | .747** | .503  | .848** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| NO3        | -.442 | -.690** | -.151 | -.257   | -.180 | -.291 | -.168 | -.302 | -.018 | -.092 | -.075 | 1 |     |     |     |    |    |    |   |   |    |     |     |
| PO4        | -.295 | -.206 | -.123 | -.222   | .159  | -.192 | .125  | -.252 | -.063 | -.191 | -.305 | .015 | 1 |     |     |     |    |    |    |   |   |    |     |     |
| Ca         | .744** | .604*  | .711** | .818**  | .539* | .612* | .545* | .591* | .527* | .816** | .716** | -.035 | -.352 | 1 |     |     |     |    |    |    |   |   |    |     |     |
| Mg         | .871** | .720** | .728** | .790**  | .605* | .893** | .793** | .863** | .731** | .891** | .898** | -.240 | -.232 | .779** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| Na         | .835** | .794** | .760** | .903**  | .734** | .791** | .776** | .747** | .729** | .882** | .717** | -.203 | -.247 | .850** | .885** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| K          | .552*  | .451  | .447  | .550*   | .589* | .778** | .688** | .752** | .503  | .597*  | .577*  | .095  | -.093 | .533** | .663** | .736** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| Fe         | -.264 | -.017 | -.168 | -.404   | -.424 | -.414 | -.543 | -.378 | -.321 | -.396 | -.369 | -.492 | -.196 | -.409 | -.404 | -.364 | -.635** | 1 |     |     |     |    |    |    |   |   |    |     |     |
| DO         | -.706** | -.839** | -.391 | -.769** | -.452 | -.603* | -.501 | -.589* | -.333 | -.511 | -.419 | .643** | .175  | -.605* | -.586* | -.685** | -.291 | .079 | 1 |     |     |     |    |    |    |   |   |    |     |     |
| BOD        | .589*  | .444  | .547* | .672**  | .444  | .569* | .555* | .538* | .568* | .639* | .596*  | -.176 | .097  | .456  | .686** | .527*  | .366  | -.678* | -.341 | 1 |     |     |     |    |    |    |   |   |    |     |     |
| COD        | .822** | .645** | .683** | .797**  | .479  | .756** | .670** | .730** | .733** | .874** | .910** | -.192 | -.309 | .768** | .939** | .808** | .480  | -.348 | -.561* | .735** | 1 |     |     |     |    |    |    |   |   |    |     |     |

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
Table 8 | Pearson correlation matrix of groundwater samples

| Parameters | pH   | EC    | TDS   | Salinity | Turbidity | TH    | TA    | Cl    | SO4   | NO3   | PO4   | Ca   | Mg   | Na   | K  |
|------------|------|-------|-------|----------|-----------|-------|-------|-------|-------|-------|-------|------|------|------|----|
| pH         | 1    |       |       |          |           |       |       |       |       |       |       |      |      |     |    |
| EC         | .129 | 1     |       |          |           |       |       |       |       |       |       |      |      |     |    |
| TDS        | -.271| .513  | 1     |          |           |       |       |       |       |       |       |      |      |     |    |
| Salinity   | -.371| .303  | .214  | 1        |           |       |       |       |       |       |       |      |      |     |    |
| Turbidity  | .378 | .391  | .347  | -.306    | 1         |       |       |       |       |       |       |      |      |     |    |
| TH         | -.057| .579* | .276  | .407     | .218      | 1     |       |       |       |       |       |      |      |     |    |
| TA         | -.405| .505  | .208  | .365     | .043      | .360  | 1     |       |       |       |       |      |      |     |    |
| Cl         | .046 | .863**| .355  | .465     | .291      | .631* | .614* | 1     |       |       |       |      |      |     |    |
| SO4        | .654**| -.055 | -.035 | -.206    | .251      | -.008 | -.423 | -.186 | 1     |       |       |      |      |     |    |
| NO3        | -.071| .406  | .102  | .513     | -.270     | .029  | .583* | .491  | -.282 | 1     |       |      |      |     |    |
| PO4        | .107 | .121  | -.150 | -.084    | .258      | -.006 | .083  | .194  | -.134 | .267  | 1     |      |      |     |    |
| Ca         | -.751**| -.469 | -.035 | .237     | -.621*    | -.150 | .188  | -.381 | -.479 | .033  | -.164 | 1     |      |      |     |    |
| Mg         | -.311| -.510 | .125  | -.009    | -.405     | -.622* | -.284 | -.543*| .051  | .046  | -.117 | .455  | 1     |      |     |    |
| Na         | .151 | -.430 | -.078 | -.710**  | .099      | -.643**| -.594*| -.672**| .298  | -.539*| -.170 | -.191 | .436  | 1     |     |    |
| K          | -.003| .509  | .432  | .439     | -.019     | .658* | .514  | .500  | .125  | .370  | -.334 | -.157 | -.324 | -.494 | 1   |    |

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).
cations and anions. Microbiological analysis of open-well samples from five stations indicated that, except for GWS5, all other samples showed the absence of E. coli bacteria and the total MPN count below the limit as prescribed for drinking water standards. Also the groundwater quality analysis revealed that saltwater intrusion in Kallada River has a negative impact on island groundwater. As no systematic scientific studies were conducted so far to determine the occurrence of saltwater intrusion, this study helps to scientifically prove the severity and occurrence of saltwater intrusion occurring at various seasons and its impact on Munroe Island water quality. Also, this paper suggests suitable management methodologies to mitigate the saltwater intrusion.

LIMITATIONS OF PRESENT STUDY

- The present study focused on the water quality of Kallada River and Munroe Island groundwater with special reference to saltwater intrusion. Besides saltwater intrusion and salinity problems, the island is under the threat of land settling, water logging, agriculture failure and increased tidal surges. Besides the present studies, other systematic studies are ongoing to tackle the above mentioned problems.
- The best way to check saltwater intrusion in Kallada River is the construction of a dike at the outlet of the lake near the mouth of the Arabian Sea at Neendakara in order to convert the brackish Ashtamudy Lake into a freshwater reservoir by blocking freshwater flowing from the Kallada River to the lake and sea and vice versa. But it seriously alters the natural estuarine ecology of Ashtamudy Lake as it is changed to freshwater.

ACKNOWLEDGEMENTS

The first author greatly acknowledges UGC-DSKPDF for the grants provided to carry out the research. The authors are also grateful to the Department of Environmental Sciences, University of Kerala for providing laboratory facilities for carrying out research work.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 11 June 2021; accepted in revised form 9 October 2021. Available online 26 October 2021