Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 21 No. 2 pp. 803-812 2022
Original Research Paper
https://doi.org/10.46488/NEPT.2022.v21i02.045
Open Access Journal

Delineation of Groundwater Salinity Zones in Shefa and Malampa Provinces, Vanuatu

K. K. Kotra*†, S. Bathula and E. Sami*****
*†School of Agriculture, Geography, Environment, Ocean, and Natural Sciences, The University of the South Pacific, Emalus Campus, Vanuatu
**Department of Applied Sciences, The Papua New Guinea University of Technology, Lae, Morobe-411, Papua New Guinea
***Department of Water Resources, Ministry of Lands and Natural Resources, Government of Vanuatu, Vanuatu
†Corresponding author: K. K. Kotra; krishna.kotra@usp.ac.fj

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 05-01-2022
Revised: 07-02-2022
Accepted: 12-02-2022

Key Words:
Groundwater
Salinity zones
Shefa
Malampa
Vanuatu

ABSTRACT

A preliminary assessment was carried out in identifying the salinity zones due to considerable concern over salty groundwater resources in Vanuatu's Shefa and Malampa regions. Electrical conductivity (EC) and pH were measured on the islands of Efate, Lamen, and Nguna in Shefa province, as well as the islands of Ambrym and Paama in Malampa province. Thirty-four percent of the samples exceeded Vanuatu's National Drinking Water Standards with an average of 3123 μS/Cm indicating possible salinity zones. Whereas the average pH of 7.21 was in the range of acceptable levels. EC values as high as 18,520 μS/cm indicate groundwater in some locations are unfit for drinking. The average Total Dissolved Solids (TDS) of 1717 $mg.L^{-1}$ is also indicating non-compliance with standards. Salinity zone maps were developed based on the observations. Further detailed studies need to be conducted to ascertain the factors that influence groundwater salinity, such as geology, island type, and seasonality.

INTRODUCTION

Groundwater is a vital resource for billions of people across the globe. For many communities around the world, coastal aquifers are a critical source of freshwater (Arfib et al. 2007), with small islands often heavily dependent on groundwater resources. However, increased salinity linked to seawater intrusion poses a significant threat to these coastal aquifers and small islands in particular (Deutsch & Siegel 1997, Somay & Gemici 2009, Kotra et al. 2017, Kim et al. 2009, Abd-Elhamid et al. 2020). It would be obvious that, more than any other water resource, groundwater in the small islands is often prone to impinging saline water and thus salinity. Notwithstanding the mere need for drinking but for all other purposes like irrigation and domestic use as well. Salinity impacts in more than one form and is not limited to reduction in crop yield (Demir et al. 2009), and restriction of flow pattern (Mayer et al. 2003) but to other factors as well. White & Falkland (2010) reported that long dry periods strongly coupled with sea surface temperatures impact the quantity and salinity of fresh groundwater. Given the conditions of limited water resources in the small islands, there is every need for concern for their survival. WHO (2007) refers "all people, whatever their stage of development and their social and economic conditions, have the right to have access to an adequate supply of safe drinking water".

Small island countries (SICs) are surrounded by the sea, and intensive groundwater withdrawal from concentrated borehole systems and wells has resulted in saltwater intrusion causing contamination of fresh groundwater reserves in coastal aquifers (Lal & Datta 2017). Salinity in groundwater may arise from various factors and there is growing concern about how climate change and associated sea-level rise will compound the issue (Ishii et al. 2006, Palut & Canziani 2007). Small islands will be particularly vulnerable to the impact of climate change on groundwater salinity (Dixon-Jain et al. 2014). Population growth and increased abstraction levels may also exacerbate the issue. Rao (2008) reported that evapotranspiration causes the accumulation of salts and thus can be infiltrated into the groundwater table leading to salinity might be a proven reason for salinity in the small islands. Fisher & Mullican (1997) reported that sodium-chloride and sodium-sulfate ratios play a key role in determining salinity levels in groundwater. It was reported from the study of groundwater in a tropical island in East Malaysia that precipitation and evapotranspiration (environmental condition) with hydraulic heads along with upward pumping were responsible for salinity in the groundwater (Praveena et al. 2011). The vulnerability of small island freshwater lenses dictates careful assessment, vigilant monitoring, appropriate development, and astute management (White & Falkland 2010). Moreover, Foster & Willettes (2018) recently reported that in Vanuatu groundwater sources in the small islands are less prone to contamination than rainwater sources. In view of the above observations and widespread concern about salinity in groundwater resources in the Shefa and Malampa provinces of Vanuatu, the present study was carried out to assess the salinity zones and possible reasons for their occurrence.

MATERIALS AND METHODS

Study Area

Vanuatu is located on the Pacific ring of fire, where the Pacific tectonic plate is sliding under the Indo-Australian plate. The Y-shaped chain of 83 islands lies between Fiji and Queensland, Australia, and forms part of the Melanesia group. Malampa and Shefa constitute the two major provinces among the six provinces of Vanuatu. Malampa lies between 16.4011° S and 167.6078° E with three main islands, Malekula, Ambrym, and Paama. Whereas Shefa which stretches in the center of the country lies between 17.65° S and 168.34° E with Efate, Epi, and Shepard's group of islands. The provinces experience a humid tropical climate and South Easterly trade winds. The average annual rainfall is 2360 mm with an average of 211 rain days per year (VMGD).

A survey was conducted in the study areas of Malampa and Shefa provinces during August and September 2018. Ambrym and Paama Islands were part of the Malampa province survey whereas Efate, Lamen, and Nguna Islands of Shefa province were surveyed. The methodology in regard to the selection of the sampling site was based on the data from the country's national water supply inventory and thus functional water points were selected in the present study. In total, 35 stations were surveyed; 21 in Malampa province and 14 in Shefa province (Fig. 1). After fixing the coordinates of the site, the water that was resting in the rising main was flushed out before the measurement of the parameters. pH, Electrical Conductivity (EC), and Total Dissolved Solids (TDS) were measured on the site using a portable Hanna multi-parameter meter.

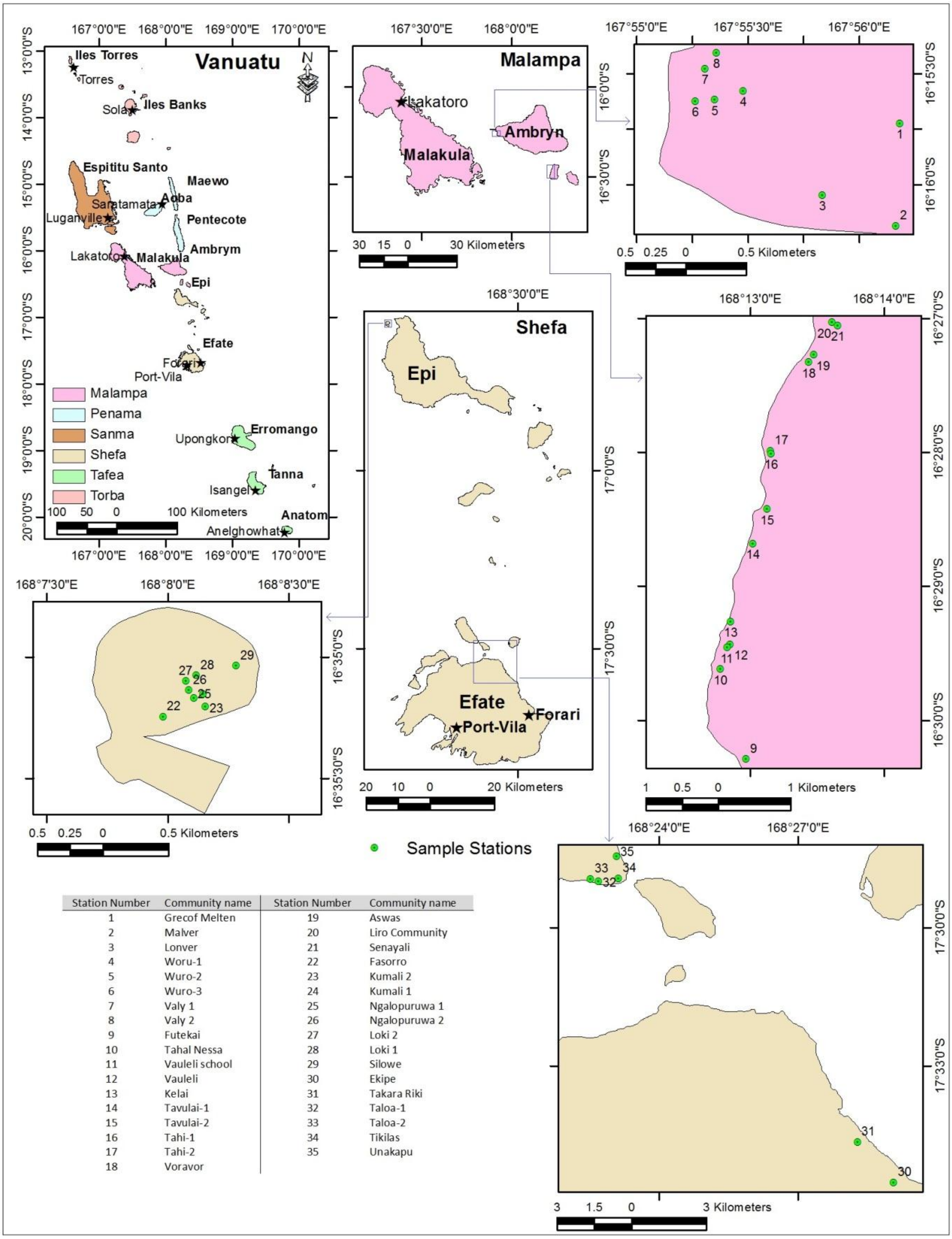
RESULTS AND DISCUSSION

Statistical Interpretation

The observed results were interesting and varied. The minimum pH, EC, and TDS observed were 6.63, 417 $\mu S.cm^{-1,}$ and 229.4 ppm respectively in Malampa province, and 6.97, 689 $\mu S.cm^{-1}$ and 379 ppm in Shefa province. The maximum values of the pH, EC, and TDS in both the provinces were 7.78, 18,520 $\mu S.cm^{-1}$ and 10,186 ppm; and 7.74, 2,786 $\mu S.cm^{-1}$ and 1,532 ppm respectively. The average pH of groundwater sources in these provinces was 7.09 (std dev. 0.28) in Malampa and 7.38 (std. dev. 0.25) in Shefa. Whereas in cases of EC and TDS, the average was 4,095 $\mu S.cm^{-1}$ (std dev. 5,119) and 2,252 ppm (std. dev 2,816) in Malampa; and 1,667 $\mu S.cm^{-1}$ (std dev. 695) and 917 ppm (std dev. 382) in Shefa. The standard deviations are 5,119 $\mu S.cm^{-1}$ and 2,816 ppm, and 695 µS/cm and 382 ppm respectively. The median values were 1,156 $\mu S.cm^{-1}$ and 636 ppm (Malampa); and 1,685 $\mu S.cm^{-1}$ and 926 ppm (Shefa). The sampling stations' location, geology, and observed values are given in Table 1. The summarized results were shown in Table 2.

It is evident from the results that there are many concerns with the palatability of groundwater in coastal areas of these provinces. In Malampa province, the very high EC and TDS values noted in Ambrym Island indicate groundwater that is not suitable for drinking (WHO 1996). Three sites on Ambrym recorded EC values over 10,000 $\mu S.cm^{-1}$, and hence are not even suitable for irrigation purposes (ADWS 2011). However, the pH levels recorded in Ambrym are close to the neutral state but point slightly towards the basic nature. In regards to Shefa province, sites in the islands of Lamen and Nguna also recorded high EC and TDS values. The pH of these stations was slightly higher than those observed in the other islands but again pointing toward the basic nature of these waters.

Rhoades (1996) referred that salinity is due to the presence of the major dissolved solutes, essentially Na^+, Mg^{2+}, Ca^{2+}, K^+, Cl^-, SO_4^{2-}, HCO_3^-, and CO_3^{2-} in aqueous samples. It is evident from the above results that the contributing factor/s to the salinity of these waters is a cumulative effect of these ions as of the results of the EC. Walton (1989) reported that EC and TDS are correlated and thus replicate the salinity in terms of the soluble salts in the water and thus these stations of confirming the salinity zones. It is very interesting to note that volcanic geology is more favorable than the limestone presence in these stations. Choudhury et al. (2001) reported that geophysical aspects surrounding the groundwater source do play a vital role in deciding the salinity. De Montety et al. (2008) earlier reported that carbonate chemistry would facilitate the origin of salinity but in the present case, it was interesting that the limestone geology doesn't show any saline zones but was observed in the volcanic zones. Thus it would be interesting to see how volcanic zones have higher salinity values than that of the limestone stations.



Station Number	Community name	Station Number	Community name
1	Grecof Melten	19	Aswas
2	Malver	20	Liro Community
3	Lonver	21	Senayali
4	Woru-1	22	Fasorro
5	Wuro-2	23	Kumali 2
6	Wuro-3	24	Kumali 1
7	Valy 1	25	Ngalopuruwa 1
8	Valy 2	26	Ngalopuruwa 2
9	Futekai	27	Loki 2
10	Tahal Nessa	28	Loki 1
11	Vauleli school	29	Silowe
12	Vauleli	30	Ekipe
13	Kelai	31	Takara Riki
14	Tavulai-1	32	Taloa-1
15	Tavulai-2	33	Taloa-2
16	Tahi-1	34	Tikilas
17	Tahi-2	35	Unakapu
18	Voravor		

Fig. 1: Map of the study area.

Table 1: Sampling stations, geology and observed results.

Island	Geology	Water point	Latitude	Longitude	pH	EC	TDS
Ambrym	Volcanic	Grecof Melten	-16.2621	167.9364	7.36	3,443	1,894
	Volcanic	Malver	-16.2697	167.9361	7.37	6,068	3,337
	Volcanic	Lonver	-16.2674	167.9306	7.59	5,547	3051
	Volcanic	Woru-1	-16.2597	167.9247	7.37	8,749	4812
	Volcanic	Wuro-2	-16.2603	167.9226	7.42	9,666	5316
	Volcanic	Wuro-3	-16.2604	167.9211	7.46	11,380	6,259
	Volcanic	Valy 1	-16.258	167.9219	7.32	11,990	6,595
	Volcanic	Valy 2	-16.2568	167.9227	7.37	18,520	10,186
Paama	Volcanic	Futekai	-16.5048	168.2162	7.16	885	487
	Volcanic	Tahal Nessa	-16.4936	168.213	6.63	1,671	919
	Volcanic	Vauleli school	-16.491	168.2139	6.91	492	271
	Volcanic	Vauleli	-16.4906	168.2142	6.84	485	267
	Volcanic	Kelai	-16.4877	168.2143	6.90	693	381
	Volcanic	Tavulai-1	-16.4781	168.217	6.76	1,156	636
	Volcanic	Tavulai-2	-16.4737	168.2188	6.88	1,121	617
	Volcanic	Tahi-1	-16.4668	168.2193	7.01	1,024	563
	Volcanic	Tahi-2	-16.4665	168.2192	6.86	1,193	656
	Volcanic	Voravor	-16.4555	168.224	6.89	532	293
	Volcanic	Aswas	-16.4546	168.2246	6.98	456	251
	Volcanic	Liro Community	-16.4505	168.2268	6.85	499	275
	Volcanic	Senayali	-16.4509	168.2276	6.89	417	229
Efate	Limestone	Ekipe	-17.5919	168.4846	7.31	1,742	958
	Limestone	Takara Riki	-17.5774	168.4715	7.43	1,127	620
Laman	Limestone	Fasorro	-16.5874	168.133	7.49	2,495	1,372
	Limestone	Kumali 2	-16.5867	168.1359	7.51	2,044	1,124
	Limestone	Kumali 1	-16.5859	168.1358	7.69	878	483
	Limestone	Ngalopuruwa 1	-16.5861	168.1351	7.47	1,674	921
	Limestone	Ngalopuruwa 2	-16.5856	168.1348	7.48	1,695	932
	Limestone	Loki 2	-16.585	168.1346	7.54	1,148	631
	Limestone	Loki 1	-16.5846	168.1353	7.78	753	414
	Limestone	Silowe	-16.5839	168.1381	7.48	1,891	1,040
Nguna	Volcanic	Taloa-1	-17.4834	168.3783	7.11	1,661	914
	Volcanic	Taloa-2	-17.4825	168.3753	7.01	2,750	1,513
	Volcanic	Tikilas	-17.4823	168.3854	7.09	2,786	1,532
	Volcanic	Unakapu	-17.4743	168.3846	6.97	689	379

Geophysical Interpretation

A "topo-to-raster" interpolation technique under the spatial analyst tool of ArcGIS was used to interpolate a hydrologically correct surface from point datasets (Samanta et al. 2012). In this study total of 35 stations (21 stations from Malampa province and 14 stations from Shefa province) were considered as input stations for interpolation with their know observations value on pH, TDS, and EC. In this first step, a raster surface was generated as an output of topo-to-raster interpolation. In the second step "raster to contour" tools under the spatial analysis of ArcGIS was used to create

Table 2: Summary of the results.

Parameter	Min		Max		Mean		Median		SD	
	SH*	MA*	SH	MA	SH	MA	SH	MA	SH	MA
pH	6.97	6.63	7.74	7.78	7.38	7.09	7.48	6.98	0.25	0.28
EC	689	417	2,786	18,520	1,666	4,095	1,685	1,156	695	5,119
TDS	483	229	1,372	10,186	917	2,252	926	636	382	2816

* SH - Shefa Province; MA - Malampa Province

contours or isolines from those raster surfaces. TDS, pH, and EC contours were overlaid with respective provincial boundaries, and maps were prepared to show the spatial variation of pH, TDS, and EC for Malampa and Shefa provinces. These contour maps are shown in Figs. 2, 3 and 4.

Based on water sample analysis average pH value was measured as 7.21 in the study area. The highest pH was measured in the Shefa province and the lowest in the Malampa province. It was observed that average pH values are higher in the coastal areas than inland areas that are located far from the sea. On the other hand, it was found that the local geology is another factor in the variation of pH value in the study area (Lenntech 2013). The average pH in the volcanic region is much lower (7.27) than in the limestone region (7.52) (Murphy 2007). The value of pH was measured high (7.69) at Kumali 1 in Laman Island under Shefa province which is situated on the limestone and low (6.63) at Tahal Nessa in Paama Island under Malampa province which is situated on the volcanic landform.

The concentration of TDS in this present study was observed in the range from 271 $mg.L^{-1}$ to 5316 $mg.L^{-1}$ in the Malampa province and 379 $mg.L^{-1}$ to 1532 $mg.L^{-1}$ in Shefa province. High TDS concentration (more than 3000 $mg.L^{-1}$) was measured in the northwest part of Ambrym Island and low (less than 700 $mg.L^{-1}$) in Paama Island under Malampa province. The average concentration of TDS in Shefa province is much lower than in Malampa province with an average value of 963 $mg.L^{-1}$ and 2169 $mg.L^{-1}$ respectively. In Shefa province TDS contours of 1200 $mg.L^{-1}$, 1500 $mg.L^{-1,}$ and 9000 $mg.L^{-1}$ can be found in Lamen, Nuna, and Efate Island respectively. High values of TDS in groundwater were generally not harmful to human beings, but a high concentration of these may affect persons who are suffering from kidney and heart diseases (Kumar & Puri 2012).

EC value was measured in the range from 417 $\mu S.cm^{-1}$ to 18520 $\mu S.cm^{-1}$ in the Malampa province and 689 $\mu S.cm^{-1}$ to 2786 $\mu S.cm^{-1}$ in the Shefa province. The level of EC in Malampa province is much higher than in Shefa province with an average value of 3943 $\mu S.cm^{-1}$ and 2169 $\mu S.cm^{-1}$ respectively. A higher EC level (more than 15000 $\mu S.cm^{-1}$) was measured in the northwest part of Ambrym Island and lower (less than 750 $\mu S.cm^{-1}$) in Paama Island under Malampa province. EC contour of 2250 µS/cm was found in Lamen, 1500 $\mu S.cm^{-1}$ in Nguna, and 1250 $\mu S.cm^{-1}$ in Efate Island respectively, which are situated in Shefa province. After critical analysis of spatial variation of contaminated TDS and EC within groundwater, it can be said that groundwater in Ambrym Island under Malampa province is facing many problems as all measurements are above the standard limit. TDS and EC measurements in Paama Island are comparatively low followed by Nguna, Laman, and Efate Island. Banerjee et al. (2011) proposed that Artificial Neural Networks (ANN) model would appreciate the safe pumping rate of groundwater salinity in island aquifers and thus it would be worthwhile to consider this in the present study area to counter the salinity zone formations.

Groundwater Salinity - Geomorphological Impacts

Coastal groundwater is always circumspect with multiple threats both in maintaining its quality and quantity. Out of many geomorphological challenges that coastal groundwater faces, the vicinity to the saline water is the most important factor to counter (Kotra 2011). Nielsen (1999) reported that the groundwater table a few tens of meters inland from the high watermark on a beach will be considerably higher than the Mean Sea Level (MSL) even if there is no outflow due to rainfall on the land. Stations 1, 2, 3, 4, 5, 6, 7, and 8 in the Malampa and 22, 23, 33, and 34 in the Shefa provinces have the higher EC values than permitted by Vanuatu National Drinking Water Standards and would pose health implications for the communities who depend on these. It would be obvious that sometimes communities who live on the small islands would have to contain what they get depending on the season and availability of the groundwater through recharge. Comte et al. (2016) reported that shallow large-diameter wells, following the traditional model, consistently prove to be less saline and more durable than deeper small-diameter boreholes, and is worthwhile to implement this approach in the current study area to negate the salinity development in the water resource.

It would be interesting to further investigate cases 2, 3, 6, 22, 23, 33, and 34 which are in the vicinity of the coastline

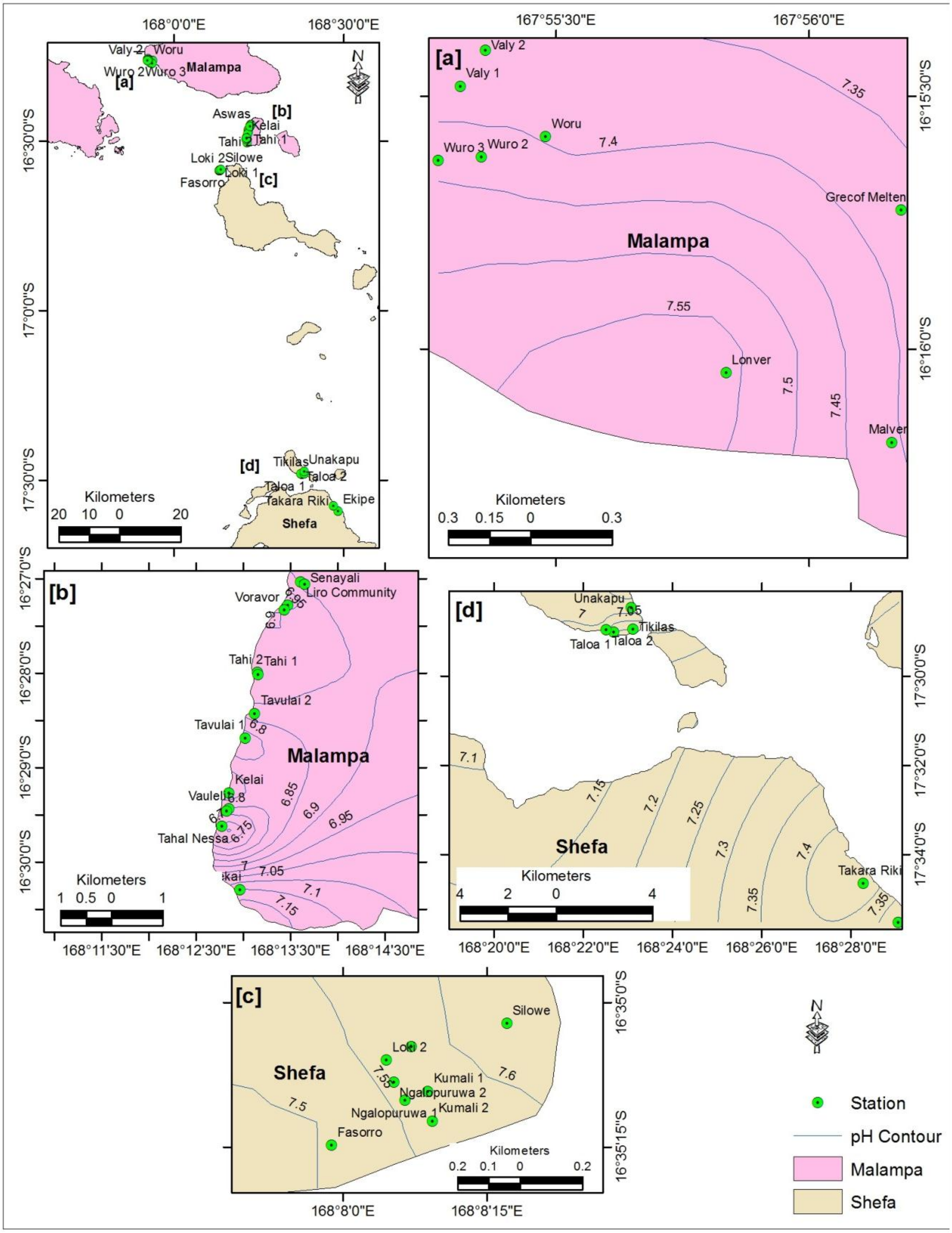


Fig. 2: Spatial distribution of pH in Shefa and Malampa provinces.

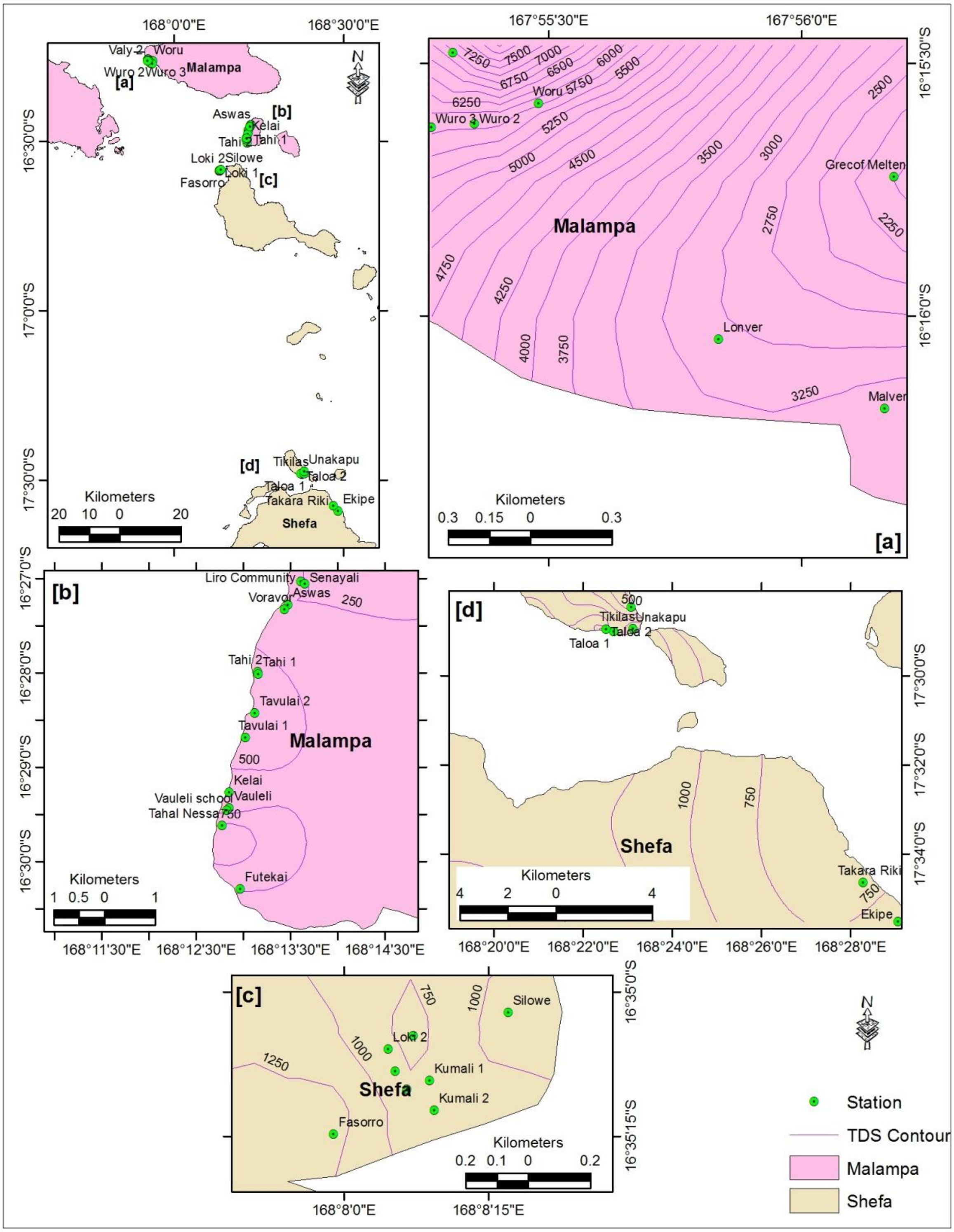


Fig. 3: Spatial distribution of TDS in Shefa and Malampa provinces.

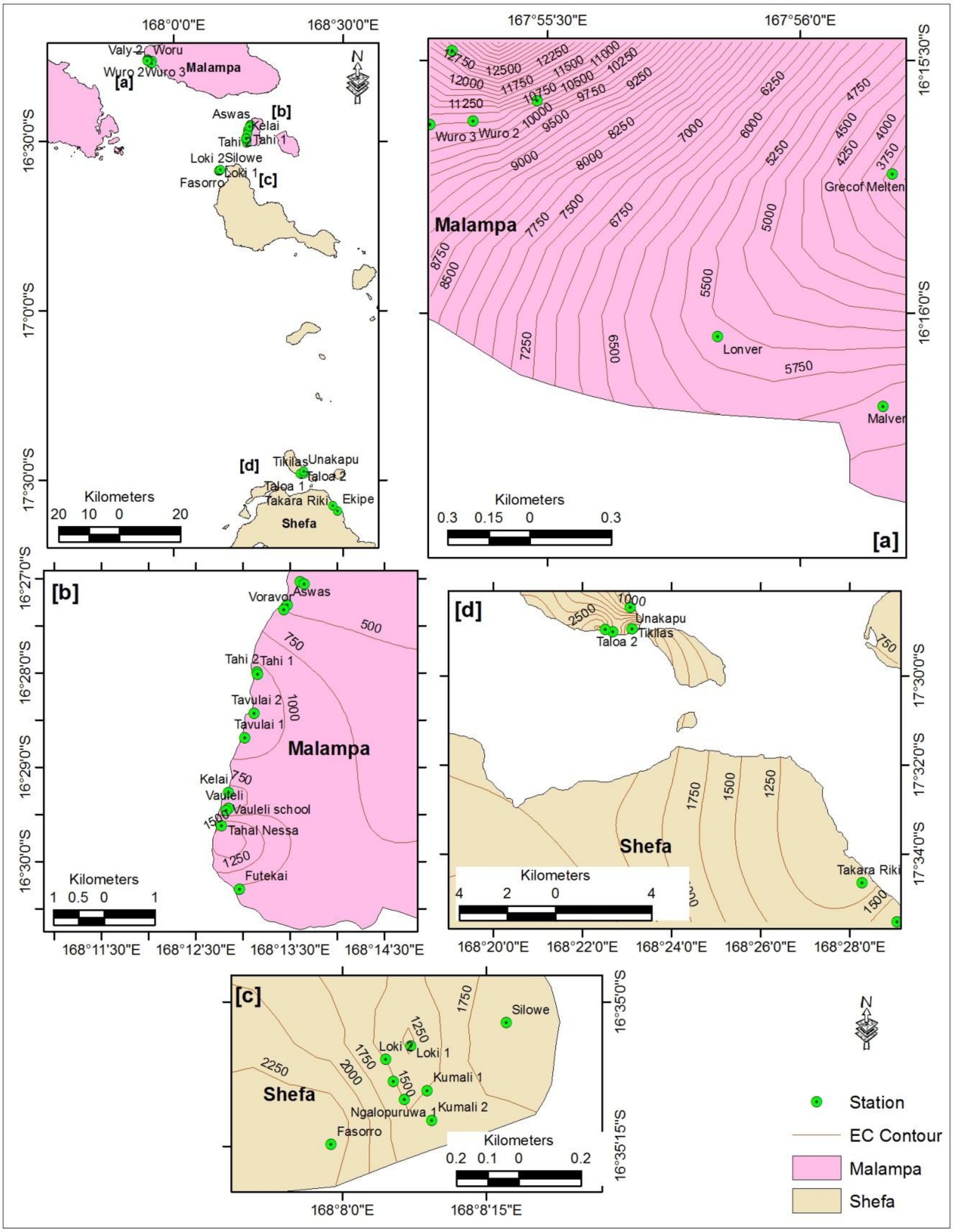


Fig. 4: Spatial distribution of EC in Shefa and Malampa provinces.

to see the intrusion impacts. Chang et al. (2011) and Guha & Panday (2012) reported that sea-level rise does impact salinity in the coastal groundwater and thus this kind of impact assessment might lead to further conclusions about the salinity of the above stations. As pumping rates and recharge often define some of the geomorphological setups, it would be worthwhile to investigate in this regard as well. Stations like 1, 4, and 5 do point in this regard as they are inland with high EC values. Willis & Finney (1988) and Mantoglou (2003) reported that saltwater intrusion can be controlled by proper planning in pumping and recharge. It seems that with fragile groundwater sources there is every need to implement proper planning for sustainability and quality. The difference in the geology i.e., volcanic and limestone in these islands doesn't primarily point to the source of salinity as these zones are observed in both regions. Whitaker & Smart (1990) reported that a difference in the carbonate build-up is capable of driving the subsurface flow of saline water and may be generated by tides, local waves, and ocean currents. Thus it would be interesting to further study the role of limestone in exposing the saline zones in the study area. The variations in the geology in terms of volcanic and limestone origin can't be a source for any prediction on the origin of salinity as cases fall both in these regions. Again there is a need to establish the geological impact on salinity with a comprehensive cation/anion analysis of the groundwater.

CONCLUSION

Salinity in the small island nations has been a problem and Vanuatu is no exemption in this regard. The first-ever investigation in identifying these in the Shefa and Malampa provinces has successfully delineated these zones. Results have been disseminated to the Department of Water Resources and inputted into their water quality database. The EC and TDS results of the stations have revealed that some of the stations were unfit for drinking and agricultural usage. Moreover, a further comprehensive study has been recommended in regard to the role of geomorphology and coastal influences in generating these zones.

REFERENCES

Abd-Elhamid, H.F., Abd-Elaty, I. and Hussain, M.S. 2020. Mitigation of seawater intrusion in coastal aquifers using coastal earth fills considering future sea-level rise. Envi. Sci. Poll. Res., 27(18): 23234-23245.

ADWS. 2011. Australian Drinking water Standards: http://www.sahealth.sa.gov.au/wps/wcm/connect/public+content/sa+health+internet/protecting+public+health/water+quality/salinity+and+drinking+water

Arfib, B., De Marsily, G. and Ganoulis, J. 2007. Locating the zone of saline intrusion in a coastal karst aquifer using spring flow data. Groundwater, 45, 28-35.

Banerjee, P., Singh, V.S., Chatttopadhyay, K., Chandra, P.C. and Singh, B. 2011. Artificial neural network model as a potential alternative for groundwater salinity forecasting. J. Hydrol., 398: 212-220.

Chang, S.W., Clement, T.P., Simpson, M.J. and Lee, K.K. 2011. Does sea-level rise have an impact on saltwater intrusion?. Adv. Water Resour., 34: 1283-1291.

Choudhury, K., Saha, D.K. and Chakraborty, P. 2001. Geophysical study for saline water intrusion in coastal alluvial terrain. J. Appl. Geophysics., 46: 189-200.

Comte, J.C., Cassidy, R., Obando, J., Robins, N., Ibrahim, K., Melchioly, S. and Noe, C. 2016. Challenges in groundwater resource management in coastal aquifers of East Africa: Investigations and lessons learned in the Comoros Islands, Kenya, and Tanzania. J. Hydrol. Reg. Stud., 5: 179-199.

De Montety, V., Radakovitch, O., Vallet-Coulomb, C., Blavoux, B., Hermitte, D. and Valles, V. 2008. Origin of groundwater salinity and hydrogeochemical processes in a confined coastal aquifer: Case of the Rhône delta (Southern France). Appl. Geochem., 23: 2337-2349.

Demir, Y., Erşahin, S., Güler, M., Cemek, B., Günal, H. and Arslan, H. 2009. Spatial variability of depth and salinity of groundwater under irrigated ustifluvents in the Middle Black Sea Region of Turkey. Environ. Monit. Asses., 158: 279-294.

Deutsch, W.J. and Siegel, R. 1997. Groundwater geochemistry: fundamentals and applications to contamination. CRC Press, New York.

Dixon-Jain, P., Norman, R., Stewart, G., Fontaine, K., Walker, K., Sundaram, B., Flannery, E., Riddell, A. and Wallace, L. 2014. Pacific Island Groundwater and Future Climates: First-Pass Regional Vulnerability Assessment. Record 2014/43. Geoscience Australia, Canberra. http://dx.doi.org/10.11636/Record.2014.043

Fisher, R.S. and Mullican, W.F. 1997. Hydrochemical evolution of sodium-sulfate and sodium-chloride groundwater beneath the northern Chihuahuan Desert, Trans-Pecos, Texas, USA. Hydrogeology J., 5: 4-16.

Foster, T. and Willetts, J. 2018. Multiple water source use in rural Vanuatu: are households choosing the safest option for drinking?. Int. J. Environ. Health Res., 28: 579-589.

Guha, H. and Panday, S. 2012. Impact of sea-level rise on groundwater salinity in a coastal community of South Florida. J. Am. Water Resour. Assoc., 48" 510-529.

Ishii, M., Kimoto, M., Sakamoto, K. and Iwasaki, S. I. 2006. Steric sea-level changes are estimated from historical ocean subsurface temperature and salinity analyses. J. Oceanogr., 62: 155-170.

Kim, K.Y., Park, Y.S., Kim, G.P. and Park, K.H. 2009. Dynamic freshwater–saline water interaction in the coastal zone of Jeju Island, South Korea. Hydrogeol. J., 17: 617-629.

Kotra, K.K., Samanta, S. and Prasad, S. 2017. Rainwater harvesting for drinking: A physiochemical assessment in Port Vila, Vanuatu. Sou. Pac. J. Nat. App. Sci., 35, 33-44.

Kotra, K.K. 2011. Geomorphological impact assessment on groundwater quality and fluoride genesis along the Bay of Bengal of Visakhapatnam district, Andhra Pradesh, India. CLEAN–Soil Air Water, 39(10): 925-930.

Kumar, M. and Puri, A. 2012. A review of permissible limits of drinking water. Ind. J. Occ. Environ. Medicine, 16: 40.

Lal, K. and Datta, R. The impact of groundwater utilization on coastal aquifers in the Pacific Island States. 2017. Proceedings of the 15th Islands of the World Conference, South Australia, Australia.

Lenntech, R. 2013. Acids and Alkalis in freshwater. In Water Treatment Solutions. Retrieved from https://www.lenntech.com/aquatic/acids-alkalis.htm

Mantoglou, A. 2003. Pumping management of coastal aquifers using analytical models of saltwater intrusion. Water Resour. Res., 39: 1-12.

Mayer, C., Grosfeld, K. and Siegert, M.J. 2003. Salinity impact on water flow and lake ice in Lake Vostok, Antarctica. Geophysics Res. Lett., 30: 8-12.

Murphy, S. 2007. General Information on Alkalinity. In City of Boulder/USGS Water Quality Monitoring. Retrieved from http://bcn.boulder.co.us/basin/data/BACT/info/Alk.html

Nielsen, P. 1999. Groundwater dynamics and salinity in coastal barriers. J. Coast. Res., 15: 732-740.

Palut, M.P.J. and Canziani, O.F. 2007. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

Praveena, S.M., Abdullah, M.H., Bidin, K. and Aris, A.Z. 2011. Understanding of groundwater salinity using statistical modeling in a small tropical island, East Malaysia. Environmentalist, 31: 279-283.

Rao, N.S. 2008. Factors controlling the salinity in groundwater in parts of Guntur district, Andhra Pradesh, India. Environ. Monit. Asses., 138: 327-341.

Rhoades, J. D. 1996. Salinity: Electrical conductivity and total dissolved solids. Chemical Methods, 417-433.

Samanta, S., Pal, D. K., Lohar, D. and Pal, B. 2012. Interpolation of climate variables and temperature modeling. Theo. App. Climatology., 107, 35-45.

Somay, M. A. and Gemici, Ü. 2009. Assessment of the salinization process at the coastal area with hydrogeochemical tools and geographical information systems (GIS): Selçuk plain, Izmir, Turkey. Water, Air, and Soil Poll., 201, 55-74.

VMGD (Vanuatu Meteorology and Geohazards Department) http://www.vmgd.gov.vu/vmgd/index.php

Walton, N. R.G. 1989. Electrical conductivity and total dissolved solids: What is their precise relationship? Desalination, 72: 275-292.

Whitaker, F.F. and Smart, P.L. 1990. Active circulation of saline groundwaters in carbonate platforms: Evidence from the Great Bahama Bank. Geology, 18: 200-203.

White, I. and Falkland, T. 2010. Management of freshwater lenses on small Pacific islands. Hydrogeol. J., 18: 227-246.

World Health Organization (WHO). Guidelines for drinking-water quality, 2^{nd} ed. Vol. 2. Health criteria and other supporting information. World Health Organization, Geneva, 1996.

Willis, R. and Finney, B. A. 1988. Planning model for optimal control of saltwater intrusion. J. Water Res. Plan. Manag., 114: 163-178.

World Health Organization (WHO). 2007. pH in drinking water. http://www.who.int/water_sanitation_health/dwq/chemicals/ph_revised_2007_clean_version.pdf