Managing Coastal Aquifers in Selected Pacific Small Island Developing States Project (MCAP)

Groundwater investigation in Peleliu, Angaur and Kayangel States – Republic of Palau

Andreas Antoniou, Carlos Miraldo Ordens, Kamal Singh, Aminisitai Loco and Peter Sinclair

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Geoscience, Energy and Maritime Division of the Pacific Community

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Contents

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This work was part of the Managing Coastal Aquifers Project in Selected Pacific SIDS (MCAP). MCAP is executed by the Pacific Community (SPC) in partnership with the United Nations Development Programme (UNDP). This project is funded by the Global Environment Facility (GEF) and is being implemented in three countries: Republic of Palau, Republic of the Marshall Islands and Tuvalu. The purpose of the project is to i) understand the potential groundwater development options for communities in three atoll nations of Palau, Marshall Islands and Tuvalu through informed scientific and technical approaches while supporting in-country capacity building to monitor, manage and protect these water sources; ii) support the three countries in better responding to droughts through improved access to groundwater systems; iii) develop the skills in the outer islands to showcase community-led water management. Supporting this through improved relationships and understanding between national response teams and lead agencies with communities is critical.

Key partners and stakeholders that contributed to the implementation of this mission are:

- Bureau of Environment, Ministry of Agriculture, Fisheries, and Environment;
- Palau Public Utilities Corporation;
- Palau Environmental Quality Protection Board; and the
- State Governments of Peleliu, Angaur and Kayangel.

Community members from the states of Peleliu, Angaur and Kayangel played a key role by participating in community meetings and sharing their knowledge and views on the proposed work, and issues of concern.

1. Introduction

1.1 Project background

The Managing Coastal Aquifers Project in selected Pacific Small Island Developing States is being implemented by the Disaster and Community Resilience Programme within the Geoscience, Energy and Maritime Division of the Pacific Community, in partnership with United Nations Development Programme. This project is funded by the Global Environment Facility and is being implemented in three countries: Republic of Palau, Republic of the Marshall Islands, and Tuvalu. The four–year (2021–2024), USD 5.2 million project aims at improving the understanding, use, management and protection of coastal aquifers towards enhanced water security, including in the context of a changing climate. More specifically it aims at: 1) identifying the extent, threats and the development potential of groundwater resources; 2) increasing awareness of groundwater as a water security supply source; 3) providing options for improved access to groundwater; and 4) improving aquifer protection and management within Pacific Small Island Developing States.

1.2 Mission objectives and outcomes

The main purpose of this investigation was to identify and characterize fresh groundwater resources in the Republic of Palau (Figure 1), and more specifically in the states of Peleliu (Figure 2), Angaur (Figure 3) and Kayangel, that could help us to better understand and/or complement existing water supplies or could serve as a backup during dry periods. Additional objectives included assessing the current state of the water supply and water distribution infrastructure, in conjunction with community expectations; and building the capacity of national government counterparts in groundwater assessment and monitoring techniques with a view towards enhancing groundwater management. Activities undertaken to achieve these objectives included: 1) a survey of water points, such as wells, large sinkholes, taro patches and abandoned pit lakes; 2) the installation of automatic groundwater monitoring loggers in selected production wells; and 3) the sampling of groundwater from selected water points for chemical analysis. This resulted in a GIS-based, water-point inventory with relevant information.

Figure 1. Palau Islands.
Source: Coral Reef Research Foundation

The development of new groundwater resources in small island environments typically requires: 1) an investigation of the groundwater resource potential and optimal drilling targets or locations; 2) the placement of horizontal wells ("infiltration galleries") or vertical wells and the assessment of yield and water quality; and 3) equipping galleries and wells with pumps and storage tanks that are suitable for the water resource potential and the community's needs. The current work focused on the first component, which was achieved using geophysics, monitoring and hydrochemistry by attempting to better understand the local hydrogeology and the groundwater storage potential. Recommendations are given with regards to the operation of existing groundwater development, treatment, and distribution infrastructure, to potential new gallery locations, expected yields and expected groundwater quality.

2. Background

2.1 Geographical location and history

The Republic of Palau is a chain of islands located in the western Pacific between latitudes 5° 53′ and 8° 12′ N, and longitudes 134° 07′ and 134° 39′ E. The 466-km^2-long archipelago is in the southwest corner of Micronesia, surrounded by Guam, Papua New Guinea and the Philippines (Figure 1). There are about 340 coral and volcanic islands that vary in size from small islets to Babelthuap (or Babeldaob), which is the largest of the Caroline Islands. Most of the archipelago is surrounded by an enormous barrier reef system, continuous on the west and broken on the east (SPC 2021). Nine of the islands are inhabited, with Babelthuap, Koror, Malakal, Arakabesan and Peleliu being the most populated. Palau's total population is 17,614 people (Office of Planning and Statistics, 2020).

The first humans to arrive in the Palauan archipelago came from Southeast Asia around 1000 BC and developed a complex, highly-organized matrilineal society where chiefs were picked by high-ranking women (World Factbook 2022). The Palauan islands were the westernmost part of the widely scattered Caroline Islands, Pacific islands north of New Guinea, explored by the Spanish in the 17th century. Spain colonised Palau until 1899, when it sold it to Germany. Japan took control of the archipelago in 1914, until it lost it to USA in 1944 following the infamous battle of Peleliu. Palau became part of the US-administered Trust Territory of the Pacific Islands as a consequence of World War II. Palau regained official independence in 1994. A key aspect of Palau's recent history was phosphate mining from 1905 to 1955, first by the Germans and then by the Japanese (Colin 2009). Phosphate mining occurred mainly in Angaur, where a large pit lake and depressions can be found throughout the landscape, and in Peleliu to a much lesser degree. Phosphate mining in Angaur strongly impacted the hydrological system, and contributed to most the hydrological knowledge available for the island as discussed below.

Peleliu

Along with two small islands to its northeast, Peleliu forms one of Palau's 16 states. Peleliu consists of limestone and late tertiary andesitic volcanics, completely capped by an uplifted and karst coral reef platform (Colin 2009). It has a land area of 6.6 mi^2 (17 km^2) and is surrounded by a thick fringe of mangrove forest comprising more than a quarter of the island's total area. The main peaks are in the northwest, and include Bloody Nose Ridge at 246 ft (75 m) and Rois ra Sang and Roischemiangel at over 164 ft (50 m) above sea level. The rest of the island generally lies below 33 ft (10 m) above sea level.

The population in 2020 was estimated to be 470 and the number of households was 154 (Office of Planning and Statistics 2020). Most of the island's population lives in the village of Kloulklubed, the state capital, on the northwestern coast. Including the capital, there are four villages.

Phosphate mining in the Bloody Nose Ridge area of Peleliu began during the German administration and continued into the Japanese administration. The phosphate was loaded onto ships at a small harbor on the island's northern tip.

During World War II, a major battle between units of the United States Marine Corps and United States Army against the Imperial Japanese Army in 1944 is referred to as the Battle of Peleliu. Many World War II relics remain on the island, including a large airfield, abandoned war tanks, fallen planes, bunkers and coastal artillery.

Figure 2. Peleliu topographical map.
Source: Treehill, Wikimedia Commons

Angaur

Angaur is a raised coral platform island with a total land area of 3.1 mi^2 (~ 8 km^2). The highest point is at 147 feet (45 m) above sea level. The island was mined for phosphate from the early part of the 20th century up until the mid-1950s. Mining occurred originally began with the Germans, then by the Japanese, and finally by the Americans. Numerous mining pits remain, principally in the northwest part of the island. During World War II, the Battle of Angaur resulted in the island's capture by US military forces who turned the island into a major airbase with numerous military installations. Today the island is largely overgrown with dense vegetation, although the World War II airstrip is still present and usable. The north, east and south sides have narrow reef flats, averaging a few hundred meters in width. Off the southwestern tip of the island, the flat extends about 0.6 mi (1 km) offshore. Beaches comprise about one-third of the shoreline.

The population in 2020 was estimated to be 114 and the number of households 49 (Office of Planning and Statistics 2020). The state capital is the village of Ngeremasch on the western side. A second village, Rois, is on the northeast side of the island.

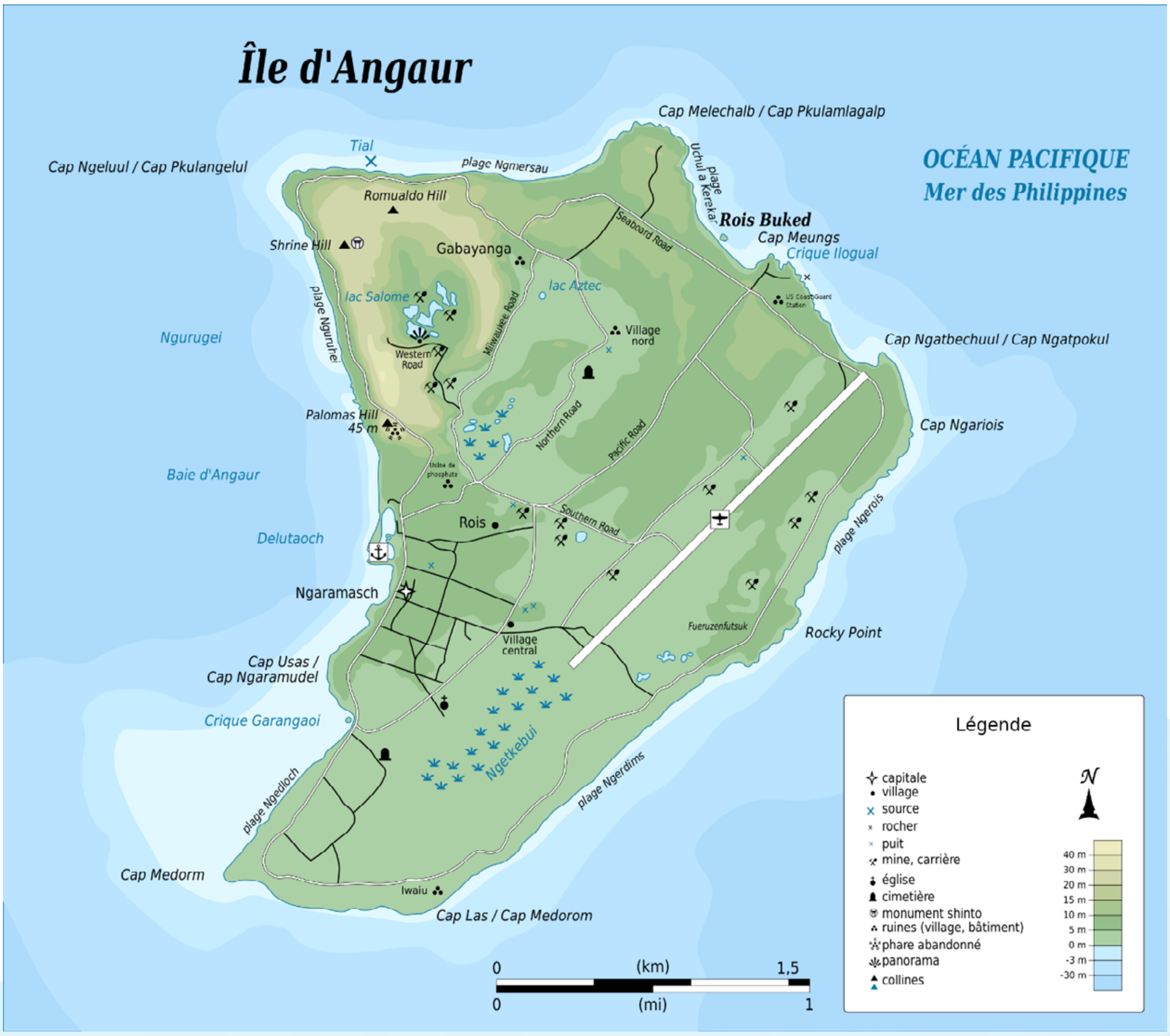


Figure 3. Angaur topographical map.
Source: Treehill, Wikimedia Commons

Kayangel

Kayangel is an atoll island with a total land area of 0.5 mi^2 (1.4 km^2) oriented north–south, and with a length of 2.1 mi (~3.3 km) and a maximum width of 0.7 mi (~1.1 km). The population in 2020 was estimated to be 41 and the number of households 25 (Office of Planning and Statistics, 2020). The main sources of employment are agriculture, services and public administration, while most income comes from fishing and social security/ pensions – the mean annual income is USD 10,475 per person (Office of Planning and Statistics 2020).

2.2 Climate

According to Colin (2009), Palau's climate is fully tropical, with year-round high temperatures, humidity and rainfall. There is a typical wet and dry season, although any month can have substantial rain, with peak rainfall usually occurring from June to August. The wet season is characterized by westerly monsoon winds, while the drier winter period experiences northeast trade winds. Palau is located in the Inter-Tropical Convergence Zone (ITCZ), an area of higher cloudiness than would be found farther north. The position of the ITCZ shifts with the seasons, hence the change in climatic regimes each year in Palau. During El Niño/La Niña cycles it shifts even more. Palau can have periods with very little rainfall for several months at a time. For example, during the El Niño/ La Niña of 1997–1998, it essentially did not rain in Palau for over five months.

BoM and CSIRO (2014) provide a description of Palau's climate, which is summarized below:

- Warming trends are evident in both annual and half-year mean air temperatures in Koror from 1951. The annual numbers of warm days and warm nights have increased, and the annual number of cool days has decreased. These temperature trends are consistent with global warming.
- Annual, half-year and extreme daily rainfall trends show little change in Koror since 1948.
- Tropical cyclones (typhoons) affect Palau mainly between June and November. An average of 28 cyclones per decade developed within or crossed Palau's exclusive economic zone between the 1977 and 2011 seasons. Over 85% of tropical cyclones between the 1981/1982 and 2010/2011 seasons were weak to moderate events (below Category 3) within Palau's exclusive economic zone. Available data are not suitable for assessing long-term trends.
- Variability of wind-waves in Palau is characterized by trade winds and monsoons seasonally, and the El Niño–Southern Oscillation and ITCZ location interannually. Available data are not suitable for assessing long-term trends.

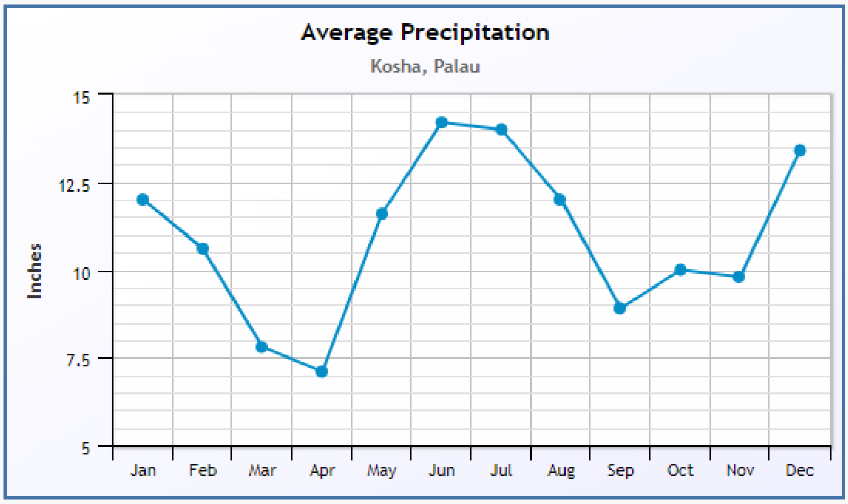
Also at country level, CSIRO et al. (2015) provide a summary of the science and tools developed through the Pacific-Australia Climate Change Science and Adaptation Planning Program, and the Pacific Climate Change Science Program prior to that, in an easily accessible and largely non-technical format. It is intended as a key point of reference on the latest science for policy developers, planners and associated decision-makers and stakeholders in partner countries. According to the report, the following is predicted for Palau:

- El Niño and La Niña events will continue to occur in the future, but there is little consensus on whether these events will change in intensity or frequency.
- Annual mean temperatures and extremely high daily temperatures will continue to rise.
- Average rainfall is projected to increase, especially in the wet season, along with more extreme rain events.
- Droughts are projected to decline in frequency.
- Sea level will continue to rise.
- Ocean acidification is expected to continue.
- The risk of coral bleaching is expected to increase.

- A reduction in wave height in the months December–March is projected by 2090, with a slight decrease in wave period. In June–September, a small decrease in period is projected, with a clockwise rotation toward the south.
- Tropical cyclones are projected to be less frequent but more intense.

Peleliu

The following weather data and description is according to weatherbase.com (2022). The weather station at Kosha, Peleliu – elevation: 10 ft (3 m), latitude: 07 02N, longitude: 134 16E – has been collecting data for over 30 years, and the data suggest that Peleliu experiences a Tropical Rainforest Climate, according to the Koppen Climate Classification. The annual average temperature is 79.6°F (26.4°C), with the warmest month being November with an average temperature of 80.3°F (26.8°C), and the coolest month being February, with an average temperature of 78.9°F (26.1°C). Annual average precipitation is 131.3 in (3335 mm), with June receiving the highest amount of precipitation of, on average, 14.2 in (360.7 mm). April has the least amount of precipitation, with an average of 7.1 in (180.3 mm). On average, Peleliu has 246 days of precipitation per year, with most of the precipitation occurring in June with 24 days, and the least precipitation occurring in April with 16 days.



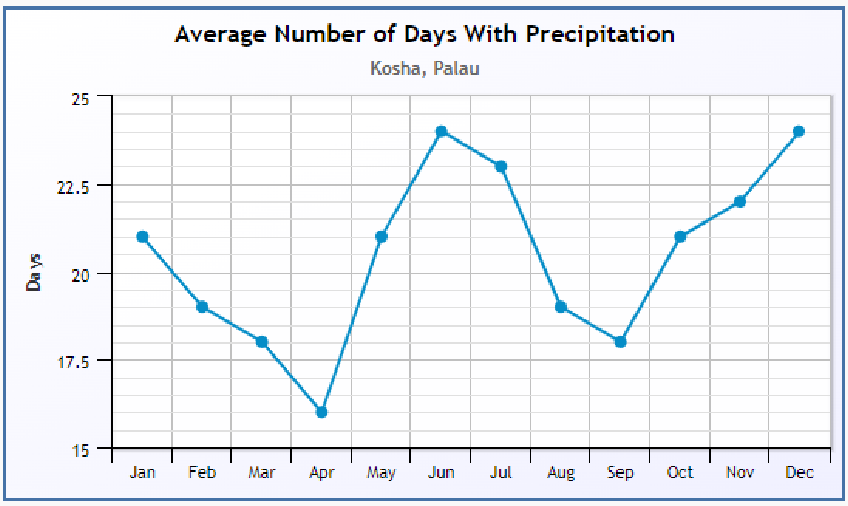
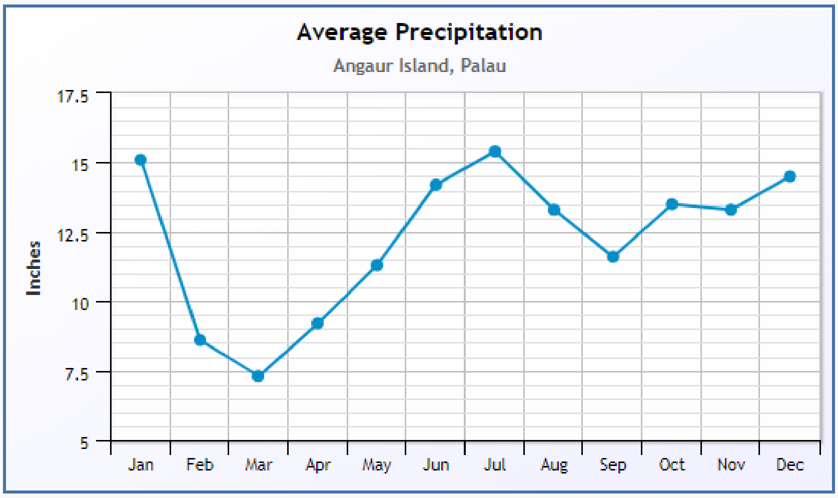


Figure 4. Monthly average precipitation (years on record: 30) and number of days with precipitation on Peleliu (years on record: 14).
Source: weatherbase.com 2022

Angaur

The following weather data and description is according to weatherbase.com (2022). There is a weather station located in Angaur (elevation: 20 ft, or 6 m; latitude: 06 54N; longitude: 134 09E). The data collected over a period of 30 years suggest a Tropical Rainforest Climate according to the Koppen Climate Classification. The annual average temperature is 81.8°F (27.7°C), with the warmest month being April with an average temperature of 83.3°F (28.5°C), and the coolest month being December, with an average temperature of 80.6°F (27.0°C). The annual average precipitation is 147.1 in (3736 mm), with July being the month with the highest precipitation with an average of 15.4 in (391.2 mm) (Figure 5). March is the month with the least amount of precipitation with an average of 7.3 in (185.4 mm). On average, there are 211 days of precipitation per year, with the most precipitation occurring in July with 20 days and the least precipitation occurring in February with 11.6 days on average.



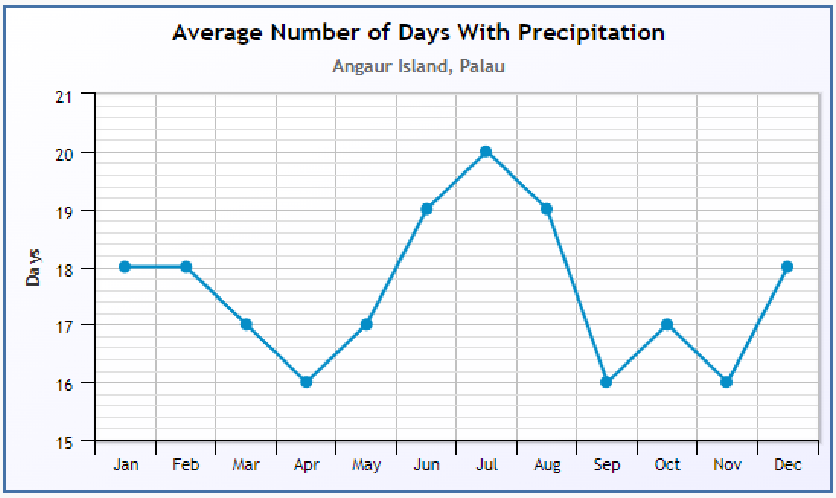
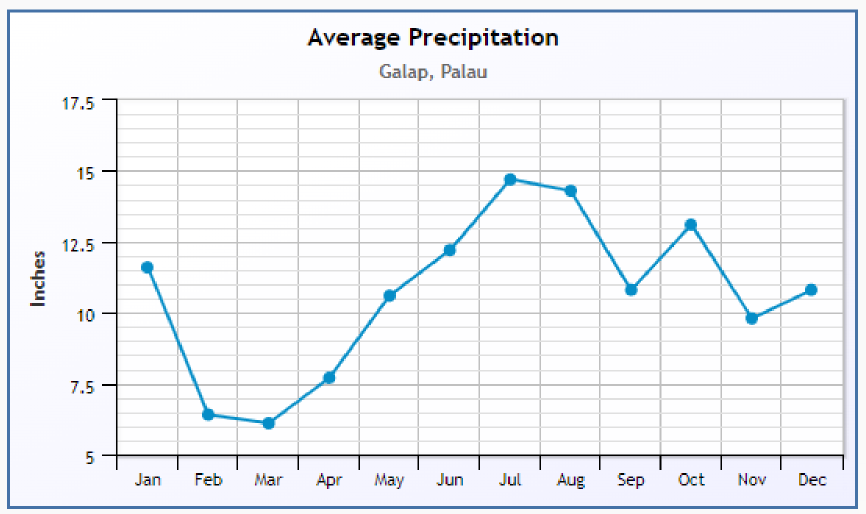


Figure 5. Monthly average precipitation (years on record: 30) and number of days with precipitation on Angaur (years on record: 14).
Source: weatherbase.com 2022

Kayangel

According to weatherbase.com (2022), the nearest operational weather station is in the village of Galap, Ngaraard State, at the northern tip of Babeldaob Island (elevation: 10 feet, or 3 m, latitude: 07 37N. longitude: 134 39E). The collected data over 25 years suggest that Ngaraard State experiences a Tropical Rainforest Climate, according to the Koppen Climate Classification. The annual average precipitation is 128.2 in (3256.3 mm), with July receiving the highest amount of precipitation of, on average, 14.7 in (373.4 mm). March receives the least amount of precipitation, with an average of 6.1 in (154.9 mm). The Galap weather station records, on average, 254 days of precipitation per year, with most of the precipitation occurring in July with 24 days, and the least amount of precipitation occurring in February with 18 days.



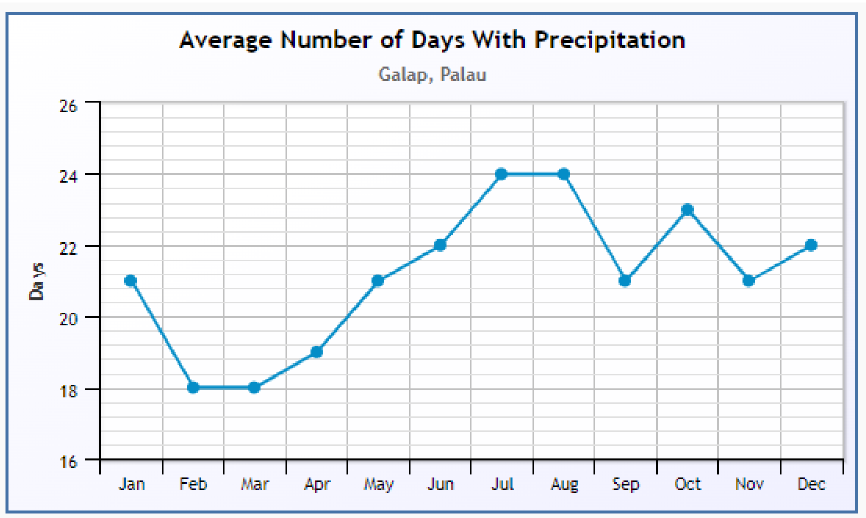


Figure 6. Monthly average precipitation (years on record: 25) and number of days with precipitation (years on record: 14) recorded by the Galap weather station in Ngaraard State (northernmost state of Babeldaob Island). Source: weatherbase.com 2022

2.3 Current water supply

The water supply system in the three states is managed by the Palau Public Utilities Corporation (PPUC). Below is a description of the current water supply conditions for each island based on our observations, information provided by PPUC and Environmental Quality and Protection Board (EQPB), and literature.

Peleliu

According to the 2020 census (Office of Planning and Statistics 2020), of the 154 households on Peleliu, 150 are connected to the public water supply system. Three households use reticulated water for cooking (97 use rainwater, 53 use both rainwater and bottled water, and 1 uses bottled water only), and one household uses reticulated water for drinking purposes (86 use rainwater, 63 use both rainwater and bottled water, and 4 use bottled water only).

The public water supply system is sourced from groundwater (Figures 7, 20 and 21). Groundwater is pumped from two infiltration galleries that were installed in the late 1980s, with each gallery consisting of three arms of unknown length (EM Chen 2001). Six vents allow for access and testing of the water inside each of the six gallery arms, but it is unclear whether the arms extend beyond the vents or not. The two galleries are connected to a central underground tank (referred to as "main well") from where groundwater is pumped into a desalination (reverse osmosis, or RO) plant that produces fresh water at a rate of 88 gal/min (333 L/min) for approximately 6 hours/day. The treated water is first pumped into a 60,000-gal (227,125-L) underground tank (referred to as "transfer tank"), then pumped into a 30,000-gal (113,526-L) elevated "distribution tank", and finally gravity fed to the main distribution pipe towards the village. It takes approximately six hours to completely fill the elevated "distribution tank", matching thus the design production rate of the RO system, and indicating the absence of losses between the desalinization plant and the tank.

The production capacity of the RO system is insufficient to meet the water demand; therefore, the desalinated water is complemented with an estimated four times the volume of raw groundwater, also pumped from the main well. The raw groundwater bypasses both the transfer tank and the distribution tank and is directly pumped towards the village through the main distribution pipe. The desalinated water is gravity fed and merged with the main distribution pipe where the two water sources (desalinated and raw) are mixed and pumped towards the two elevated village tanks that keep the system pressurized for supplying water to the households farther away from the source. It is unclear whether the water is first pumped into the two village tanks and then distributed to the households, or whether water is first fed to some of the households on its way to the tanks and then distributed again. According to PPUC, there are substantial losses in the existing distribution system due to leaks and potential open connections with parts of the old distribution system, which is supposed to be disconnected (Marson Aderiano, PPUC, 2022, pers. comm.). Recently, PPUC's leak detection team repaired a number of leaks associated with fire hydrants and household connections, thus improving the pressure in the system and allowing the two village tanks to fill up, something that was not possible prior to the repairs. Nevertheless, major losses are still expected to be present, preventing the system from fully operating on desalinated water.

Until recently, groundwater pumped from the main gallery well was complemented with groundwater pumped from a nearby sinkhole (sinkhole 1 in Figure 20) to meet the village water demand. This source was recently abandoned due to water quality concerns related to "rotten egg" smell of hydrogen sulfide (H_2S) and the appearance of white foam on the water surface.

Figure 7. Peleliu pump station and treatment plant: a) reverse osmosis system, b) and c) gallery wells, d) and e) main well, and f) gallery vent.

Angaur

According to the 2020 census (Office of Planning and Statistics 2020), out of 49 households, 47 are connected to the public water supply system. None of the households use reticulated water for drinking or cooking purposes; 41 households use rainwater for drinking purposes while the remaining use a combination of rainwater and bottled water; and 44 households use rainwater for cooking while the remaining use a combination of rainwater and bottled water. According to PPUC, part of the island population collects water from the school rain tank for drinking and cooking purposes. The school rainwater harvesting system is maintained by the Ministry of Education and the State of Angaur. According to EQPB, however, the water is untreated and frequently contaminated with *Escherichia coli* (E. coli) bacteria.

Groundwater is pumped from two wells – A and B (formerly known as wells 1 and 2, respectively) (Figures 9 and 10), which were drilled before World War II for mining. Their depth is approximately 22 ft (7 m). After the American occupation of the island, when more than 10,000 men were stationed on Angaur, groundwater was abstracted from nine wells in total (Van der Brug, 1984). Monthly abstraction from wells A and B averaged about 3 Mgal (~11.3 ML) between 1950 and 1954. Abstraction almost ceased after mining ended in 1955 due to the high mineral content, resulting in the use of that water for cooking and washing only.

Nowadays, wells A and B alternate pumping groundwater which is consequently treated prior to gravity-fed distribution from an old concrete 50-Kgal (189.3-KL) tank on Palomas Hill (old lighthouse, Figure 8) to households. At the time of our visit in June 2022, the pump in well A was out of order, and well B was not capable of producing enough water to fill the distribution tank (Marson Aderiano, PPUC, 2022, pers. comm.). The pump is manually stopped every day at 02:00 and restarted at 06:00 when the tank level is running low (Marson Aderiano, PPUC, 2022, pers. comm.). This might point to leakages in the distribution system as water usage between 02:00 and 06:00 is not expected to be high.

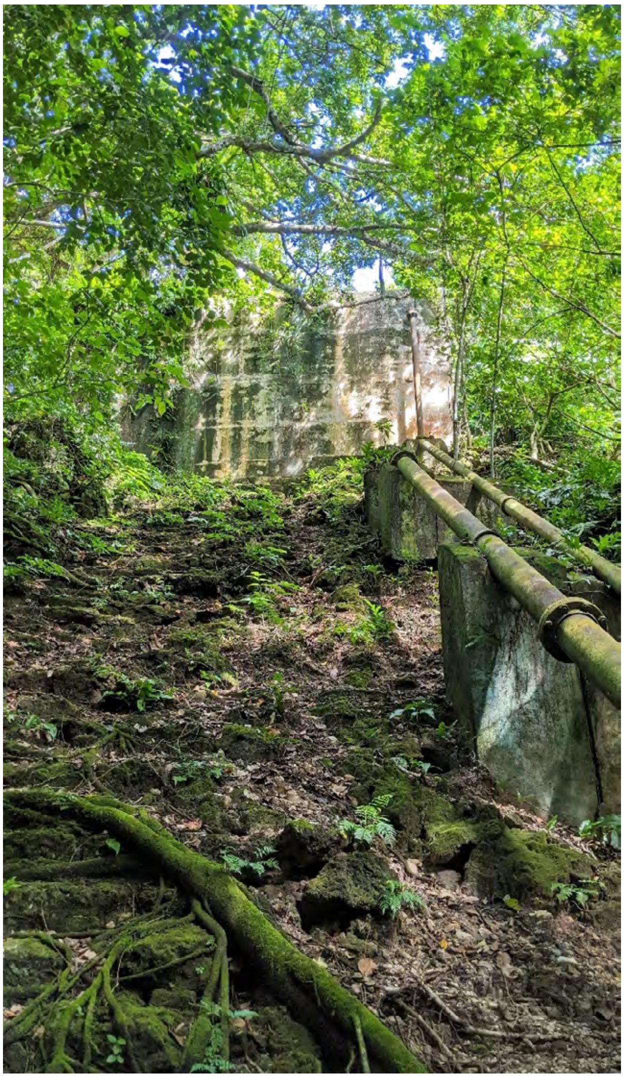


Figure 8. Distribution tank on Palomas Hill.

Historically, the Koska well (formerly called well 6) – located in the eastern part of the island – was used to supply water to the US Coast Guard facility from 1953 until around the 1970s. In 2014, the Koska well was rehabilitated as a water supply for emergency purposes as part of the European Union-funded Global Climate Change Alliance Project (SPC 2016). A solar pump, panels and a 15-Kgal (~56.8-KL) concrete tank were installed but the connection to the supply line was never made, and at the time of our visit, the well was abandoned. As part of the well rehabilitation, a pumping test was conducted by PPUC as well as water sampling and analysis. According to the pumping test report, no drawdown was observed, and a high yield could be achieved (104.8 gal/min, or 396.7 L/min), enough to cover community needs. In fact, no major drawdown is expected when pumping from a freshwater lens, but the groundwater salinity should be constantly monitored for any salinity changes due to potential saltwater intrusion. Such salinity monitoring was not part of the pumping test conducted by PPUC. The sustainable yield of the well should then be determined based on the rate at which the well can be pumped without inducing salinity changes to the abstracted water. Such a test has yet to be conducted for the Koska well.

Figure 9. Pumping well in Angaur.

Figure 10. Pumping well in Angaur.

The United Arab Emirates-funded treatment plant (Figure 11) was manufactured by Pure Aqua Inc. and installed in 2016 by CBS Power Solutions (CBS Power Solutions 2022). It consists of a multimedia filter, an active carbon filter, a softener, an automatic chlorinator and a UV sterilizer. At the time of our visit, the treatment plant was operating at a limited capacity, with the automatic chlorinator and UV sterilizer being out of order due to electrical issues (Marson Aderiano, PPUC, 2022, pers. comm.). Lack of maintenance skills and capacity, and challenges with obtaining guidance from the manufacturer with regards to spare parts have contributed to this problem (Marson Aderiano, PPUC, 2022, pers. comm.). Chlorination is conducted manually by the local PPUC operator, resulting in a high fluctuation of residual chlorine concentration throughout the day, with frequent exceedances of 5 mg/L (10 times higher than WHO guidelines). Further, the proximity of the treatment plant to the sea has accelerated corrosion of the various plant components as well as of the container inside, in which the plant is installed. Land disputes and ownership of most of the land by clans create a complex environment for building infrastructure. Maintenance of the treatment plant is considered a priority for Angaur.

Figure 11. Treatment plant in Angaur.

Kayangel

According to the 2020 census (Office of Planning and Statistics 2020), of the 25 households on Kayangel, 18 are connected to the public water supply system. All 25 households use exclusively rainwater collected from roof harvesting systems for primary purposes (cooking and drinking) while the reticulated groundwater supply is used for secondary purposes such as washing.

The public water supply system extracts groundwater from an infiltration gallery system that was installed in the north-central part of the island – the widest part of the island – where a fenced "groundwater catchment" area exists (Figures 12 and 13). The gallery was installed in 2006 and consists of two parallel 120-ft (37-m) gallery arms (6-in diameter slotted pipes) extending towards the north and feeding into an underground 8-ft-deep (2.4-m) concrete tank ("well") (Figure 14). It is unclear whether the two arms feed separately into the well or if they are connected to a common header leading to a single intake at the well. Substantial sedimentation was observed inside the well resulting in the arm intake being almost completely buried. It is likely that these sediments infiltrate through the gallery arms and accumulate over time inside the well. A similar observation was made by Pollock (2014) after the island suffered major damage by Typhon Haiyan. Pollock stated that the original well design indicates a concrete flooring. A land area of 200 by 200 ft (61 by 61 m) surrounding the wells was fenced to protect the groundwater from contamination and the infrastructure from vandalism. Groundwater is pumped into a 68-ft (21-m)-tall overhead storage tank of 5000-gal (~19 KL) capacity, located outside the perimeter fence, and then gravity fed to households through a 6-in pipe. The tank requires approximately eight hours to fill up (Marson Aderiano, PPUC, 2022, pers. comm.), suggesting a pumping rate of approximately 625 gal/hour (2.4 KL/hour). A floating valve shuts the pumps down when the overhead tank is full; however, the valve was not operational at the time of our visit. As a result, the pumps had to be manually stopped by the PPUC operator. An automatic chlorination system exists in the pumphouse but is not operating optimally and consistently. According to EQPB and PPUC, quarterly testing is conducted for coliform bacteria, which are occasionally detected throughout the distribution system, in tap water samples from households, and in school and government buildings.

Several issues associated with the existing infrastructure were identified at the time of our visit. The fence surrounding the catchment area was substantially damaged while the stairs and floor to the overhead tank were considerably corroded and partly missing, inhibiting safe access to the tank for conducting repairs. In addition, the two pumps were placed on top of a low concrete base making the pumps prone to flooding from heavy rainfall (Figure 13). The pumphouse gate was also damaged and displaced. Several repairs and improvements addressing these issues will be completed as part of this project.

Figure 12. Groundwater catchment area with pumphouse in the background. The two steel poles indicate the edge of the trench that was dug for the two parallel gallery arms to be installed. The trench was then refilled with sands.

Figure 13. Pumphouse and the two alternating pumps.

Figure 14. Overhead tank and gallery "well" with damaged lid.

2.4 Geology

Early descriptions of Palau's geology are provided by the US Army Intelligence Division (1944, 1956), Van der Brug (1984) and Kelletat (1991). More recently, Colin (2009) presented a description of Palau's geology that can be summarized as follows. The Palau Islands are part of an arc-trench system between the Philippine and Pacific plates. Palau sits near the southern end of the submarine Palau–Kyushu Ridge, which formed roughly 65–70 million years ago, not long before the formation of the Palau Islands. Erupted material on the ridge was largely basaltic. Volcanic activity, mostly submarine, ceased about 20–25 million years ago, and the Palau Islands did not reach the surface until subsequent uplift occurred. Once uplifted into shallow water, calcium carbonate was deposited on the volcanic basement, primarily through the growth of reef-building corals and calcareous algae. These processes produced the organic limestone that sits atop the volcanic rocks today. The Palau Islands were thus formed by the accumulation of both volcanic materials and organically produced (biogenic) limestone, and can be categorized as volcanic islands, high limestone islands, low platform islands, and coral atolls. The volcanic islands are basaltic, and include most of the large island of Babeldaob, Arabesang, part of Koror, and some adjacent smaller islands. The so-called Rock Islands, high limestone islands, are uplifted and eroded ancient reefs that can be found from southern Babeldaob and Koror to Peleliu. Low platform limestone islands include Angaur and most of Peleliu – uplifted reef flats with clastic material deposited on or behind them. Although usually relatively flat and only 10–50 ft (3–15 m) above sea level, elevated and rugged limestone ridges can occur on top of the low flat platform terrain, making what is called a compound island. The atoll islands are Kayangel and Ngeruangl in the north of Palau. Basaltic rock undoubtedly underlies the entire group, but it is covered, in most places, by a limestone layer of unknown thickness. A few islands near Koror have both basaltic and limestone formations on their surface.

Peleliu

Peleliu, a low platform island, is composed of late tertiary andesitic volcanics completely capped by an uplifted and karst coral reef platform. The limestone ridges found in the northwest of the island are old reef fronts now elevated and eroded. They are riddled with solution caverns and crevices. A low platform without any ridges is found in the south and east. A map – including a digital representation of the most recent geological map of Peleliu by Van der Brug (1984) (based on geological descriptions by US Army Intelligence Division (1956) – is presented in Figure 20**,** and is summarized below.

The Palau Limestone formation is the oldest outcropping in Peleliu and is a relatively pure limestone. The Palau Limestone developed in warm tropical seas by processes of calcareous deposition and accumulation that probably have been continuous since the Miocene, by which time enough volcanic material had accumulated to result in water shallow enough for coral growth. It consists of light-colored, poorly bedded, porous to dense, raised reef and lagoonal coralline deposits. The beds are composed chiefly of clastic material irregularly cemented by secondary deposition. The fragments are remains of animals and algae that secreted calcite. Calcareous algae were most important in supplying material, followed by corals, foraminifers, pelecypods, gastropods and other forms. The material has been pulverized not only by physical processes, but by animals, such as holothurians, which engorge and grind great quantities of bottom sediments. Corals in position of growth (i.e. insitu and in the state when they were growing) are rare; some complete shells are preserved.

The Peleliu Limestone, which is of Pleistocene age, consists in general of white, porous, compact reef limestone and accumulations of unconsolidated coralline detritus. The reef limestone is composed mainly of calcareous algae and coral commonly in position of growth. The coralline detritus consists of fragments of calcareous algae. The Peleliu Limestone is lithologically similar to the Palau Limestone, and accumulation of the one followed the other without a time lapse at some locations. It is, however, fresher appearing, less modified, and less cemented than the Palau Limestone. Where the two formations are in contact, generally the Peleliu Limestone comprises a flat platform flanking the base of a high limestone ridge. Large sinkholes can be found throughout the island within this formation, and two of them have been used in the past as freshwater sources. (These are discussed in more detail below.) There are widespread, small karstic dissolution features at the surface, which are likely to contribute to groundwater recharge by facilitating preferential infiltration. The Peleliu Limestone formation has an estimated thickness of about 100 ft (~ 30 m). Its upper surface is generally at a height of 30 ft (~9 m) or less.

The sand areas correspond to beach deposits mostly made up of calcareous sand, gravel, cobble stones and coral heads, sourced from nearby living reef. The height of the deposits above sea level is usually 5–8 ft (1.5–2.5 m). The beach deposits in some cases have been built above sea level by wave action, and in other cases have been raised to their present elevation. The presence above tide level of beach rock (cemented beach material) indicates a raised beach deposit or a lowering of sea level. The building of beach lines has, in some cases, enclosed depressions, resulting in the development of swamps at the back of the beach. The texture of a deposit reflects its exposure to wave action. An inland of raised beach deposit stands 25 ft (7.6 m) above sea level on the west side of the main road near the center of the north peninsula, and consists of gravelly sand with shell fragments.

Mangrove swamps are common along the coasts of most Palau Islands. The mangrove-associated slimy materials usually consist of clay mixed with considerable organic materials and are partly stabilized by the intermeshing mangrove roots. The slimes are up to several feet in thickness and are underlain by bedrock or calcareous muds. Mangrove swamps bound most of the Peleliu shoreline in the shallow bay on the northeast side between the two peninsulas, and also fill the head of a sea reentrant on the southeast coast.

Angaur

In addition to the references mentioned above, Wentworth et al. (1955), Arnow (1961) and Van der Brug (1984) describe the geology of Angaur and the history of phosphate mining operations, the island hydrogeology (including characteristics of wells and test holes; Table 1) and the impacts of mining on groundwater quality and availability. According to Wentworth et al. (1955), the low platform island of Angaur has two distinct topographic sections of distinct geological characteristics (Figures 15 and 22): province A composed of high limestone ridges in the northwestern one-third of the island, and province B consisting of a limestone platform to the west, and calcareous sand at the southern end of the island including a large swamp of 124 acres (~0.5 km^2).

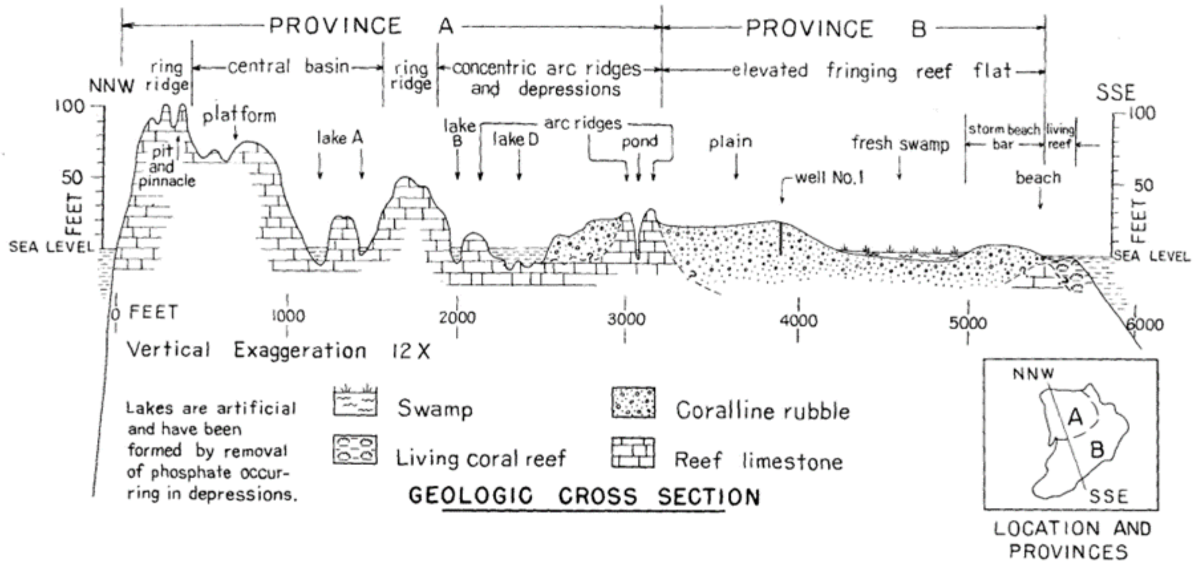


Figure 15. Geological cross-section of Angaur. Source: US Army Intelligence Division 1956

The coralline limestone of province A is of Pleistocene and Pliocene age, and corresponds to the Palau limestone identified in other parts of the country. The Palau Limestone is the oldest formation outcropping in Angaur and is a relatively pure limestone. The Palau Limestone developed in warm tropical seas by processes of calcareous deposition and accumulation that probably have been continuous since the Miocene, by which time enough volcanic material had accumulated to result in water shallow enough for coral growth. It consists of light-colored, poorly bedded, porous to dense, raised reef and lagoonal coralline deposits. The beds are composed chiefly of clastic material irregularly cemented by secondary deposition. The fragments are remains of animals and algae that secreted calcite. Calcareous algae were most important in supplying material, followed by corals, foraminifers, pelecypods, gastropods, and other forms. The material has been pulverized not only by physical processes, but by animals, such as holothurians, which engorge and grind great quantities of bottom sediments. Corals in position of growth are rare; some complete shells are preserved.

The coralline rubble and coralline limestone of province B is of Holocene and Pleistocene age, and corresponds to the Peleliu Limestone formation identified in other parts of Palau (also known as Angaur limestone when specifically referring to this island's formation). It consists in general of white, porous, compact reef limestone and accumulations of unconsolidated coralline detritus. The reef limestone is composed mainly of calcareous algae and coral commonly in position of growth. The coralline detritus consists of fragments of calcareous algae. This formation is lithologically similar to the Palau Limestone, and accumulation of the one followed the other without a time lapse at some locations. There are widespread small karstic dissolution features at the surface of both limestone formations, which are likely to contribute to groundwater recharge by facilitating preferential infiltration. It is, however, fresher appearing, less modified, and less cemented than the Palau Limestone. Where the two formations are in contact, generally the Peleliu Limestone comprises a flat platform flanking the base of a high limestone ridge.

The sand areas of province B are from the Holocene and correspond to beach deposits mostly made up of calcareous sand, gravel, cobbles, and coral heads, sourced from nearby living reef. The elevation of the deposits above sea level is usually 5–8 ft (1.5–2.4 m). The beach deposits in some cases have been built above sea level by wave action, and in other cases have been raised to their present elevation – a single storm in Angaur has built a beach line of cobbles 25 ft (7.6 m) above mean sea level. The texture of a deposit reflects its exposure to wave action. A sandy beach has formed behind the protection of the broad reef at the southwest end of Angaur, whereas coral heads and cobble stones compose segments of the beach fronting the narrow fringing reef on the southeast side of the island. The presence above tide level of beach rock (cemented beach material) indicates a raised beach deposit or a lowering of sea level.

The swamp areas are from the Holocene and largely composed of organic muck. The development of beach lines has enclosed a depression resulting in the development of the large swamp on the southeast side of Angaur. Mangrove swamps are common along the coasts of most Palau Islands, and small mangrove swamps exist at the south end of Angaur. The slimy sediments usually consist of clay mixed with considerable organic materials, and are partly stabilized by the intermeshing roots.

Table 1. Characteristics of selected historical wells and test holes in Angaur.

Well / test hole	Depth (ft)	Diameter (in)	Altitude of measuring point above mean sea level (ft)	Aquifer
W 1	24	48	22.62	Rubble
W 2	21	42	21.50	Rubble
W 3	11	60	9.99	Rubble
W 4	10	22	9.14	Beach deposits
W 6	16	96	16.42	Rubble
W 11	17	22	2.56	Backfill
W 13	8	42	6.27	Clayey phosphatic limestone
W 14	6	22	5.45	Clayey phosphatic limestone
TH 12	41	2.5	9.90	Beach deposits
TH 13	36	2.5	14.63	Rubble
TH B7	21	2.5	2.22	Clayey phosphate

Sources: Arnow 1961; Van der Burg 1984

Kayangel

Atolls, such as Kayangel, are geologic structures deriving from basaltic volcanoes that have subsided into the ocean. Reef growth results in a cap of calcium carbonate minerals extending from sea surface to the top of the submerged volcano. Chemical alteration and weathering of these carbonate minerals, induced by precipitation and sea level changes, have governed the shallow subsurface geology, which is generally described by the following three-layer model: 1) upper sediment unit composed of unconsolidated and well-sorted coral sand and gravel; 2) lower sediment unit composed of unconsolidated lagoonal sands and gravel of Late Pleistocene/ Early Holocene age; and 3) dense and well-consolidated limestone unit of Pleistocene age, which formed during subaerial exposure and recrystallization to calcite. The unconformity between the younger sediments and the underlying Pleistocene limestone is called the Thurber Discontinuity and is typically encountered at depths ranging between 16 and 82 ft (5 and 25 m).

According to Gressitt (1953), most of the eastern (ocean) shore of Kayangel consists of relatively narrow, sloping beaches made up of a mixture of rough coral gravel or accumulations of coral rocks and sand. On the western or lagoon shores, the beaches are predominantly made up of sand, although the sand is rather coarse and partly mixed with coral fragments. The northern end is primarily gravelly, whereas the southern end is sandy with some rocks or gravel. The soil in Kayangel is mainly composed of coarse loamy sand, sometimes mixed with coral gravel. However, in certain areas, such as much of central Kayangel, the soil primarily consists of gravel with or without a thin layer of sand or loamy sand at the top.

Additionally, Gressitt described the agricultural production on the island in 1952: "In the northcentral, broadest part of the main island are the taro beds, consisting almost entirely of the large false [swamp] taro (*Cyrtosperma chamissonis*, "b'rock") growing in large, submerged areas. Some small areas of ordinary taro (*Colocasia esculenta*, "ku-kao") are found near the village."

Fresh groundwater occurs in atolls as a thin lens buoyantly supported by dense underlying saline water. A freshwater lens is formed within the unconsolidated sediments due to suitable hydraulic conditions. In wider islands (> 0.6 mi or 1 km) that receive an appreciable amount of rainfall, the base of the freshwater lens can reach the Thurber Discontinuity. The higher permeability of the underlying limestone cannot support the formation of a lens which is truncated at that point due to immediate mixing with the underlying saltwater (Hamlin and Anthony 1987; Hunt 1997). The thickness of the freshwater lens across the width of the island depends on the recharge rate, the width of the island, hydraulic conductivity (K) of the upper sediment units, and the depth to the Thurber discontinuity and the presence or absence of a reef flat plate (Bailey et al. 2013).

A zone of transitional salinity typically exists between the infiltrated rainwater and underlying saltwater, and is commonly referred to as "transition zone". This zone is formed by mixing of the two water types promoted by tidal forces and its thickness largely depends on the hydraulic properties of the aquifer sediments.

The hydraulic properties of freshwater lens aquifers strongly depend on the position of the island with respect to the direction of prevailing winds. Freshwater lens aquifers tend to acquire a coarse sediment structure on islands that are in the direct path of the prevailing winds and associated high-energy waves. In contrast, aquifers on islands located on the partially protected leeward side of atolls tend to acquire finer sediment structure. Considering that the prevailing direction of trade winds in Palau is from the northeast, it is expected that Kayangel does not offer ideal hydraulic conditions for the development of a thick freshwater lens.

2.5 Historical groundwater investigations and supply

The hydrogeology and historical water supply of Palau is mainly described by Van der Brug (1984) and is based on earlier studies by the US Army Intelligence Division (1944, 1956). All background hydrogeological information provided in this report comes from Van der Brug (1984), unless clearly stated otherwise. SPC (2012) provides background data for the rivers of Palau, although without providing information about Peleliu. More recently, Miles et al. (2020) analyses climate-change challenges for Palau but does not provide details regarding the three project islands.

Peleliu

According to Van der Brug (1984), in the low plain section and in sandy areas near the shore, groundwater was historically obtained from a thin freshwater lens by digging shallow wells. In 1948, 43 wells were counted, mostly within 295 ft (90 m) of the coast (Figure 20). Except for two wells near the old airfield (wells 5 and 6), the rest were not used by the local population because they were either brackish or contained trash. A pump test on well 6 in 1948 showed a drawdown of 3.5 ft (1.07 m) when pumped for 45 minutes at a rate of 60 gal/min (~227 L/min), with a recovery time of 30 minutes. No provision was made for tidal fluctuation in this test.

According to Van der Brug (1984), during much of the period between 25 August 1971 and 20 April 1978, continuous records of groundwater levels were obtained for well 5, which was not in use during that period. Water levels in this 12-ft (3.6 m)-deep well, located near the center of the island, followed the tides closely. A sample collected from this well on 10 June 1971 demonstrated a very high hardness (hardness as $CaCO_3$ >180 mg/L). No information is given on how the sample was collected.

Until the early 1980s, water was supplied from a source developed by the Japanese prior to 1950 (EM Chen 2001). This is referred to throughout our report as "sinkhole 2" or "old water source". EM Chen (2001) suggests this source was abandoned either because of increased water salinity, or a pump failure.

In 1980, a new system utilizing a rain catchment area of six acres at the northeastern end of the airfield runway was constructed. Runoff from the catchment was stored in a 2.6-Mgal (9.8 ML) reservoir lined and covered with synthetic rubber. Water was pumped from the reservoir to an old 60,000-gal (227,125 L) tank, a nearby 10,000-gal (~37,854 L) tank, and to three new 10,000-gal (37,854 L) tanks at the village at the north end of the island.

Angaur

Most geological and groundwater knowledge and data exist because of concerns about mining and its impacts on groundwater quality due to seawater intrusion, and efforts to minimize such impacts. Arnow (1961) provides records of selected wells and test holes and maps of respective tidal lags and ratios (Annex B). Van der Burg (1984) provides characteristics for nine wells recorded in 1948 and 1949, including groundwater levels and chloride concentration, tidal ranges and ratios, diameters, altitudes and depths.

Phosphate was extracted in Angaur by strip mining, from 1909 to 1954, which removed phosphate deposits that formed a protective seal over the highly permeable limestone. In the early days, ore above the water table was mined mainly by hand from pockets in the limestone, which left pits scattered throughout the land surface. In later operations, the ore occurring in extensive beds below the water table was removed by draglines, which had a bucket capacity of 1.5 yd^3 (~1.12 m^3) and could mine to a maximum depth of about 17 ft (~5.2 m). Wherever the mining operations extended below the water table a pit lake was created in which mining could be continued to a maximum depth of 26 ft (~7.9 m) by a floating suction dredge. The mining capacity of the dredge was 8800 short tons (~8,000,000 kg) per month.

Many pit lakes and ponds, created by early phosphate mining, were scattered over most of the island until the US Trust Territory Administration became concerned about the intrusion of saline water and how it affected groundwater quality, owing to the large volumetric capacity of the lakes (Arnow 1961). All the pit lakes were in province A, where the bedrock contains long dissolution channels. Some of the channels extend from the lake bottoms directly to the sea or to zones where the ground water is saline. Influx of saline water through the dissolution channels at high tide caused the water in the lakes to become saline soon after they were formed. Because of the intrusion of saline water into the excavations, pit lakes that remained after the completion of mining, in addition to being useless for agriculture, were considered a potential menace to adjacent wetlands where taro was grown and to the public water supply in the southern part of Angaur. Thus, after 1950, mining operations (at the time solely conducted by Phosphate Mining Co.) were required to fill the lakes with limestone quarried outside the mining area and to backfill each excavation immediately after mining was completed to reduce the possibility of salinization. The lakes were filled to a level slightly above the water table, and the surface of the fill was made level so that the land could eventually be suitable for farming. Before the lakes had been filled, the water was brackish when tested and showed the effect of the tides. No potable water could be recovered from lakes or ponds. Water samples collected in February 1950 from most lakes, ponds and wells were analyzed for chloride, sulphate, calcium, total solids, and pH.

From January 1951, mining was carried out in a manner calculated to reduce to a minimum the length of time that the lakes were allowed to remain unfilled. This was done by mining each new area in sections, and by backfilling each section immediately after mining was completed. Daily groundwater samples were collected from a series of observation wells around the mining area to observe any movement of saline water out of the mining area into the surrounding farmland or into province B. There was no indication of appreciable spreading of saline water from the lakes. Groundwater chloride concentration in province A was systematically above 1000 ppm, while it was below this level for the rest of the island, and below 100 ppm in the southern and central parts of the island. The boundary between provinces A and B in the central part of the island roughly corresponds with the position of the 1000-ppm isochlor (line of equal chloride concentration). Little significant change in the position of this isochlor is noticeable during the 5.5-year monitoring period, December 1949–May 1955.

No data are available to indicate the salinity of the groundwater in province A before mining began in 1909, and it is not certain whether the water in that province was fresh at that time. Groundwater chloride concentrations suggest that provinces A and B apparently function as independent groundwater units, and that the quality of the groundwater in province B has not been noticeably affected by mining activities in province A. Based on observation well data, backfilling of the lakes reduced the rate of influx of saline water, and the salinity of the groundwater in the backfilled areas decreased within one year, although not uniformly across the mining-affected area.

Kayangel

The earliest description of Kayangel's water supply is given by Gressitt (1953). The main water source for the community was just north of the village. It comprised a 2.5 m^2 pool of slightly brackish water enclosed by large square blocks of coral rock. The water level fluctuated with the tides. Additionally, there were smaller, less elaborate pits dug in the area, typically holding a few inches of water. Toads introduced after the war to control lizard populations were present in great numbers in the pool, contaminating the water.

Pollock (2014) provided a comprehensive assessment of Kayangel's water supply system post Typhoon Haiyan, focusing on water quality, quantity, and physical infrastructure. According to Pollock:

i) groundwater salinity measurements from the first trench that was dug prior to the gallery construction were obtained in 2003 and 2004. Two, somewhat contradictory datasets were available: one collected during an initial pumping test in November 2003 indicating a total dissolved solids (TDS) of 280–325 ppm and chloride concentrations of 155–350 ppm, and a second dataset indicating a TDS concentration of 610–760 ppm and sulphur odour. Some inconsistency most probably exists with the first dataset as chloride concentration cannot be higher or even similar to TDS.

ii) EQPB measured TDS in 17 shallow wells in September 2001 and reported a range of 200–800 ppm, mostly from 200 ppm to 500 ppm;

iii) No further testing was done from 2003 to 2013;

iv) Two sampling campaigns were conducted by EQPB one week (15 November 2013) and one month (16 December 2013) post Typhoon Haiyan. The system was not operating at the time and the samples were collected directly from the gallery well. The results were as follows:

Date	Salinity (ppm)	Total coliforms (count/100 mL)	*E. coli* (count/100 mL)	Turbidity (NTU)	pH
15 Nov 2013	3500	>2400	600	1.30	
16 Dec 2013	2700 (top) 4600 (bottom)	>2400	1	0.98	7.1

In summary, it is generally accepted that groundwater salinity prior to the construction of the infiltration gallery was in the 250–750 ppm TDS range and after the typhoon, the salinity increased tenfold to 3500–4000 ppm. It is also highlighted that the flooding resulted in an increase in *E. coli* contamination which, however, disappeared after a month.

Pollock (2014) further mentions that the Coral Reef Research Foundation installed a rain gauge, one groundwater level logger inside the well, and one water level logger at the main pier for monitoring tidal fluctuation. No information on this equipment was available at the time of visit.

3. Field survey methodology

3.1 Electrical resistivity tomography survey

Electrical resistivity tomography (ERT) geophysics were used to assess, visualize and identify the lateral and vertical variability in electrical resistivity response within the different geological units. The method works on the principle of injecting direct current into the ground using a pair of electrodes. This current causes a potential voltage difference in the ground, which is measured by a separate pair of electrodes. The voltage measured can then, using the parameters of the survey, be converted into an apparent resistivity value. Resistivity of the subsurface is a function of the porosity of a geological medium, hydraulic permeability, electrical conductivity or salinity of pore fluids, and clay mineralization, and can provide insight into the underlying geology and hydrogeology.

The ABEM Terrameter LS2 (GuidelineGeo Inc.) was used in combination with the multiple gradient array as the preferred survey protocol, offering a high horizontal and vertical data resolution (Dahlin and Zhou 2006). The depth of investigation is a function of the electrode spacing and the subsoil resistance; in general, the greater the electrode spacing, the deeper the investigation. In general, an electrode separation length of 16.4 ft (5.0 m) was selected to investigate in detail depths up to 230 ft (~70 m). In selected cases, either because the survey profiles were short due to road length, or the interested depth of investigation was shallower, shorter separation distances were chosen. The orientation of the survey profiles and traverse distance was guided by the review of satellite photos, geological maps, the presence of suitable roads, and existing water points to adequately investigate the groundwater potential of the shallow coastal sediments. No elevation surveys could be conducted along the resistivity profiles. Therefore, the inverted profiles were not corrected for elevation differences. While elevation differences along each profile were small, up to 10 ft (3 m), it is expected that the shallow resistivity variations were somewhat affected by the assumption of a flat surface.

Illustrated in Table 2 are the different geological materials that may be encountered in Peleliu, Angaur and Kayangel, and the corresponding resistivity range that is likely to be measured.

Table 2. Typical resistivity ranges for different sediment types**.**

Rock and sediment type	Resistivity (Ohm.m)
Dry limestone	> 3000
Dry coral sediments	500–3000
Coral sediments saturated with freshwater	30–300
Limestone saturated with freshwater	50–400
Hard coral saturated with seawater	5–15
Coral sand saturated with seawater	2–10

Sources: Dale et al. 1986; Loke 2000b; Greggio et al. 2018; Islami 2019

3.2 Model inversion methodology

Model inversions were performed using RES2DINV software (Loke 2000a). The program automatically creates a two-dimensional model by dividing the subsurface into rectangular blocks, and subsequently calculates the apparent resistivity of these blocks using either a finite difference or finite element method and compares these to measured data. The resistivity of the model blocks is adjusted iteratively until the calculated apparent resistivity values of the model agree with the actual measurements. A uniform resistivity color bar was used to allow comparisons between the inverted profiles. The two-dimensional models are shown in Annex A.

Prior to running the model inversions, the raw exported database was first treated to remove any "negative resistivity" readings that might affect the accuracy and reliability of the inversion. These erroneous readings indicate the electrode's inability to read a realistic difference in electrode potential and contribute substantially to the total absolute error. This is usually related to poor electrode contact, misplaced electrodes, the presence of human-made objects in the ground (e.g. cables or pipes) and above the ground (e.g. metal fences), and noise from electrical fences or power lines. Other reasons are related to incorrect transmitter and/or receiver settings with respect to field conditions, and finally to highly variable geological conditions in two or three dimensions, forcing the electrical current to travel in unexpected ways and cause negative readings (Fredrik Nyqvist, Product Manager, Guideline Geo Group MALÅ/ABEM, 2017, pers. comm.). The presence of seawater with very low resistivity along the coastal survey lines is another factor that can contribute to "noisy" datasets. After removing the negative values, a preliminary inversion was carried out using all the remaining data points. Then, using the "RMS error statistics" option that displays the distribution of the percentage difference between the logarithms of the measured and calculated apparent resistivity values, bad data points having an error of 100% and above were further removed. A final inversion was then carried out using the new filtered dataset, allowing for a much lower absolute error compared to the first run, providing improved confidence in the datasets.

3.3 Survey of water points

A number of water points were surveyed to characterize the water supply system, including past and potential future supply sources. Other types of water points that could help characterize the islands' hydrology were also surveyed, including a large sinkhole in Peleliu (locally known as the Ngermelt swimming hole), swamp taro pits in Kayangel, a pit lake in Angaur and standing water along the resistivity survey lines.

GPS locations and key information from the water points were collected to create a well database for planning and monitoring purposes. The information captured included well construction and condition, groundwater levels and groundwater-specific electrical conductivity (EC). Groundwater levels, temperature and EC were monitored through the entire study period by installing automatic loggers (In-Situ Aqua TROLL) in the wells used for water supply: two gallery wells (1 and 2) in Peleliu, two (vertical) wells (A and B) in Angaur and the gallery well in Kayangel. The loggers were suspended on stainless steel wire at a depth that ensured they were submerged below the water table at all times. A barometric logger was also installed to compensate for barometric influences. The loggers were set up to record data every two hours. Manual water level and EC readings were taken at the beginning and end of the monitoring period in order to validate the readings recorded by the loggers.

Figure 16. Shallow well in Kayangel.

On small islands, groundwater levels and salinities are affected by tides. These tidal effects decay inland exponentially and diminish over a certain distance, depending on the amplitude of a given tide and on the aquifer's properties (hydraulic conductivity and effective porosity) (Li et al. 1999). The tidal effect at a specific location also decays upward as the distance to the transition zone increases – transition zone can be briefly defined as the mixing zone between fresh and saline groundwater and is characterized by a rapid increase in salinity with increasing depths. Tidal effects can thus cause some fluctuations in groundwater salinity, particularly at distances close to the freshwater–saltwater interface. During the water-point survey, groundwater levels and EC were recorded at different moments in time and, therefore, were partly influenced by the tides at different degrees. The tidal component of the groundwater level fluctuation was filtered out using the "UTide" Matlab functions (Codiga 2023). The reconstructed astronomical tide with the constituents determined by UTide is subtracted from the raw groundwater level as measured by the loggers (as height above sensor) and the resulting residuals represent groundwater level variations due to recharge and pumping. The results were averaged to 24 hours to clean the remaining "tidal noise" related to small error in the raw and reconstructed data sets (instrument and tidal prediction error).

Eight unfiltered and unacidified samples were collected for chemical analysis either from an existing tap, or using a bucket when no water outlet was available. The bucket and sampling bottles were rinsed three times with sampled water before the samples were collected. The samples were prepared and analyzed at Activation Laboratories (Ontario, Canada) for major, minor and trace elements by ICP-MS and ion chromatography. The lab is ISO 17025 accredited and certified to ISO 9001: 2008. Analytical blanks and potential instrumental drifts were carefully monitored, and instrument standardization and reproducibility were performed with certified standard reference materials from the National Institute of Standards and Technology (NIST 1643 and SLRS-5 for ICP). QA/QC results within an error of less than 2% indicated that the analytical instruments were operating within pre-defined specifications.

Peleliu

The loggers were suspended roughly 4 in (10 cm) above the bottom of the gallery wells and opposite of the gallery arm inlet pipes to ensure aquifer-representative groundwater quality. Four water samples were obtained in total, one from the main gallery well (sample 2), one from the desalination plant (sample 3) and two from the large sinkholes that were utilized as water supply sources in the past (samples 1 and 4). The objective of sampling these two sinkholes was to better understand water quality concerns and assess whether these sources could be reconsidered as viable water supply sources in the future, and the type of treatment that would be required.

Table 3. Summary of the 10 surveyed water points in Peleliu, including EC at the top and bottom, depth to water table (DWT) and total depth.

Site	Site	Date	Sample ID	EC top (µS/cm)	EC bottom (µS/cm)	DWT (ft)	Total depth (ft)
1	Main well (pumps water from galleries 1 and 2)	28 May 2022	2 – tap	1111	1132	10.2 (3.1 m)	14.4 (4.4 m)
2	Gallery well 1 (connected to vents 1, 2 a nd3)	28 May 2022	n/a	1184	1179	10.2 (3.1 m)	12.5 (3.8 m)
3	Gallery well 2 (connected to vents 4, 5 and 6)	28 May 2022	n/a	894	894	10.2 (3.1 m)	12.1 (3.7 m)
4	Vent 1 (part of gallery 1)	28 May 2022	n/a	421	n/a	10.0 (3.05 m)	few inches
5	Vent 4 (part of gallery 2)	28 May 2022	n/a	396	938	10.8 (3.3 m)	11.5 (3.5 m)
6	Vent 5 (part of gallery 2)	28 May 2022	n/a	n/a	542	n/a	few inches
7	Reserve osmosis plant	28 May 2022	3 – tap	85	n/a	n/a	n/a
8	Sinkhole 1 (recently decommissioned well)	28 May 2022	4 – bucket	609	697	n/a	~ 6.6 (2 m) of water column
9	Sinkhole 2 (old water source)	28 May 2022	1 – bucket	311	593	8.2 (2.5 m)	18.1 (5.52 m)
10	Sinkhole 3 (Ngermelt swimming hole)	29 May 2022	n/a	16,038	25,472	9.7 (2.95 m)	n/a

n/a denotes "not available"

Angaur

The loggers were suspended on stainless steel wire at a depth that ensured they were submerged below the water table at all times, roughly 2 in (5 cm) above the bottom of the two production wells (well A and B). Three water samples were collected in total, one from well B (only operational well at the time of our visit), one from the main pit lake to confirm its high salinity, and one from the Koska well due to its potential use as an emergency water supply source.

Table 4. Summary of the five surveyed water points in Angaur, including EC at the top and bottom, depth to water table (DWT) and total depth.

Site	Date	Sample ID	EC (µS/cm)	DWT (ft)	Total depth (ft)
Well A (former W1)	1 June 2022	n/a	471	21.0 (6.37 m)	23.4 (7.12 m)
Well B (former W2)	1 June 2022	5 - tap	664	19.8 (6.02 m)	22.4 (6.82 m)
Koska well (former W6)	9 June 2022	7 - bucket	495	14.0 (4.27 m)	n/a
Standing water along ANG09 survey line	8 June 2022	n/a	7170	few in	few in
Large pit lake (former lake 7)	9 June 2022	6 - bucket	28500	n/a	n/a

n/a denotes "not available"

Figure 17. Saltwater pit lake in Angaur.

Kayangel

In total, 16 water points were surveyed to assess groundwater quality and to characterize taro patch salinity, shallow wells and traditional bathing pools (Diong er a Olekang, Figs. 18 and 19). Information captured included well construction and condition, groundwater levels and groundwater specific EC. A logger was installed inside the gallery well to allow for long-term monitoring. The logger was suspended on a stainless steel wire at a depth that ensured it was submerged below the water table at all times, roughly 2 in (5 cm) above the bottom of the gallery well. One sample was collected for chemical analysis from the gallery well.

Table 5. Summary of the 16 surveyed water points in Kayangel, including EC at the top and bottom, depth to water table (DWT) and total depth.

Site	Site	Date	Sample ID	EC top (µS/cm)	EC bottom (µS/cm)	DWT (ft)	Total depth (ft)
1	Gallery well	13 June 2022	8 - bucket	600	n/a	3.3 (1 m)	4.7 (1.44 m)
2	Well 1	16 June 2022		832	935	0.9 (0.3 m)	4.8 (1.45 m)
3	Well 2	16 June 2022		117	138	3.9 (1.2 m)	5.2 (1.6 m)
4	Well 3	16 June 2022		783	783	1.1 (0.35 m)	3.6 (1.1 m)
5	Well 4	16 June 2022		496	500	0.9 (0.3 m)	4.6 (1.4 m)
6	Well 5	16 June 2022		700	789	1.8 (0.55 m)	6.6 (2 m)
7	Well 6	16 June 2022		976	1560	1.5 (0.45 m)	5.9 (1.8 m)
8	Traditional pool 1	16 June 2022		1069	n/a	few in	n/a
9	Traditional pool 2	16 June 2022		1274	n/a	few in	n/a
10	Traditional pool 3	16 June 2022		327	n/a	2.0 (0.6 m)	n/a
11	Taro patch 1	16 June 2022		1133	n/a	few in	n/a
12	Taro patch 2	16 June 2022		692	n/a	few in	n/a
13	Taro patch 3	16 June 2022		1100	n/a	few in	n/a
14	Taro patch 4	16 June 2022		525	n/a	few in	n/a
15	Taro patch 5	16 June 2022		560	n/a	few in	n/a
16	Taro patch 6	16 June 2022		1200	n/a	3.3 (1 m)	n/a

Figure 18. Monitoring of a traditional bathing pool in Kayangel.

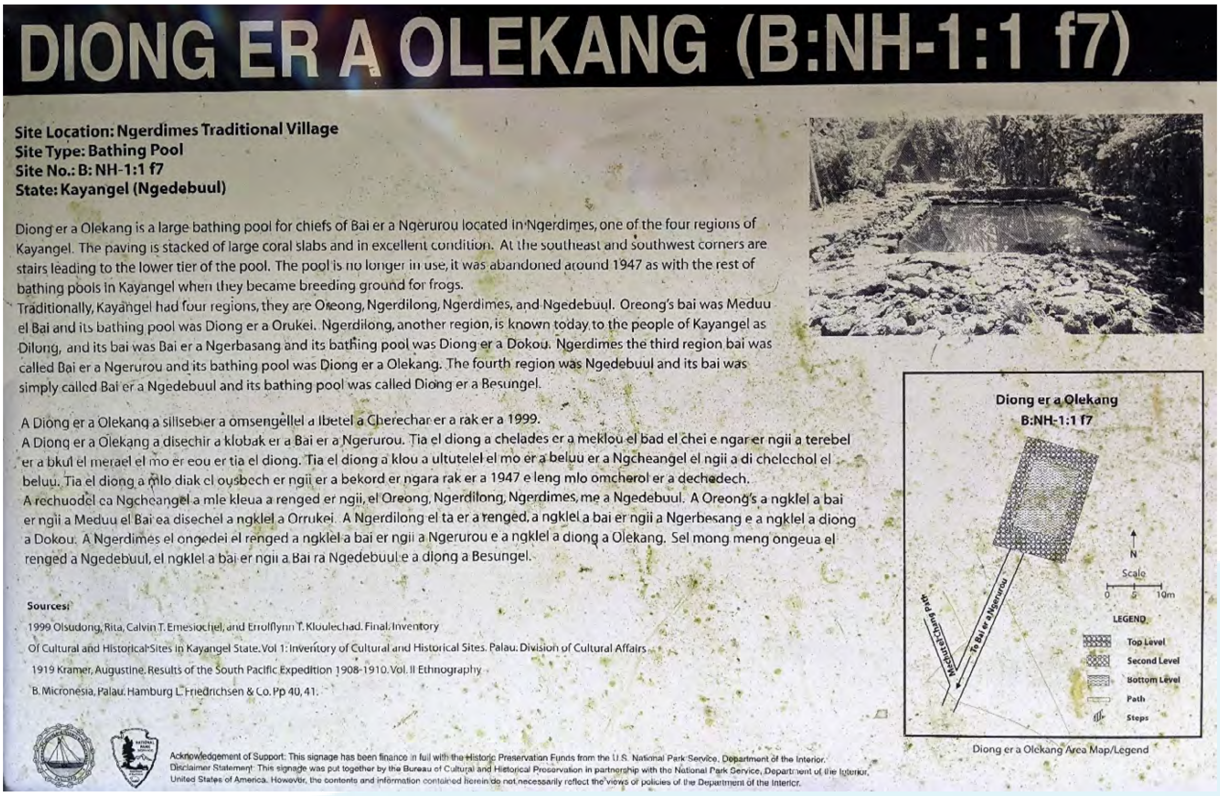


Figure 19. Signage explaining the cultural significance of traditional bathing pools in Kayangel.

4. Results and discussion

4.1 Geophysical results and interpretation

Peleliu

The selection of ERT survey lines (Table 6) in Peleliu was informed by the geological map of Peleliu, the location of groundwater development infrastructure and of monitoring points, and the presence of roads to allow access (Figure 20). To improve the reliability of the survey, an effort was made to maintain the survey lines as straight as possible through the selection of suitable road sections. A damaged survey cable caused some erroneous, high resistivity measurements along survey lines 8 and 9. These erroneous results were not considered during the interpretation.

Table 6. Summary of survey lines in Peleliu.

Survey line	Distance (ft)	Electrode spacing (ft)	Starting station	Final station
Pel01	2625 (800 m)	16.4 (5 m)	7°00′08.4″N 134°14′04.9″E	7°00′22.9″N 134°13′52.3″E
Pel02	2887 (880 m)	16.4 (5 m)	6°59′48.0″N 134°13′45.6″E	7°00′06.2″N 134°13′32.9″E
Pel03	1640 (500 m)	16.4 (5 m)	7°00′22.7″N 134°14′30.2″E	7°00′27.0″N 134°14′38.7″E
Pel04	1969 (600 m)	16.4 (5 m)	7°00′02.4″N 134°14′55.9″E	6°59′54.7″N 134°15′06.0″E
Pel05	3281 (1000 m)	16.4 (5 m)	7°00′09.0″N 134°14′15.8″E	6°59′51.0″N 134°13′56.8″E
Pel06	984 (300 m)	8.2 (2.5 m)	7°00′06.2″N 134°14′42.5″E	7°00′05.5″N 134°14′48.7″E
Pel07	3937 (1200 m)	16.4 (5 m)	7°01′52.5″N 134°15′11.6″E	7°01′27.1″N 134°14′51.5″E
Pel08	1969 (600 m)	16.4 (5 m)	7°00′15.1″N 134°14′18.8″E	7°00′22.9″N 134°14′08.3″E
Pel09	919 (280 m)	11.5 (3.5 m)	7°01′45.0″N 134°15′01.7″E	7°01′47.6″N 134°14′57.9″E

Survey line 1 was conducted along the existing well field, also capturing the area around the nearby freshwater sinkhole (sinkhole 1) with the recently decommissioned production well. The intention was to assess the extent of the underlying freshwater body around the wellfield while simultaneously benefiting from groundwater salinity measurements allowing for calibration of the modelled resistivity profiles. Line 6 was conducted along sinkhole 2, which was developed in the past as a water supply source (Marson Aderiano, PPUC, 2022, pers. comm.). PPUC has indicated that it is considering redeveloping this old water source to complement the existing volume of groundwater currently developed from the main well field. All survey lines were conducted within the Peleliu Limestone formation except for lines 7 and 9, which were conducted along the Calcareous Sands formation to also investigate the groundwater potential within this particular geological formation.

Overall, the ERT lines conducted over the Peleliu Limestone formation, as suggested by the geological map, indicate the presence of very limited freshwater resources, with the thickness of the freshwater lens ranging between 10 ft and 40 ft (3 m and 12 m). According to groundwater salinity measurements obtained from the two freshwater sinkholes and the two galleries (Table 3), and typical resistivity ranges for limestone saturated with freshwater (Table 2), we conclude that the freshwater lens along the profiles is demarcated approximately between 40 Ohm.m and 200 Ohm.m.

The thicker parts of the lens seem to be patchy, scattered around the formation, limited in areal extent and largely influenced by karstic geological features. Fresh groundwater "pockets" of limited extent were identified around the two freshwater sinkholes (lines 1 and 6), around the northeast side of the airstrip (line 5), and along part of line 8. It should be noted that the lateral extent of the freshwater pockets (away from the survey lines) was arbitrarily sketched as it could not always be confirmed through perpendicular survey lines. The observation that during droughts, the galleries can run dry with pumping (Marson Aderiano, PPUC, 2022, pers. comm.) indicates that the water table can drop below the level where the gallery arms were installed. This may be due to a combination of natural decline due to head-induced freshwater exfiltration around the coast and localized pumping-induced drawdown. It also suggests that aquifer conditions and the groundwater system are heavily controlled by the presence of karstic conduits, and preferential hydraulic connectivity. It appears that groundwater abstraction might not necessarily be controlled by water quality (gradual increase in salinity) as water quantity (recharge) might be an equally important controlling factor. Long-term monitoring of groundwater salinity and pumping rates through the dry season would shed more light on this issue.

As opposed to the patchy nature of the freshwater lens present within the limestone, a more solid freshwater lens appears to have developed within the beach deposits which extend between the two roads (main road and back road) leading to the village. It is probable that the hilly Peleliu Limestone formation present along the entire eastern border of the beach deposits, concentrates recharge into the sands, laterally feeding the groundwater lens – a process normally known as mountain-block recharge. The lens thickness appears to be up to 40 ft (12 m) and its continuous nature and vicinity to the village and existing pipeline could make for a more reliable source if developed through a suitable infiltration gallery system. Such development should, however, consider the presence of a graveyard and dump site, which could act as contamination sources to the underlying lens. The presence of a freshwater lens within this geological formation has also historically been demonstrated by the presence of multiple wells with a depth range of 5.2–12.1 ft (1.6–3.7 m) (Van der Brug 1984). Some of these wells were indicated as tapping "swamp water", possibly suggesting the presence of lower-quality groundwater. Even though the sketched lens area was limited within the length of the resistivity profile (line 7), the actual extent of the lens is potentially covering the entire area occupied by the beach deposits (Figure 20).

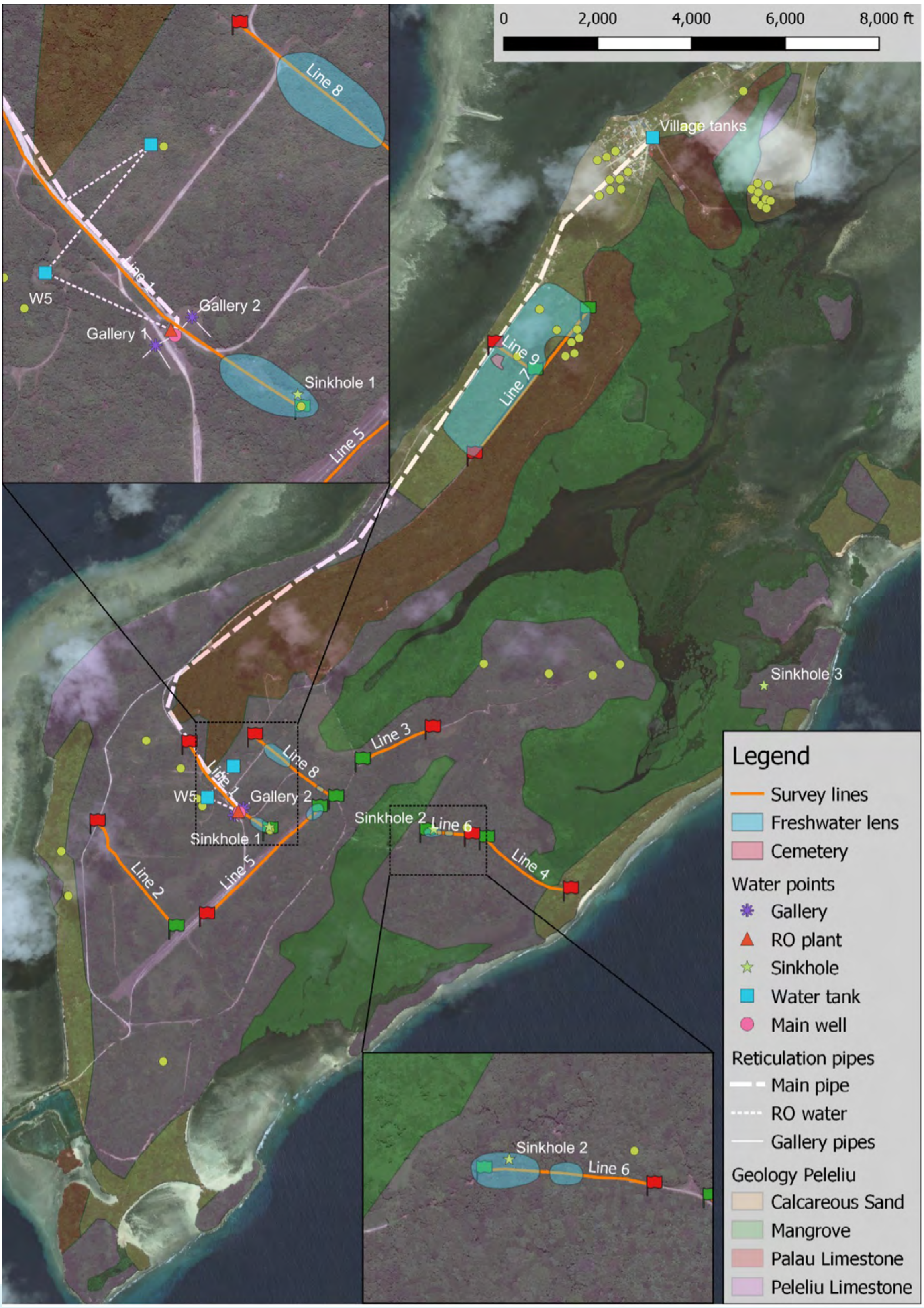


Figure 20. Geological map of Peleliu adapted from Van der Brug (1984). Included are the current water supply system, the water points measured and sampled in this study, and the old wells 5 and 6, the ERT survey lines (green flag for its beginning and red flag for the end), and the potential extension of the freshwater lenses.

Figure 21. Peleliu's groundwater abstraction and treatment system for public supply. Vent locations 2, 3 and 6 are approximate.

Angaur

The selection of ERT survey lines in Angaur (Table 7) was informed by the geological map of Angaur (Figure 22), the location of groundwater development infrastructure and of monitoring points, and the presence of roads and buried electrical cables. Early in the survey, it was observed that the resistivity measurements were heavily affected by the presence of buried electrical cables and potentially water pipes. This impeded surveys along certain road sections, along the existing well field, and around the village area.

Table 7. Summary of survey lines in Angaur.

Survey line	Distance (ft)	Electrode spacing (ft)	Starting station	Final station
Ang02	1296	16.4 (5 m)	6°54’47.9”N 134°08’40.2”E	6°54’43.3”N 134°08’44.8”E
Ang03	836	16.4 (5 m)	6°53’37.2”N 134°07’37.8”E	6°53’34.7”N 134°07’39.9”E
Ang04	787	16.4 (5 m)	6°53’25.8”N 134°07’38.6”E	6°53’23.1”N 134°07’39.3”E
Ang05	2625	16.4 (5 m)	6°55’04.8”N 134°08’10.9”E	6°54’47.0”N 134°08’02.6”E
Ang06	2280	16.4 (5 m)	6°54’20.3”N 134°08’23.6”E	6°54’25.8”N 134°08’08.3”E
Ang07	2625	16.4 (5 m)	6°54’07.5”N 134°08’18.2”E	6°54’22.2”N 134°08’31.0”E
Ang08	1969	16.4 (5 m)	6°53’37.1”N 134°07’44.2”E	6°53’27.1”N 134°07’35.8”E
Ang09	2280	16.4 (5 m)	6°54’30.9”N 134°08’04.1”E	6°54’42.2”N 134°08’15.4”E
Ang10	869	16.4 (5 m)	6°54’49.9”N 134°08’18.9”E	6°54’51.7”N 134°08’21.5”E
Ang11	640	16.4 (5 m)	6°53’27.7”N 134°07’30.5”E	6°53’27.7”N 134°07’30.5”E

A number of survey lines were conducted around the more recent limestone formation occupying the majority of the island. No survey lines could be conducted around the older Palau Limestone formation in the northwest due to limited accessibility. A focused survey was performed around the beach deposits in the southwestern part of the island, due to the geological conditions offering a high potential for the development of a freshwater lens.

Overall, the ERT lines conducted around the coralline rubble and limestone formation, as suggested by the geological map, indicate the presence of limited freshwater resources with the thickness of the freshwater lens ranging between 10 ft and 40 ft. Discrete freshwater “pockets” appear to be present along the first part of survey line 6 and along survey line 7. A freshwater body of unknown extent is also present around the existing well field, but the presence of buried cables did not allow for surveys to be undertaken. As in Peleliu, it is expected that the freshwater lens present within the limestone does not behave like a conventional lens within a sandy aquifer, but rather is scattered around the formation, limited in areal extent, and largely influenced by karstic geological features and associated preferential hydraulic connectivities. This may have consequences in the operation of the well field, whereby groundwater abstraction might not necessarily be controlled by water quality (gradual increase in salinity) but water quantity (recharge) might be an equally important limiting factor. No fresh groundwater was identified in the northern part of the island along survey lines 5, 9 and 10, while the salinity of the large pit lake present within the older limestone formation was measured at ~50% seawater. There is permanent standing water by the side of the lower parts of line 9, from which we measured EC at 7170 µS/cm (Table 4). This indicates that the water table at this location is very shallow and salty.

An important, untapped fresh groundwater resource was identified within the sandy beach deposits present in the SW part of the island. Survey line 8 suggests the presence of a continuous 40-60 ft thick freshwater lens, also extending laterally towards the coast as demonstrated by survey lines 3, 4, and 11. The total fresh groundwater volume was roughly estimated at 50 million ft³ (375 million gallons), assuming a porosity of 30%, a substantial renewable volume capable of covering the entire water demand of Angaur. In fact, according to information we collected during the community meeting, the old Angaur village was located in this part of the island and the presence of multiple old wells, now lost in the dense vegetation, confirm the presence of this important resource. The approximate location of an old Japanese well was indicated by locals, and was supposedly used during the Japanese occupation as a water supply. At the time of our visit, the well could not be located due to dense vegetation in the area.

Figure 22. Geological map of Angaur adapted from Van der Brug (1984) depicting the current water supply system, the water points measured or sampled in this study, lakes, historical wells, ERT survey lines and the potential extension of freshwater bodies. The approximate location of the "old Japanese well" was indicated by locals.

These findings are in agreement with those of Arnow (1961), who stated that groundwater chloride concentration in province A was systematically above 1000 ppm, while it was below this level for the rest of the island, and below 100 ppm in the southern and central parts of the island, which did not change significantly during the 5.5-year monitoring period December 1949–May 1955. Further, several indications can be found in Arnow (1961) that support the conclusions stated above.

- Well 4 (beach deposits), well 10 (province A limestone), and well 12 (province B limestone) (Figure 33) all show water-level fluctuations that are strongly influenced by rainfall, indicating that Angaur's aquifers do not behave like typical freshwater lenses, but are strongly controlled by recharge and not just by seawater tidal fluctuations (Figure 33). Despite its proximity to the sea, well 4 shows higher water levels, potentially indicating that the beach deposits allow for more effective storage of fresh water and that groundwater does not flow laterally as much as in the limestone area (due to lower horizontal permeability of beach deposits).
- Despite its proximity to the sea, well 4 shows considerably lower Cl concentrations (~25–100 mg/L) than well 1 (province B limestone) (~50–250 mg/L) and especially lower than wells 10, 11, 13 and 14 (province A limestone) (~500–3500 mg/L) for the period 1950–1954 (Figures 34, 35 and 37). Although the combined abstraction from wells 1 and 2 averaged more than 3 million gallons per month (at times exceeding 6 million gallons per month), at no time during the period of record did the moving average exceed 250 ppm of Cl, which is considered to be the threshold for detectable taste in water (which is not a health-based guideline). In contrast, the Cl content in well 13 increased substantially with pumping. This confirms the suitability of the currently used wells by PPUC (wells 1 and 2) in producing fresh groundwater. The low Cl concentrations recorded in well 4, although not pumped, reinforces the indications of fresh groundwater present in the beach deposits. Well 11 also shows a dramatic reduction in Cl, from ~3500 mg/L to 500 mg/L during this period, following the backfilling of nearby lake 11, indicating strong groundwater lateral movement in the limestone aquifer.
- The vertical variation of Cl concentration in test hole 12 (TH 12) in the beach sands, TH 13 (province B limestone) and TH B-7 indicate different transition zone depths (Figure 36). In TH B-7, the transition zone was at a depth of 7–8 ft (2.1–2.4 m) and in TH 13 at 11–12 ft (3.4–3.6 m) below sea level, while fresh groundwater in TH 12 was found up to at least 31 ft (9.4 m) below sea level, clearly indicating the considerable thickness of the freshwater lens present in the beach deposits compared to the limestone formations.

Kayangel

The selection of ERT survey lines in Kayangel (Table 8) was informed by the location of groundwater development infrastructure and monitoring points (shallow wells and traditional pools), and the presence of roads and buried electrical cables. Two perpendicular survey lines were conducted around the groundwater catchment area where the gallery system is installed. The intention was to assess the extent of the underlying freshwater body around the gallery while simultaneously benefiting from groundwater salinity measurements, thus allowing for the calibration of the modelled resistivity profiles. Three more survey lines were conducted along existing roads to investigate the southward extension of the freshwater lens.

Overall, the freshwater lens in Kayangel is of very limited thickness, with a slightly thicker freshwater body of up to 10 ft (3 m) in the northern and wider part of the island, where the existing gallery system is installed (Figure 23). The thickness of the freshwater lens appears to slightly increase just north of the groundwater catchment area.

Figure 23. Aerial photo of Kayangel, including the location of water supply infrastructure, water points measured or sampled, ERT survey lines, and the potential extent of the freshwater lens. Numbers in white indicate measured EC (μS/cm) in the respective water points.

Table 8. Summary of survey lines in Kayangel.

Survey line	Distance (ft)	Electrode spacing (ft)	Starting station	Final station
Kay01	1936 (590 m)	16.4 (5 m)	8°05′22.2″N 134°43′08.5″E	8°05′21.0″N 134°42′55.7″E
Kay02	1312 (400 m)	8.2 (2.5 m)	8°05′20.6″N 134°43′00.9″E	8°05′30.0″N 134°42′59.1″E
Kay03	648 (198 m)	8.2 (2.5 m)	8°04′35.3″N 134°43′10.9″E	8°04′36.8″N 134°43′07.4″E
Kay04	780 (234 m)	8.2 (2.5 m)	8°04′53.9″N 134°43′09.1″E	8°04′55.5″N 134°43′04.9″E
Kay05	820 (250 m)	8.2 (2.5 m)	8°04′30.3″N 134°43′06.7″E	8°04′31.9″N 134°43′02.1″E

4.2 Groundwater monitoring data

Peleliu

Table 3 and Figure 20 summarize and provide the locations of the 10 surveyed water points, including the sampling points. At the time of sampling, the main gallery well measured EC values of 1111–1132 µS/cm. This main well collects water from both gallery wells 1 and 2 (Figure 21), which had significant EC differences at the time of sampling (with groundwater in gallery well 2 demonstrating a lower EC by ~25%).

The loggers installed in gallery wells 1 and 2 demonstrate EC fluctuations between 807 µS/cm and 1632 µS/cm, and 420 µS/cm and 1571 µS/cm, respectively (Figures 24 and 25 and Table 9), influenced by tides, pumping, groundwater discharge, and climatic forces (rainfall and evapotranspiration). Table 9 shows that 95% of the time, gallery 1 pumps water of EC > 1178 µS/cm, while gallery 2 pumps water of EC > 755 µS/cm, corresponding to a 36% lower EC for gallery 2. Surprisingly, even though gallery 2 demonstrates a lower average EC, it also demonstrates a higher range in EC variations.

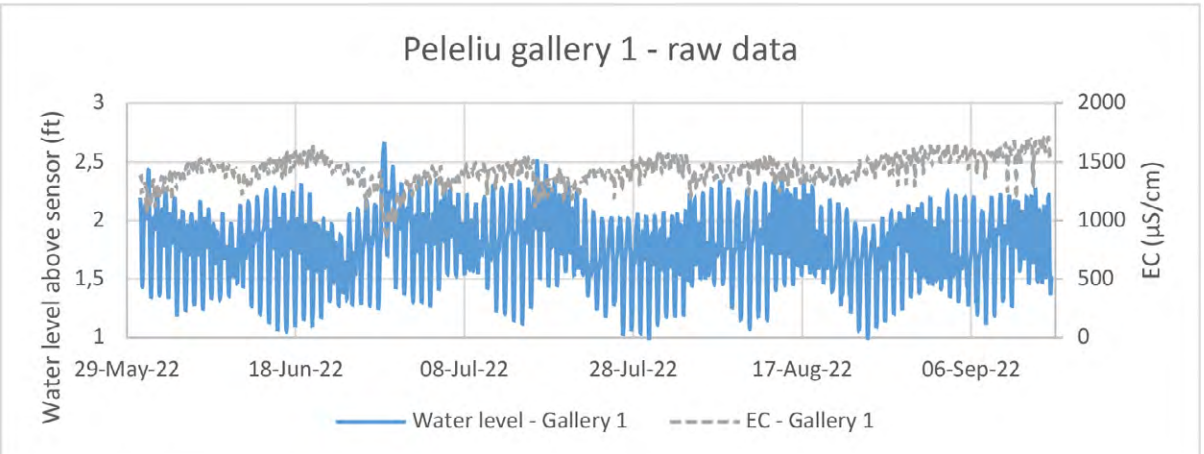


Figure 24. Groundwater level and EC fluctuation in Peleliu gallery 1 (raw data).

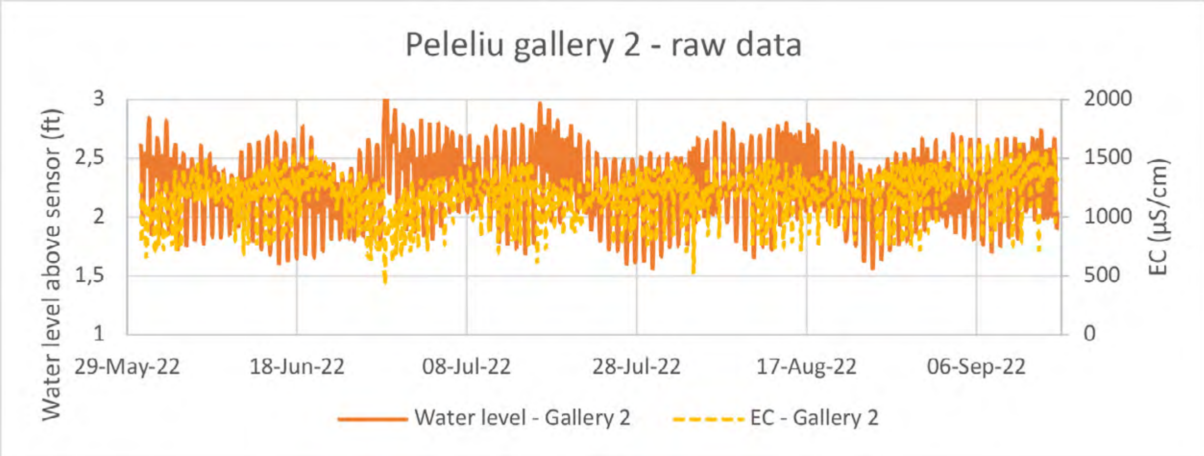


Figure 25. Groundwater level and EC fluctuation in Peleliu gallery 2 (raw data).

The tide-corrected, day-averaged water level fluctuations in the two gallery wells reveal a very similar behavior as expected due to their hydraulic connection (Figure 26). Peaks in water levels reflect recharge events, whereas troughs reflect dry conditions and pumping. Peaks in water levels are accompanied by EC decreases as expected during recharge events and freshening of the aquifer, whereas decreases in water levels are accompanied by increasing groundwater salinity. A maximum range of 0.7 ft (0.21 m) of water level fluctuation is observed for the two wells. The rainfall events recorded by the manual rain gauge do not correlate well with water levels and EC, probably due to the distance and possible errors associated with the manual monitoring procedure. The day-averaged EC fluctuation clearly indicates that gallery 2 consistently abstracts fresher groundwater than gallery 1 by approximately 200 µS/cm. The difference in average EC values is possibly related to aquifer heterogeneity along the galleries and different contributions of salt concentrations contributing to EC. Groundwater abstracted from the two galleries is, however, merged into the main gallery well and then supplied. Isolating gallery 1 and abstracting water exclusively from gallery 2 could potentially increase the quality of supplied water in terms of salinity.

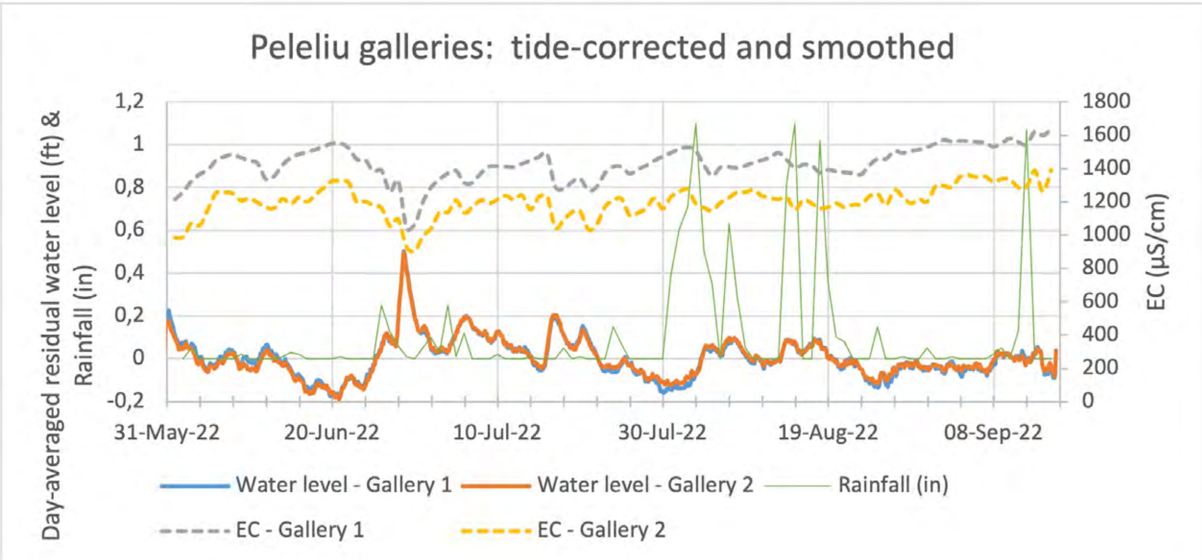


Figure 26. Tide-corrected, day-averaged groundwater level fluctuations and day-averaged EC fluctuations (including tidal effect) in Peleliu gallery wells 1 and 2. Rainfall observed manually by the Palau Weather Service near the Peleliu Elementary School is also plotted on the primary axis.

Table 9. Statistical summary of water levels and ECs in the gallery wells 1 (G1) and 2 (G2) from 30 May to 15 September 2022. Raw water level graphs provided in Annex C.

	EC G1 (µS/cm)	EC G2 (µS/cm)
Minimum	807	420
Percentile 0.1*	1231	876
Average	1365	1153
Maximum	1632	1571

* Salinity is above this value 90% of the time.

Groundwater salinity was also recorded in several gallery vents, allowing access to the groundwater contained within the gallery arms (Figure 21). As for gallery 1, it was only possible to locate one of the three vents (vent 1). The EC in vent 1 was quite low (421 µS/cm) compared to the EC measured in gallery well 1 (1180 µS/cm). This could potentially mean that gallery arms 2 and 3 contribute higher groundwater salinity to the gallery well. Another explanation could be that the groundwater in gallery arm 1 becomes more saline towards the gallery well due to a possible slight slope of the arm or due to geological heterogeneity. Although vents 2 and 3 could not be found, it would be important to locate them and measure groundwater salinity in gallery arms 2 and 3, and understand the groundwater salinity contribution of each gallery arm to gallery well 1 for management purposes.

As for gallery 2, it was only possible to locate two of the three vents (vent 4 and 5). The EC measured in vent 4 was between 396 µS/cm and 938 µS/cm, depending on measurement depth. The EC measured in vent 5 was 542 µS/cm whereas the EC measured in gallery well 2 was 894 µS/cm. Similar to gallery well 1, it would be useful to locate vent 6 to better understand the behavior of gallery well 2 and improve its management.

Angaur

Two automatic monitoring loggers were installed in well A and well B recording EC, temperature, and water level (height of water column above sensor) every two hours. Figures 27 and 28 present the raw monitoring data for a period of just over four months (1 June–5 October 2022). It should be noted that well A was not operating throughout this monitoring period since April 2022. While both wells demonstrate a very similar behavior in terms of tidal-driven water level fluctuation throughout the entire period (up to 2 ft, or 0.6 m, of daily fluctuation), only well B demonstrates a variation in salinity of up to 250 µS/cm daily. This suggests that the mixing of groundwater inside the well is the result of abstraction.

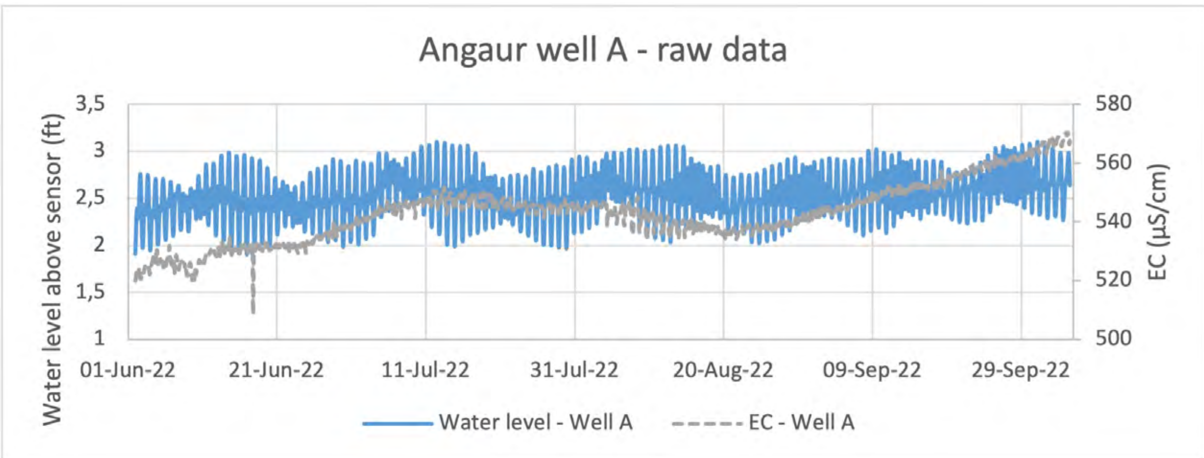


Figure 27. Groundwater level and EC fluctuation in Angaur well A (raw data).

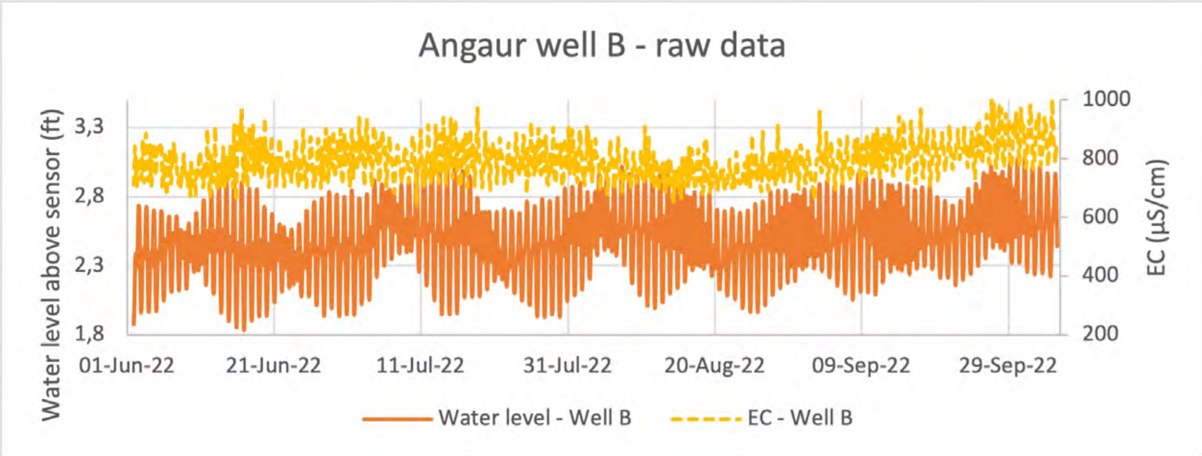


Figure 28. Groundwater level and EC fluctuation in Angaur well B (raw data).

Similar to Peleliu, the tide-corrected, day-averaged water level fluctuations in the two pumping wells show very similar behavior, as expected due to their close proximity to one another (Figure 29). Peaks in water levels reflect recharge events whereas troughs reflect dry conditions and pumping. A maximum range of 0.4 ft (0.12 m) of water level fluctuation is observed for the two wells. Despite well B being exclusively pumped, the average daily salinity did not exceed 900 µS/cm during the monitored period indicating the high potential of well B to provide good quality water (from a salinity perspective) over extended pumping periods. A mild EC incline is observed from 21 August onwards, suggesting that EC should continue being monitored to understand how well B behaves during the dry season (December–April), especially if it continues being pumped exclusively.

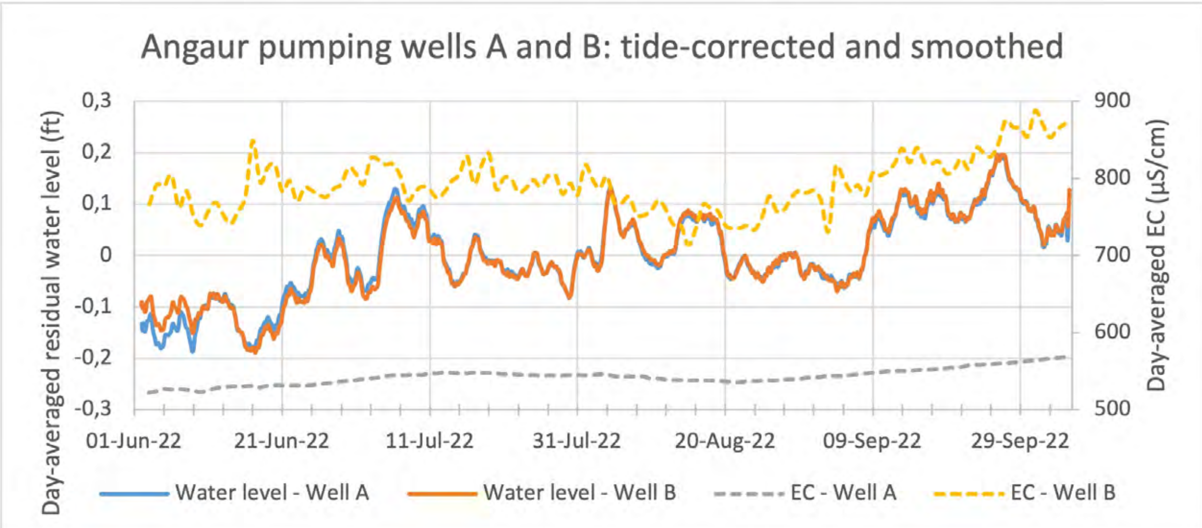


Figure 29. Tide-corrected, day-averaged groundwater level fluctuations and day-averaged EC fluctuations (including tidal effect) in Angaur pumping wells A and B.

Interestingly, Arnow (1961) showed that wells 13 (pumping well) and 14 (monitoring well) in province B limestone, despite being very close to each other, show very different Cl content fluctuation patterns during pumping from well 13 in 1951–1952. Well 13 shows strong and sharp fluctuations, from ~50 mg/L to 2500 mg/L, while well 14 shows more smooth fluctuations from ~50 mg/L to 500 mg/L. This is similar to the situation with well A and B described above.

Kayangel

A groundwater monitoring logger was installed in the gallery well to automatically record EC, temperature and water level (height of water column above sensor) every two hours. Figure 30 presents the monitored EC and groundwater level for a period of five months (13 June–9 November 2022). Unfortunately, no rainfall or pumping data were available to allow for a better understanding of the behavior of these two parameters. Nonetheless, the data still allow the inference of some processes that might be occurring.

As discussed in section 2.4, in a freshwater lens system the depth of the transition zone fluctuates with the tides. During high tide, the transition zone moves upward causing groundwater salinity in the deeper part of the lens to increase. The shallow depth of the transition zone in Kayangel (6–12 ft, or 1.8–3.6 m depth) causes the salinity in the gallery, and thus of the abstracted water, to heavily fluctuate with the tides. For example, on a single day, the EC can fluctuate between 700 µS/cm and 1900 µS/cm (Figure 30), with an average EC of 1600 µS/cm of the groundwater stored in the overhead tank and subsequently supplied to households. The water level inside the gallery well can fluctuate by up to 2 ft (0.6 m) due to the tides (Figure 30). Theoretically, if the pumping schedule could be automatically programmed to match the tides (e.g. through a water level gauge), the pump could only operate during low tide to potentially allow pumping fresh groundwater only for storage in the overhead tank and subsequent distribution to households. The feasibility of such an intervention would obviously require further research.

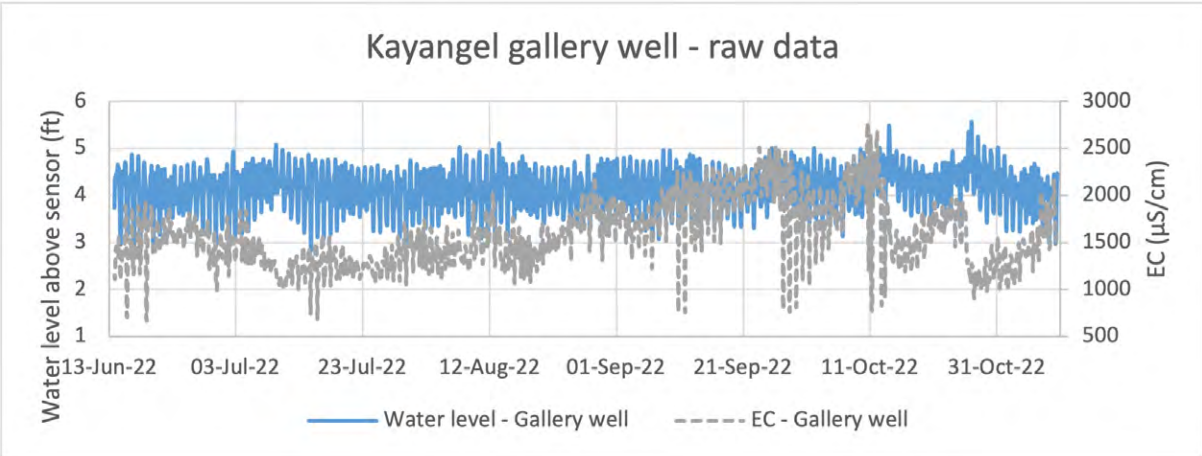


Figure 30. Groundwater level and EC fluctuation in Kayangel gallery well (raw data).

The tide-corrected, day-averaged water level fluctuation (Figure 31) reveals a maximum range of almost 1 ft (0.3 m). Peaks in water level represent recharge (rainfall) events, and are accompanied by EC declines, indicating a freshening of the groundwater from rainwater infiltration. The water level quickly drops within a few days as the freshwater lens reattains equilibrium through submarine groundwater discharge along the shore. In the absence of rain, the EC has a tendency to increase as the freshwater lens gradually shrinks, with the transition zone moving upwards. Pumping can accelerate this process. The data indicate that EC is < 1500 µS/cm 44% of the time, indicating some suitability of water quality for domestic supply.

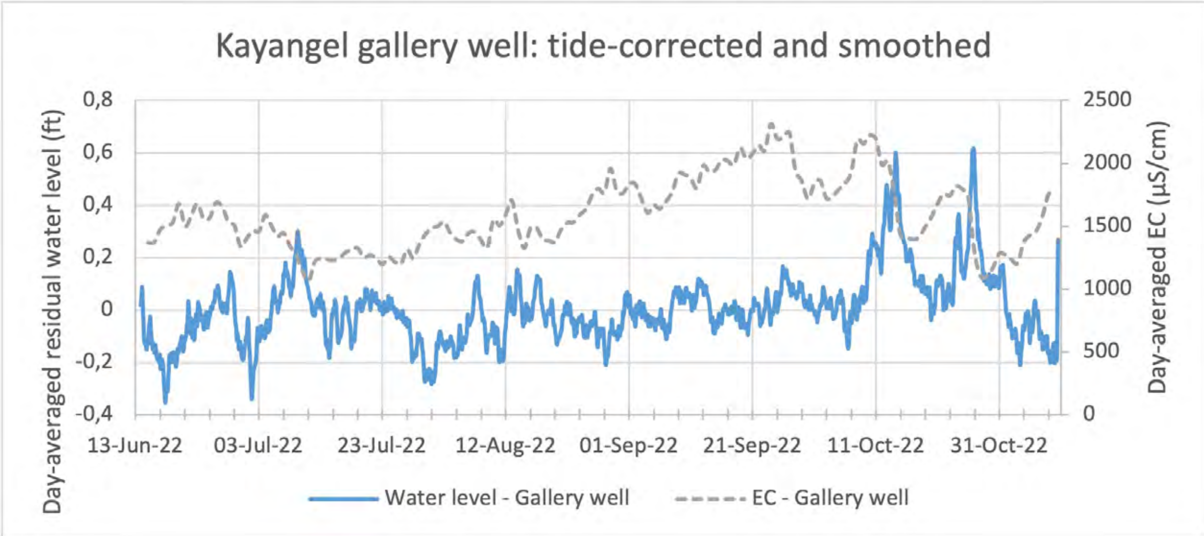


Figure 31. Tide-corrected, day-averaged groundwater level fluctuations and day-averaged EC fluctuations (including tidal effect) in Kayangel gallery well.

4.3 Hydrochemistry of groundwater

The complete results for the chemical analysis of collected water samples are in Annex C. The results do not suggest chemical contamination risks for human health (i.e. all values are below WHO 2022 guideline values). All concentrations and element ratios referred to here are expressed in mg/L, and the reference seawater composition is obtained from Goldberg et al. (1971). It would have been useful to have rainwater samples to characterize the water recharging the islands' aquifers. However, collecting representative rainwater samples requires constant monitoring over at least one year to account for seasonal variations, and wet and dry depositions. Such a monitoring system is not in place in Palau. In the absence of rainwater samples, it was assumed that rainwater has the composition of diluted seawater, a fair assumption due to the proximity to the sea, and the absence of known atmosphere-polluting activities. Figure 32 depicts a piper diagram where the sample results and typical seawater are plotted, including a freshwater-seawater conservative mixing line proposed by Appelo and Postma (2005). This helps with understanding the type of groundwater and the underlying geochemical processes.

Elemental ratios were used to better understand the geochemical processes influencing water chemical composition The chloride to bromine ratios (Cl:Br) were used to confirm the origin of the recharging water. This is based on the fact that these elements are conservative and there are no Cl- and/or Br-bearing rocks on the islands. The other ratios considered were chloride to sodium (Cl:Na), sodium to calcium (Na:Ca) and calcium to magnesium (Ca:Mg)

Water hardness is calculated as the sum of Ca and Mg and is expressed as mg/L (USGS 2018). General guidelines for the classification of water hardness are: 0–60 mg/L is soft; 61–120 mg/L is moderately hard; 121–180 mg/L is hard; and more than 180 mg/L is very hard. According to WHO (2022), water hardness is not a health concern, although it may affect the acceptability of drinking water. Very hard water causes scale to form in water pipes, plumbing fixtures and appliances, which is enhanced by heating. Scale build-up in hot water tanks and boilers increases heating costs and can lead to premature equipment failure. Scale deposited on clothing during washing will cause increased wear and tear of fabrics. Soap reacts with hard water to form a curd and can cause skin flaking and irritation. In addition, when washing or doing laundry with hard water, more soap or detergent is required.

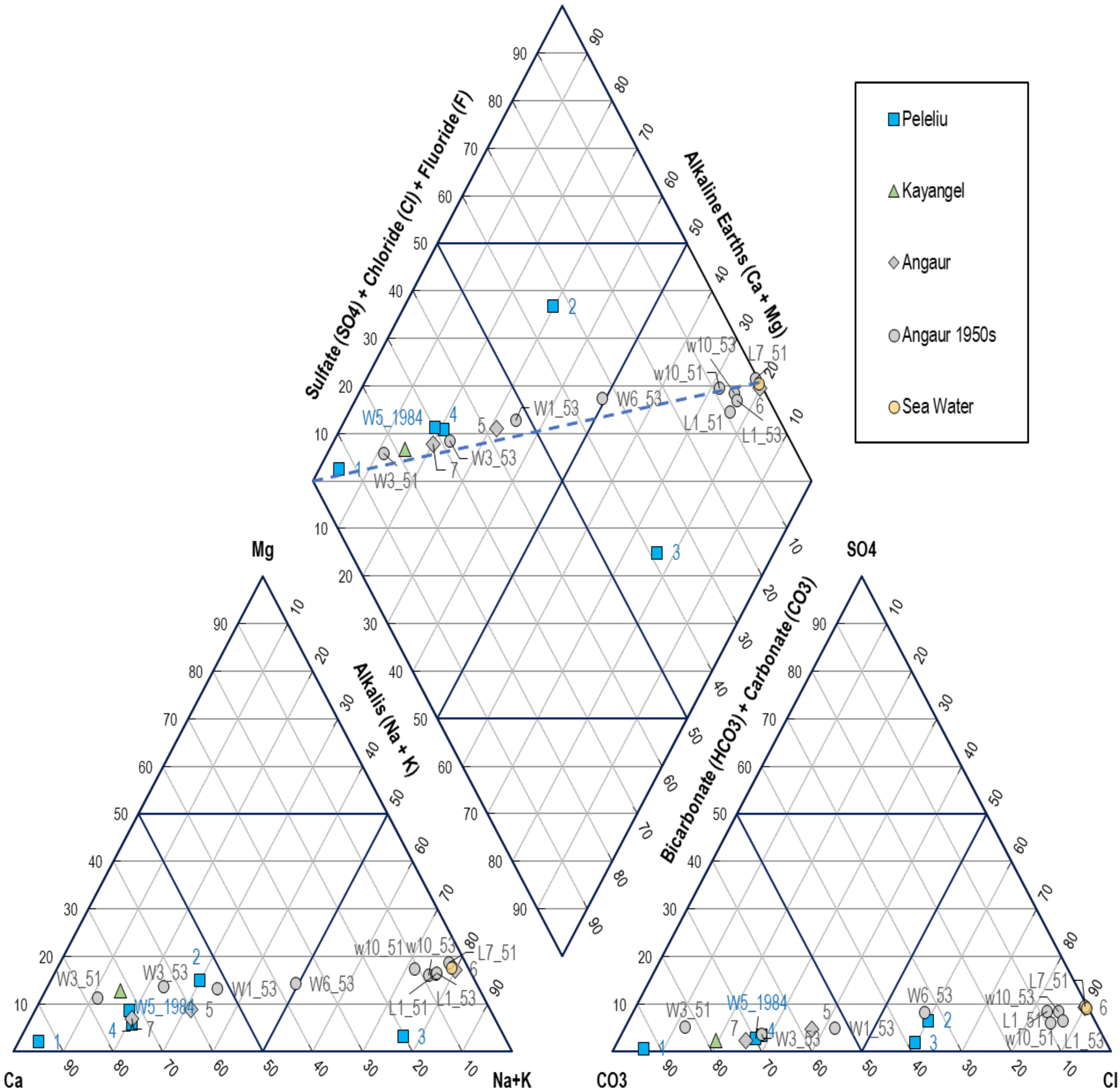


Figure 32. Piper diagram displaying the water type of sampled groundwater, typical seawater and the conservative freshwater–seawater mixing line (dashed blue) proposed by Appelo and Postma (2005).

Peleliu

Samples 1 (sinkhole 2), 4 (sinkhole 1) and W5 are of a calcium-magnesium (Ca-Mg) bicarbonate type, sample 2 (main well) is a mixed type while sample 3 (RO plant) does not represent aquifer conditions. Figure 32 shows that the groundwater samples plot very distantly from the typical seawater composition, demonstrating the ionic enrichment of recharged water through the water–rock interaction, which is discussed in more detail below. Samples 1, 4 and W5 plot on the freshwater–seawater conservative mixing line proposed by Appelo and Postma (2005), with sample 1 being the freshest. Sample 2 plots above that line, indicating a surplus of Ca compared to the conservative mixture, suggesting seawater intrusion with a cation exchange between sodium (Na) and Ca, resulting in the release of Ca. This is due to constant pumping from the gallery, resulting in saltwater intrusion.

Although sample W5_1984 is relatively fresher, it plots very close to sample 4, indicating similar geochemical processes.

Table 10. Summary of results from the chemical analyses of collected samples as part of this work, and from well 5 by Van der Brug (1984) in Peleliu. Concentrations are in mg/L.

Sampling point	EC top (µS/cm)	EC bottom (µS/cm)	Na	Mg	K	Ca	Cl	Br	NO_3 (as N)	SO_4	HCO_3
Sinkhole 1 (sample 4)	609	697	35.9	5.2	1.17	110	59.8	0.2	0.11	10	249
Sinkhole 2 (sample 1)	311	593	3.38	0.929	0.06	69.9	5.96	< 0.06	0.06	0.86	163
Main well (sample 2)	1111	1132	64.9	17.2	4.93	105	214	0.76	0.24	31.6	205
RO plant outflow (sample 3)	85	n/a	15.1	0.324	0.52	3.5	18	< 0.03	0.05	0.76	20
Well 5 (sample W5_1984)	498	n/a	22	5.4	0.8	75	43		0.21	6	190

n/a denotes "not available"

The Cl:Br ratios in the groundwater samples are all very close to the Cl:Br ratio of seawater of 288 (using concentrations expressed in mg/L) (Table 11), indicating that both dissolved salts in rainwater and groundwater are marine derived. This observation is consistent with the vicinity of the ocean, land-use activities (fertilizers and pesticides are not used), and the lithology of the basin (i.e. absence of Cl-bearing rocks). It rules out the contribution of Cl from sources other than both rainfall and dry deposition of marine aerosols. This fact fulfils one of the key assumptions for the application of the chloride mass balance (CMB) method to calculate recharge, which would require the knowledge of the average chemical composition of rainwater and, therefore, can be applied in the future should rainfall quality (at least Cl concentration) is appropriately monitored. Unfortunately, Van der Brug (1984) did not report Br concentrations and, as such, it was not possible to compare this ratio between modern and old water samples.

Table 11. Elemental ratios (using concentrations in mg/L) of samples collected as part of this work, from well 5 by Van der Brug (1984) and from typical seawater (Goldberg et al. 1971).

Sampling point	Cl:Br	Cl:Na	Na:Ca	Ca:Mg
Sinkhole 1	299	1.67	0.33	21.15
Sinkhole 2	Br below detection limit	1.76	0.05	75.24
Main well	282	3.30	0.62	6.10
RO plant outflow	Br below detection limit	1.19	4.31	10.80
Well 5	Br not measured	1.95	0.29	13.89
Typical seawater (proxy for rainwater)	288	1.8	26.28	0.32

The chloride to sodium ratio (Cl:Na) shown in Table 11 is similar to that of seawater (1.8 using concentrations expressed in mg/L) for both sinkhole 2 (1.76) and sinkhole 1 (1.67). The gallery sample resulted in a ratio twice as high (3.3). This difference indicates that the gallery sample represents fresh groundwater that is influenced by saltwater intrusion with cation exchange between Na and Ca/Mg (abundant in the local limestone rock matrix) being the dominant process.

The sodium to calcium ratio (Na:Ca) in the groundwater samples is much lower (0.05–0.60) than in seawater (26.3 using concentrations expressed in mg/L). This likely indicates that the groundwater is enriched with Ca as compared to recharge water (assumed rainwater from diluted seawater), which is logical considering the wells are located in limestone aquifers. A consistent ratio of 0.3 was found by Van der Brug (1984).

The calcium to magnesium ratio (Ca:Mg) in our groundwater samples show much higher values (75.2 for sinkhole 2, 6.1 for the gallery and 21.2 for sinkhole 1) as compared to seawater (0.32), indicating Ca dissolution in the limestone aquifer. A consistent ratio of 13.9 was found by Van der Brug (1984). The gallery shows a much higher Mg content than the other wells, potentially indicating saltwater intrusion as seawater is enriched in Mg.

According to USGS (2018) hardness classification, the groundwater samples from the island are all very hard, with hardness of 179–333 mg/L, which is consistent with the value reported by Van der Brug (1984) of 209 mg/L. Interestingly, the gallery shows the highest hardness of all samples. Not surprisingly, the RO results in a soft water with a hardness of 10 mg/L.

One of the main complaints about water quality in Peleliu is the bad smell and taste, especially when the water is heated. In fact, only three households use reticulated water for cooking and one for drinking, according to the latest census as stated above. The smell is likely due to the conversion (reduction) of sulphate (SO_4) to hydrogen sulfide (H_2S) due to anoxic conditions and the presence of organic matter, usually referred to as sulphur-reduction conditions. Groundwater in the gallery has a relatively high concentration of SO_4 (31.6 mg/L) due to saltwater intrusion, but without the odor. Groundwater seems to be in nitrate (NO_3)- reducing conditions because concentrations of NO_3 are below 0.25 mg/L for all sampled points. It is likely that SO_4 reduction occurs during the supply in the pipes, or when the water is heated for cooking or showers, or a combination of both. This is consistent with the fact that increasing the water temperature contributes to the increase in the reduction potential (Sokolova 2010). It would, therefore, be interesting to analyze samples of water after distribution, and after heating, to verify if these processes are indeed occurring.

Sinkhole 2 (sample 1) however shows a very low concentration of SO_4 of 0.9 mg/L, which together with the fact that is from a sinkhole located very close to the mangroves, indicates that it might be in Sulphur-reduction conditions. This is important because it shows that the closeness to the mangroves is an important factor for groundwater quality, and because if this sinkhole were to be chosen for supplementing the water supply system, it is likely that it would worsen the problem of bad smell and taste. This sinkhole has been used as the source of drinking water in the past, and it was abandoned for unknown reasons, and replaced by sinkhole 1 (which was recently also abandoned). Sinkhole 1 (sample 4) and well 5 show a SO_4 concentration of 10 mg/L and 6 mg/L, respectively, suggesting that they might be in, or approaching, sulphur-reduction conditions. This is compatible with the fact that sinkhole 1 was also recently abandoned as a source of water supply because of the bad smell and taste of the pumped water. Well 5 was also abandoned as a water source in the past, although no information as to why could be found. It would have been important to have measured redox potential, dissolved oxygen (O_2) and total organic carbon, which would have given us important information about the redox processes.

Angaur

Although the 5 water points surveyed (Table 4) are not sufficient to give a full picture of Angaur's groundwater quality, they are useful to understand the hydrochemistry dynamics, and to compare with previous data collected by Arnow (1961) in 1951–1953 (Table 12). The ionic balance error for the sample analyses is between 3 and 6.5%, which is considered acceptable as it is below +/-10%. The lake shows a chemical composition close to half of seawater (55% of seawater typical Cl content), while the groundwater samples are much fresher (0.2–0.4% of typical seawater Cl content).

Table 12. Summary of the results from the chemical analyses of samples collected as part of this work, and from samples collected from 1951 to 1953 (Arnow 1961) in Angaur. Concentrations are in mg/L.

Sampling point	Date	EC (µS/cm)	Na	Mg	K	Ca	Cl	Br	NO_3 (as N)	SO_4	HCO_3
This study											
Well B (Sample 5)	1/6/2022	664	52.3	7.96	1.69	89.4	82.8	0.33	0.06	14.1	219
Pit lake (Sample 6)	9/6/2022	28,500	6,770	791	262	219	10,600	32.3	< 2	1,470	137
Koska well (Sample 7)	9/6/2022	495	26.3	4.81	0.9	84	41.1	0.14	0.07	5.28	200
Previous studies											
W1	3/7/1951	896	n/a	n/a	n/a	92	142		_ _	_.	..
W1	21/5/1953	810	62	13	2.9	85	120		1.4	19	260
W3	2/2/1951	570	14	7.9	1.8	90	24		4.8	14	286
W3	21/5/1953	687	38	12	1.7	92	70		2	12	294
W4	7/4/1952	533	n/a	9.2	n/a	53	38		--	7.8	248
W4	21/5/1953	487	9.7	n/a	2.5	n/a	42		1.5	2.3	204
W6	7/4/1952	1140	n/a	18	n/a	77	260		--	47	130
W6	21/5/1953	670	70	11	3	46	126		4.1	24	124
W10	2/2/1951	6150	974	127	35	132	1810		1.7	246	324
W10	22/5/1953	7350	1300	149	41	135	2280		3.8	304	292
W13	7/4/1952	4910	n/a	92	n/a	117	1450		--	209	218
W15	7/4/1952	2100	n/a	37	n/a	54	570		--	55	150
TH8	7/4/1952	2470	n/a	43	n/a	54	680		--	10	270
TH10	3/7/1951	1090	n/a	n/a	n/a	30	260		--	--	--
TH13	7/4/1952	1793	n/a	26	n/a	70	420		--	34	319
TH13	7/4/1952	5580	n/a	121	n/a	99	1680		--	244	180
TH16	7/4/1952	16,200	n/a	342	n/a	205	5690		--	713	110
TH16	7/4/1952	25,100	n/a	617	n/a	287	9520		--	1,210	260
Lake 1	2/2/1951	3820	607	71	38	52	1120		0.8	109	162
Lake 1	22/5/1953	3230	534	62	19	43	950		2.7	94	102
Lake 7	2/2/1951	36,200	7400	953	269	289	13,700		--	1960	112

Groundwater chemical characteristics

The piper diagram (Figure 32) shows a cluster of samples plot close to seawater indicating that these locations have a strong influence from seawater, most likely because of the effects of the pit lakes in the 1950s as suggested by Arnow (1961). This is despite the fact that these samples have varying EC (3230–36,200 µS/cm) and represent different percentages of seawater (4.9–70.6% Cl content). The remaining samples plot on the fresh-seawater conservative mixing line proposed by Appelo and Postma (2005), with sample W3 being the freshest.

Our samples 5 and 7 plot close to freshness as well, with sample 7 being fresher, which is also reflected in the percent of seawater as Cl content (0.4% and 0.2%) and EC differences (664 µS/cm and 495 µS/cm), respectively. This however might be because sample 5 is from a supply well that is continually pumped, while sample 7 is from the abandoned Koska well, and as such the water sampled might be fresher than what would a sample representative of the aquifer be.

Samples 5 and 7, and W3 and W1 are of calcium-magnesium bicarbonate type. W6 is of mixed type (close to sodium-potassium chloride-sulphate type) – this is interesting as sample W6 and 7 are from the same location, the Koska well, and may mean that when being pumped (sample W6) this well shows fewer fresh characteristics. The other samples are of sodium-potassium bicarbonate type, plotting very close to seawater, indicating the stronger influence of seawater in their composition.

Cl/Br ratios in the groundwater samples are all very close to the Cl/Br ratio of seawater of 288 (Table 13), indicating that dissolved salts in rainwater and groundwater are marine derived. This observation is consistent with the vicinity of the ocean, the land use (no application of fertilizers and pesticides) and the lithology of the basin (i.e. absence of Cl-bearing rocks). It rules out the contribution of Cl from sources other than both rainfall and dry deposition of marine aerosols. This fulfills one of the key assumptions for the application of the CMB method to calculate recharge, which would also require the knowledge of rainwater average chemical composition, and therefore can be applied in the future should rainfall quality (at least Cl concentration) is appropriately monitored. The pit lake sample shows a slight enrichment in Cl, although no obvious reason can be found for this, and it could be because this sample has a higher analysis error (6.5%) probably due to its high salinity and need for a dilution. Unfortunately, Arnow (1961) did not analyze Br, and so we are unable compare this ratio between modern and old water samples.

Table 13. Elemental ratios (concentration in mg/L) of samples collected as part of this and previous work Van der Brug (1984) and from typical seawater (Goldberg et al. 1971)

Sampling point	Cl:Br	Cl:Na	Na:Ca	Ca:Mg
well B	251	1.58	0.59	11.23
large pit lake	328	1.57	30.91	7.37
Koska well	294	1.56	0.31	17.46
W1		n/a	n/a	n/a
W1		1.94	0.73	6.54
W3		1.71	0.16	11.39
W3		1.84	0.41	7.67
W4		n/a	n/a	5.76
W4		4.33	n/a	n/a
W6		n/a	n/a	4.28
W6		1.80	1.52	4.18
W10		1.86	7.38	1.04
W10		1.75	9.63	0.91
w13		n/a	n/a	1.27
w15		n/a	n/a	1.46
TH8		n/a	n/a	1.26
TH10		n/a	n/a	n/a
TH13*		n/a	n/a	2.69
TH13**		n/a	n/a	0.82
TH16*		n/a	n/a	0.60
TH16***		n/a	n/a	0.47
Lake 1		1.85	11.67	0.73
Lake 1		1.78	12.42	0.69
Lake 7		1.85	25.61	0.30
seawater	288	1.8	26.28	0.32

The Cl:Na ratio is similar to seawater (1.8) for both sampled wells and pit lake, which was also found for all samples collected by Arnow (1961) in 1951–1953, except for well 4 whose ratio was around twice of that. Well 4 is located very close to the sea on the beach deposits. This ratio is around twice for the pit lake. This indicates that Na may be being removed from solution (lake water) due to cation exchange with Ca and Mg (abundant in the local limestone rock matrix). Interestingly, the lake samples by Arnow (1961) in 1951–1953 show a ratio very close to seawater. This is compatible with the fact that there was a more direct connection to the sea then due to the ongoing mining, resulting in a shorter residence time at the lake, not allowing for geochemical processes to occur as much. Because mining ceased in the 1950s, and most lakes have since been backfilled, the connection to the sea is currently limited, the residence times are longer, and as such slow geochemical processes such as cation exchange can occur. Further, Cl concentration in our sample is lower (10,600 mg/L) than the sample collected in lake 7 in 1951 (13,700 mg/L), which is consistent with a more limited connection to the sea (10,600 mg/L Cl) currently.

The Na:Ca ratio in our groundwater samples is much lower (0.3–0.6) than in seawater (26.3). This likely indicates that the groundwater is enriched in calcium when compared to recharge water, which is logical considering the wells are located in limestone aquifers. Very similar ratios were found for the samples collected by Arnow (1961) in 1951–1953 (0.2–0.7), although wells 6 and 10 showed higher ratios (1.5 and 7.4–9.6, respectively). Well 10 was located very close to a pit lake, and therefore is plausible that it was more influenced by seawater. Well 6 however was located over 1 km to the west of the lakes. Our lake sample has a ratio of 30.9, much higher than the groundwater samples, which is consistent with the seawater influence on the lake. The lake samples by Arnow (1961) show ratios of 11.7 to 25.6, further indicating the seawater influence was stronger then.

The Ca:Mg ratio in our groundwater samples show much higher values (11.2–17.5) when compared to seawater (0.32), indicating Ca dissolution in the limestone aquifer. A range of ratios were found for the samples collected by Arnow (1961) in 1951–1953 (0.5 to 11), likely indicating stronger seawater influences in some of the wells, which is consistent with proximity with the lakes. Our lake sample returned a ratio (0.28) similar to seawater, and so did the lake samples (0.3 to 0.7) by Arnow (1961), which is likely explained by a strong seawater influence.

According to the USGS (2018) hardness classification, the groundwater samples from the island are all very hard with hardnesses of 256–230 mg/L. Water hardness from the lake is much higher at 3791 mg/L. Previous measurements by Arnow (1961) show hardness values of 160–3250 mg/L in wells, and 422–4640 mg/L in the lakes.

Temporal evolution of water chemical composition for selected sites

Comparing historical and chemical analyses conducted under this study can provide insight into the water quality temporal evolution. The Koska well was sampled in 1952 and 1953 (sample W6) (Arnow 1961), and during our campaign (sample 7). It is worth remembering the Koska well was used for supply from 1953 until probably the 1970s. Well 1 was sampled in 1952 and 1953 (Arnow 1961), and nearby well B (well 2) was sampled during our campaign. These two wells have been used since before WWII and are still being used.

The Koska well shows much fresher water in 1953 compared to 1952. This is intriguing but could be because of pumping induced access to fresher water or because of the effects from pit lake backfilling, although we cannot rule out other potential explanations such as analytical errors or others. The water for the well is even fresher now, with lower EC and Cl content, although it shows higher hardness and Ca content. Because of the current lower NO_3 and SO_4 content, the water might be approaching sulphur-reduction conditions, which may cause bad small and taste due to the production of H_2S. It is worth remembering the well has not been pumped for a long time and was sampled with a bucket – a proper assessment of its hydrochemical signature and potential for use for abstraction would require purging, a pumping test, and sampling under those conditions.

Well 1/Well A shows very little differences between 1951 and 1953, although the latter analysis is much more complete. Compared to the current sample from well 2/well B, it shows similar chemical signature but slightly less fresh. The current sample has lower NO_3 (0.06 compared to 1.4 mg/L), which might indicate that the current conditions are more prone to the production of H_2S from SO_4 reduction.

Interestingly, well 3 has the fresher water (Figure 32), despite Arnow (1961) mentioning its high mineral content and that the community would only use it for cooking and washing. Looking at the analysis, the water is very hard, with a high Ca content, but with a relatively low Cl and Na content, and EC. This may indicate the well was pumping water that was not affected by the transition zone, but freshwater from the aquifer, that is lower in Cl and higher in Ca. Well 3 is in the province B limestone but very close to the sand area, which might mean the well is influenced by the sand aquifer (or perhaps that there are impressions in its location and/or geological cartography). As seen above, the limestone aquifer has the transition zone at a shallower level, and its water is expected to have higher Cl content. According to the available historical data, well 3 could be a valid option for Angaur's water supply, but we would have to find it, understand why it was abandoned, conduct a pump test, and collect new samples for analysis.

As for lake 7, it shows lower hardness, EC and Cl content currently than what it did in 1951. This might mean is being less influenced by seawater. Nevertheless, the water is still very salty and unsuitable for human consumption or agriculture.

Kayangel

The 16 water points surveyed give a good indication of Kayangel's groundwater quality, and together with the water sample collected in the gallery for chemical analyses, are useful to understand the hydrochemistry dynamics, and to compare with scarce previous data compiled by Pollock (2014). The water sample does not show chemical contamination risks for human health (i.e. all values are below WHO 2022 guideline values). The ionic balance error for the sample analysis is 4.17%, which is considered acceptable because it is below +/-10%.

The spatial distribution of EC can be seen in Figure 23 and Table 5. EC ranges from 117 µS/cm to 1274 µS/cm, with an average of 774 µS/cm and a median of 741 µS/cm. This corresponds to a TDS of 59–637 (mg/L), with an average of 387 mg/L and median of 371 mg/L. The higher values are found in some taro patches and traditional pools, which is consistent with higher evapotranspiration rates and contribution of other elements to salinity that are not related to input from seawater, such as nitrates associated with organic matter. If consider shallow wells only, EC ranges from 117 µS/cm to 976 µS/cm, with an average of 651 µS/cm and median of 741 µS/cm. This corresponds to TDS of 59–488 mg/L, with an average of 325 mg/L and median of 371 mg/L. This compares well with TDS measurements in 17 shallow wells measured by EQPB in September 2001, recording a range of 200–800 ppm, mostly from 200 to 500 ppm (Pollock 2014). The EC spatial distribution around Kayangel suggests that groundwater in the northern part of the island is fresher, showing EC values of 327–600 µS/cm, validating the results obtained by the resistivity surveys. In contrast, the southern part shows higher ECs of 692–1200 µS/cm. Interestingly, shallow well 2 in the southern part shows a very low EC of 117 µs/cm, probably because it is located in the center of the freshwater lens.

Table 14. Summary of the results for the chemical analysis (concentration in mg/L) of the Kayangel gallery sample collected as part of this work.

Sampling point	Sampling date	EC top (µS/cm)	Na	Mg	K	Ca	Cl	Br	NO_3 (as N)	SO_4	HCO_3 (-)
Kayangel gallery	16 June 2022	600	22.6	10.7	2.26	99.4	37.3	0.91	0.07	5.96	258

The gallery sample has a Cl concentration of 37.3 mg/L, which is much lower than the concentrations from the early 2000s reported by EQPB of 155–350 mg/L, further indicating that those values were likely wrong. TDS concentrations range from 300 mg/L (based on EC measurements) to 439 mg/L (based on laboratory analysis), which are in a similar range as the ones reported by Pollock (2014) of 220–800 ppm. The gallery sample is of calcium-magnesium bicarbonate type (Figure 32). It plots on the hypothetical fresh water–seawater mixing line proposed by Appelo and Postma (2005), showing the sample is relatively fresh, and dominated by aquifer-water interaction and not by seawater influence.

The Cl:Br ratio in the groundwater sample is 41, which is much lower to the Cl:Br ratio of seawater of 288 (Table 15). This means that groundwater in Kayangel is relatively enriched in Br when compared to seawater. This may be an indication that groundwater is subject to ongoing evapotranspiration, whereby Cl salts precipitate while Br remains in solution. This observation is consistent with a very shallow aquifer (3 ft or 1 m deep), the vicinity of the ocean, the land use (no application of fertilizers and pesticides) and the lithology of the basin (i.e. absence of Cl-bearing rocks). It rules out the contribution of Cl from sources other than both rainfall and dry deposition of marine aerosols. This fulfills one of the key assumptions for the application of the CMB method to calculate recharge, which would also require the knowledge of rainwater average chemical composition and, therefore, can be applied in the future should rainfall quality (at least Cl concentration) be appropriately monitored. Unfortunately, there are no previous records of Br concentrations, and so we cannot compare this ratio between modern and older water samples.

Table 15. Elemental ratios (concentration in mg/L) of the gallery sample collected in Kayangel and from typical seawater (Goldberg et al. 1971).

Sampling point	Cl:Br	Cl:Na	Na:Ca	Ca:Mg
Gallery	40.99	1.65	0.23	9.29
seawater	288.26	1.8	26.28	0.32

The Cl:Na ratio is 1.7, which is similar to that of seawater (1.8). This indicates that groundwater is directly related to rainwater that reflects diluted seawater, and that the residence times are probably very small, not allowing for geochemical processes such as cation exchange to occur. The Na:Ca ratio in the groundwater sample is much lower (0.2) than in seawater (26.3). This likely indicates that groundwater is enriched in calcium when compared to recharge water, which is logical considering the aquifer has a carbonate matrix. The Ca:Mg ratio in the groundwater sample shows a much higher value of 9.3 when compared to seawater (0.32), also indicating Ca dissolution in the carbonate sand aquifer. According to the USGS (2018) hardness classification, the water sample is very hard, with a hardness of 290 mg/L.

5. Recommendations for water resources management

A common issue for the three islands is very high level of water hardness. As mentioned above, water hardness is caused by the weathering of limestone and other Ca-bearing rocks, and is primarily the amount of Ca and Mg, and to a lesser extent iron (Fe), in the water. Hard water is mainly an aesthetic concern because of the unpleasant taste from a high concentration of Ca and other ions. It also reduces the ability of soap to produce a lather and causes scale formation in pipes and on plumbing fixtures. Although people may become accustomed to a high level of hardness in drinking water, it is recommended to treat hard water to prevent the issues mentioned above. Besides desalination techniques, water hardness can also be eliminated by using ion exchange type water softeners and non-chemical techniques such as electromagnetic field (EMF).

With the ion exchange process, water is pumped through a tank containing a resin that causes Ca and Mg ions to be exchanged for Na or K ions. The water leaving the unit still contains essentially the same amount of dissolved minerals, but the hardness-forming minerals have been replaced with Na or K. When the softening material's ability to exchange Na and K for Ca and Mg is exhausted, it must be "regenerated" by running a given amount of salt brine (NaCl) through the softener tank. The effectiveness of a softener can be reduced substantially when the water contains Fe, as the exchange material may become coated with Fe deposits.

EMF is a water treatment process dating back to the 19th century (Jiang et al. 2019) where water passes through an electric, magnetic or electromagnetic field to reduce potential fouling and scaling on the membrane surface. EMF treatment employs: 1) fixed permanent magnets or fixed electromagnets to induce a magnetic field; 2) alternative current through solenoid coils that wrap around or are positioned near an existing pipe to induce an EMF; or 3) an electric field by directly putting discharge electrodes in contact with water. A commercially available EMF device typically includes a signal generator and a treatment module.

Peleliu

Currently, Peleliu's water demand cannot be fully met by the water produced by the RO plant operating at its maximum capacity of 88 gal/min (333 L/min). Leaks in the distribution system are the most probable reason why water production is not capable of meeting the water demand. To address that, PPUC complements the desalinated water with raw groundwater pumped from the same gallery well. As a result, the mixed distributed water suffers from increased salinity (EC up to 1600 µS/cm), increased hardness, and high H_2S content, which causes a bad odor and bad taste. As a short-term plan, a suitable treatment facility could be installed to address the issues of hardness, scaling and odor to make the supplied mixed water more acceptable for secondary purposes. Even though palatability may slightly improve with the treatment, it is expected that it will still be an issue due to the relatively high NaCl content. In the longer term, however, servicing the entire distribution system would be necessary to ensure that no water is lost through leaks.

Water quality and treatment options

Besides water hardness, odor and palatability are other critical water quality issues on Peleliu. These are very likely related to H_2S, which in groundwater is usually produced by sulfur-reducing bacteria that use sulfur as an energy source, chemically changing SO_4 to H_2S. Hydrogen sulfide can occur naturally in groundwater formed from decomposing underground deposits of organic matter such as decaying plant material. It can be found in deep or shallow wells, and it can even enter surface water through springs, although it quickly escapes to the atmosphere. The most commonly used method for removing H_2S from water is continuous chlorination followed by an activated carbon filter. This method can handle relatively large quantities of H_2S and does not release odor to the air. It can also be removed using an aerator, whereby the gas is released in the air and dissipated through the sides of the aerator. However, because of the bad odor produced by this method, it is not always a desirable approach. EMF can also contribute to solve the odor and taste H_2S-related problem because the electron generation in water, induced by magnetic effect, increases dissolved oxygen concentration, thus potentially inhibiting the reduction from SO_4 to H_2S (Yep et al. 2021).

Potential additional water sources

Three potential additional water sources are proposed in Table 16 and described below: 1) rehabilitating sinkhole 2 (old water source); 2) developing the freshwater lenses in the beach sandy deposits south of the village; and 3) rehabilitating the runway rainwater catchment (as suggested and described by EM Chen 2001).

Table 16 Potential water supply options for Peleliu

Water supply option	Pros	Cons	Further studies required	Implementation requirements
1. Rehabilitation of sinkhole 2	fresh groundwater under current (unpumped) conditions; it has sustained the water supply in the past	distance to the treatment system (~5800 ft or ~1768 m); groundwater might require treatment and the RO is at full capacity; proximity to mangroves and potential to develop H_2S	pumping test with continuous monitoring of salinity	well rehabilitation; solar-powered pump; reticulation system up to the current treatment plant
2. Development of freshwater lens identified in the beach deposits south of the village	potentially a good water source quantity/quality wise; proximity to village and existing reticulation system	presence of potential contamination sources (e.g. cemetery, dump site, households)	groundwater chemical analysis; exploration drilling	gallery construction; solar-powered pump; reticulation to existing system
3. Rehabilitation of runway rainwater catchment	land already cleared; high quality water; existing preliminary study (EM Chen 2001); proximity to current water supply system	high cost, but could be considered as part of a broader runway rehabilitation plan	updated engineering plans for the construction; updated calculations of potential volume collected	rehabilitation of the runway (impermeabilization); drains collecting water along the edges of runway; construction of storage tanks

Option 1 involves complementing the existing water supply by redeveloping the old water source (sinkhole 2 in Table 4) located along survey line 6 (Figure 20). This water source was utilized in the past but was eventually abandoned in the early 1980s for unknown reasons, potentially due to land or water quality related issues, or alternatively pump failure (EM Chen 2001). Although the measured salinity suggests the presence of fresh groundwater (EC = 300–600 µS/cm), a pumping test would need to be conducted, whereby the EC of the abstracted water is continuously monitored to assess the potential of the source to sustain prolonged pumping. As mentioned above, it is possible that this water is of poor quality and with potential to develop H_2S because of its proximity to the mangroves, which strengthens the need for continuous water monitoring before deciding to use this water source. A distribution system to the current wellfield would also need to be installed, which is a distance of ~5800 ft (~1770 m).

Option 2 is to develop the newly identified freshwater lens present in the beach deposits near the village (Figure 20) – could prove to be an effective option given its proximity to the existing distribution system, proximity to village and suggested vertical and areal extent of the freshwater supply. The vertical extent of the freshwater lens would have to be proven through drilling of test holes around the area while measuring the EC of the groundwater at various depths. Such test holes could be drilled using a small portable rig. Groundwater development from the beach deposits should be done by means of horizontal galleries skimming the fresh groundwater just below the water table to prevent early salinization of the well as shrinking of the fresh groundwater body occurs by means of the upward movement of the transition zone. Eventual galleries should consider the sensitivity of freshwater lens thickness to tidal processes and rainfall events. Gallery construction in freshwater lenses involves excavating a trench approximately 3 ft (1 m) below the lowest level of the water table from tidal impact and installing horizontal PVC-slotted pipes that lead to a central pumping station. The horizontal wells would be backfilled with suitably sized rounded gravel to help develop a gravel pack before being backfilled with the excavated sand. It is suggested that during the excavation of the trench for the gallery, if reef rock is encountered and remains weathered to moderately weathered, trench construction should continue. If the reef rock is hard or well cemented or thick reef rock is intercepted, then the continued construction of the trench should be assessed. In the areas where thick and unweathered reef rock is encountered, it is expected that the recharge may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery.

Option 3 is to rehabilitate the runway rainwater catchment as suggested by EM Chen (2001) and store the captured water in underground tanks connected to the water supply system. EM Chen (2001) provides preliminary calculations for potential collected water volumes although based on very rough rainfall estimates; therefore, more accurate rainfall measurements would be needed for more reliable volume estimates. They also provide a preliminary design of how the catchment system could work. If the runway was to be rehabilitated to receive flights, the rehabilitation could include a system to capture and store rainwater for public supply.

Summary of recommendations

The integrated and coordinated development and management of freshwater resources on Peleliu will be key to the community's long-term health and security. Thus, it will be critical to:

1. Conduct an audit of water supply systems, including water usage and demand, groundwater abstraction, and infrastructure, to provide an insight to how much water is required by the local community under normal and extreme climatic conditions.
2. Install flow meters to quantify the volume that feeds the desalination system and the volume of raw groundwater that is abstracted from the main gallery to better assess groundwater abstraction, water usage and leakage, if any, and improve the management of water across the different reservoirs and to the end users.
3. Conduct a pumping test in sinkhole 2 to assess its potential as an additional groundwater source by monitoring the salinity and redox potential response. It is expected that groundwater parameters will vary during the pumping test, and samples for hydrochemistry analyses should be taken throughout the test as parameters stabilize. This will help determine whether the quality of the groundwater is suitable for water supply, and whether salinity rises to unacceptable levels with continuous pumping.
4. Consider the development of a new water source at the newly identified freshwater lens present in the beach deposits near the village. This would require further assessment to test water quality and aquifer productivity. The proposed abstraction system would consist of an infiltration gallery, also known as horizontal well.
5. Undertake regular rainfall analyses from the existing station to determine the temporal variability of rainfall and to estimate the groundwater recharge rate. This will require the strengthening of links between the island government and the national weather service on the compilation, archiving and sharing of rainfall data and climate forecasts. A new rainfall gauge, or weather station, may need to be installed. Understanding the climatic patterns will be critical to managing the water system.
6. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management, especially during prolonged dry periods. This is critical to better managing and protecting the freshwater lenses to ensure their longevity.
7. Install a water treatment system that can improve water quality in terms of hardness and H_2S content. Solar-powered options that require little-to-no maintenance, no chemicals, and no filters are recommended.

Angaur

Based on the monitoring data collected during the period 1 June–5 October 2022 and while the pump in well A was not operational, well B was able to sustain continuous abstraction without the water quality being compromised by increases in salinity. Moreover, no instances of the well running dry were reported. As more data are being collected through the loggers that have been installed in the two wells, particularly during the dry season, more insights will be gained regarding the behavior of the well and groundwater system, allowing for more informed operational and management decisions.

Water quality and treatment options

The currently supplied water, after going through the treatment plant, is of acceptable quality except for the extremely variable free chlorine levels resulting from the manual chlorination currently conducted. It is important to urgently evaluate options to repair or replace the automatic chlorinator and potentially the UV sterilizer systems. Relocating the treatment plant to a location that is less prone to sea-spray corrosion would be advisable, although it may not be possible. It would also be useful to measure the treated water for hardness to ensure this is within acceptable levels.

Potential additional water sources

A number of alternative groundwater sources were identified that could be considered in the future. The Koska well, which has recently been rehabilitated, could potentially provide additional water to the system. A pumping test should first be performed where the salinity/EC of the abstracted water is continuously monitored to assess the well's sustainable pumping rate without compromising the abstracted water quality. A pumping test might also give indications with regards to the potential for sulfur-reducing conditions to develop, resulting in odor and taste issues. Nevertheless, the existing treatment system should be able to deal with this potential issue, as it currently does with the water produced by wells A and B. Another requirement would be connecting the existing overhead tank to the main distribution line.

Alternatively, the old wells 3 and 4 appear to have sustained good water quality over time, as reported by Arnow (1961). Locating these wells and conducting pumping tests would be required to ensure their suitability.

Finally, the newly identified resource present in the southwest part of the island could provide for a solid and resilient water supply, if needed. The chemical analysis associated with well 4 from 1952 (Arnow 1961) is the only information available on the quality of groundwater that is present in the sandy aquifer. According to this information, groundwater is fresh (EC = 533 µS/cm), with a low Cl content (38 mg/L) and a hardness of 170 mg/L, and is of suitable quality for human consumption. In comparison, the water currently pumped from well B is very hard and with much higher Cl content.

Groundwater development from the beach deposits should be done by means of horizontal wells (infiltration galleries) skimming the fresh groundwater just below the water table to prevent early salinization of the well as shrinking of the fresh groundwater body occurs by means of the upward movement of the transition zone. Eventual galleries should consider the sensitivity of freshwater lens thickness to tidal processes and rainfall events. The system should be equipped with a pump and header tank while a distribution system would have to be installed to supply the water to the village

Gallery construction in freshwater lenses involves excavating a trench approximately 3 ft (1 m) below the lowest level of the water table from tidal impact, and installing horizontal PVC-slotted pipes that lead to a central pumping station. The horizontal wells would be backfilled with suitably sized rounded gravel to help develop a gravel pack before being backfilled with the excavated sand. It is suggested that during the excavation of the trench for the gallery, if reef rock is encountered and remains weathered to moderately weathered, trench construction should continue. If the reef rock is hard or well cemented or thick reef rock is intercepted, then the continued construction of the trench should be assessed. In the areas where thick and unweathered reef rock is encountered, it is expected that the recharge may be reduced and/or delayed, thereby reducing the effectiveness of the horizontal gallery.

Summary of recommendations

The integrated and coordinated development and management of freshwater resources in Angaur will be key to the community's long-term health and security. Thus, it is critical to:

1. Have an audit of water supply systems including the usage and demand, abstractions, and infrastructure, to provide an insight into how much water is required by local communities under normal and extreme climatic conditions.
2. Install flow meters to measure the pumped water from the wells. This is critical to understand how much water is pumped, and the impacts it has on the freshwater lenses, so it can be better managed and protected to ensure its longevity.
3. Undertake regular rainfall analysis to determine the temporal variability of rainfall and to estimate groundwater recharge. This will require the strengthening of the links between the Island Government and the national weather office on the compilation, archiving and sharing of rainfall data and climate forecast. A new rainfall gage, or a weather station, may have to be installed. Understanding the climatic patterns will be critical to manage the water system.
4. Undertake efforts to locate wells 3 and 4, and test hole 12. These would be tested to better understand the water quality of the sand aquifer corresponding to the beach deposits south of the village, and would potentially be considered as new water sources.
5. Conduct pumping tests in the Koska well, and wells and test hole mentioned above if located. This would allow assessing the well response to pumping in terms of groundwater levels, salinity, pH, dissolved O_2 and redox potential. It is expected that groundwater parameters vary during the pump tests, and samples for hydrochemistry analyses are to be taken throughout the test as parameters stabilize. This will allow us to understand if the groundwater quality is suitable for water supply, and if salinities rise to unacceptable levels with continuous pumping. For these pumping tests, the water inlet should be located as close as possible to the bottom to allow for the sampled water to represent aquifer conditions as much as possible.
6. Consider a new water source to be developed in the newly-identified freshwater lens present in the beach deposits south of the village. This would require further assessment to test water quality and aquifer productivity. The proposed abstraction system would be a gallery, also known as horizontal well.
7. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management, especially during prolonged dry periods. This is critical to better managing and protecting the freshwater lenses to ensure their longevity.
8. Protect the Koska well by installing a deadlock on the fence gate and a lid on top of the well.

Kayangel

Even though the existing gallery in Kayangel is capable of producing enough water, it is the quality (salinity) of the produced water that limits its potential for human consumption. This is the case in freshwater lens situations where the volume of good quality groundwater that can be abstracted is limited by the thickness of the freshwater lens. This volume can be maximized by using the appropriate infrastructure (infiltration galleries) and suitable abstraction rates that have been informed by long term monitoring and the resulting improved understanding of the freshwater lens. As more data are being collected through the automatic loggers, particularly during the dry season, more insights will be gained over the well and groundwater system behavior, allowing for more informed operational and management decisions.

The shallow depth of the transition zone in Kayangel (6–12 ft or 2–4 m) causes the salinity in the gallery, and thus of the abstracted water, to heavily fluctuate with the tides. Theoretically, if the pumping schedule could match the low tide periods (by using a floating valve for example), it could potentially pump fresher groundwater which would be stored in the overhead tank for subsequent distribution to the village. Such sophisticated approach would require further research to prove its applicability.

Bacterial contamination is present in Kayangel, and because the chlorination system is not operating this could cause problems with the consumption of the supplied water. It is recommended installing an automatic chlorination system to ensure the safety of the supplied water.

The integrated and coordinated development and management of freshwater resources in Kayangel will be key to the community's long-term health and security. Thus, it is critical to:

1. Conduct repair works in the water supply infrastructure, namely repairing the fence around the gallery, the lid of the gallery tank, and the structure and the base of the header tank. This is critical to protecting the water supply infrastructure and the water quality, and to ensuring it stays operational for decades to come.
2. Install a flow meter to measure the pumped water from the gallery. This is critical to understanding how much water is pumped, and the impacts it has on the freshwater lenses, so it can be better managed and protected to ensure the longevity of the lenses.
3. Raise the height of the pumps so they are less prone to potential inundations. This is critical to protecting the infrastructure from future extreme weather events that create inundations.
4. Clean the gallery well the sediments that have accumulated in the bottom. This is important to ensuring that the well capacity is maximized and the water quality is not compromised.
5. Install a rain gauge or weather station to collect data and undertake regular rainfall analysis from the existing station to determine the temporal variability of rainfall and estimate groundwater recharge. This will require strengthening the links between the island government and the national weather office on the compilation, archiving and sharing of rainfall data and climate forecast. Understanding the climatic patterns will be critical to managing the water system.
6. Identify appropriate trigger levels for groundwater salinity and rainfall to support water resources management. This is critical to better managing and protecting the freshwater lenses to ensure their longevity.
7. Install a water treatment system to address the negative effects of water hardness and improve palatability. This will be critical to improving the acceptability of groundwater for drinking and cooking.
8. Improve the supplied water disinfection by installing an automatic chlorinator. This is critical to ensuring that groundwater is bacteria-free and safe for cooking and drinking.
9. Finally, to conduct a study to understand the reasons for taro-patch health decline, and what can be done to improve the situation. This will be critical to understanding the connection between the hydrological system (including sea-level rise) and food production, and to contributing to food security and protecting culturally significant agricultural practices.

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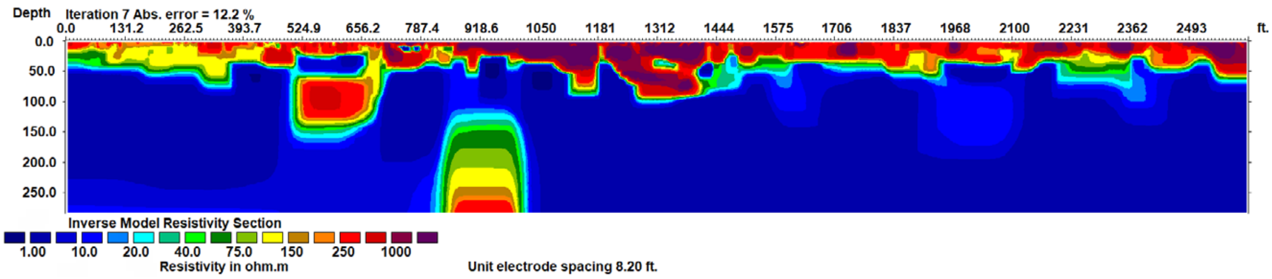
Annex A – Inverted resistivity profiles

Peleliu

PALAU PEL01N



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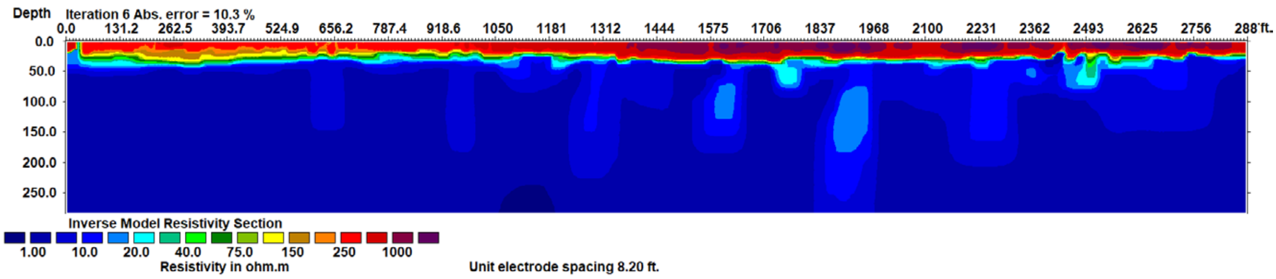

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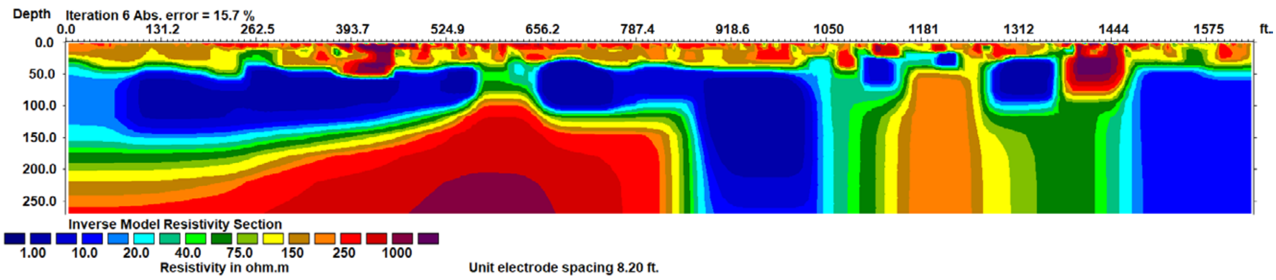

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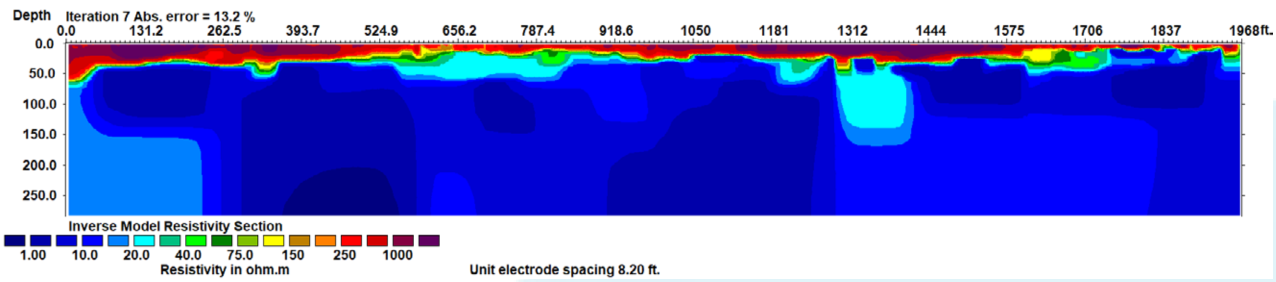

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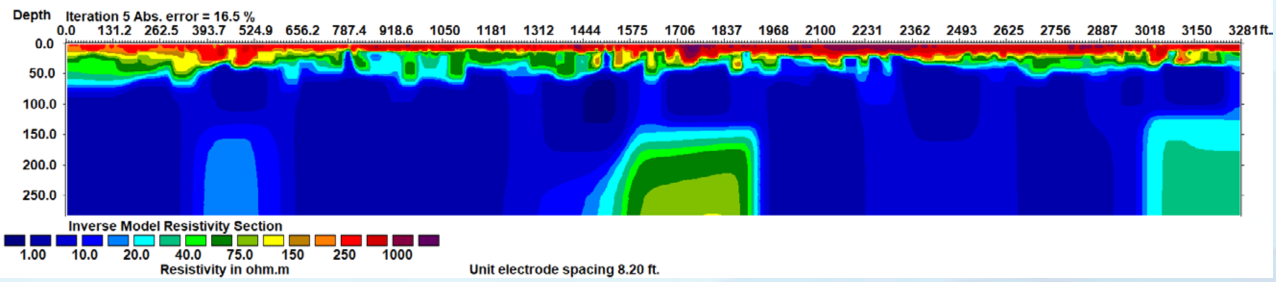

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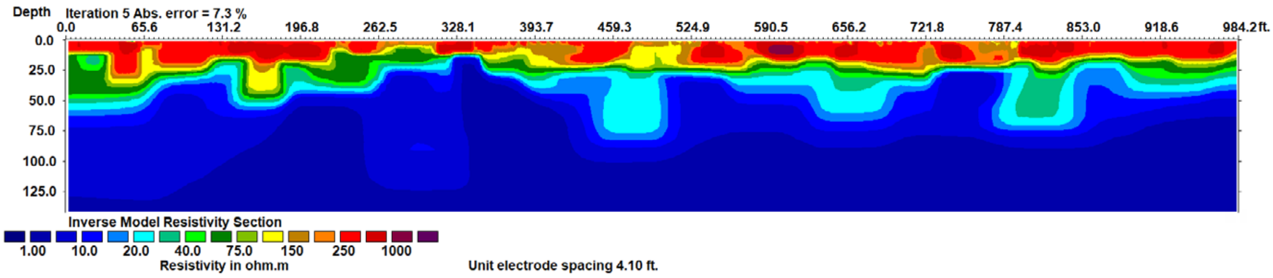

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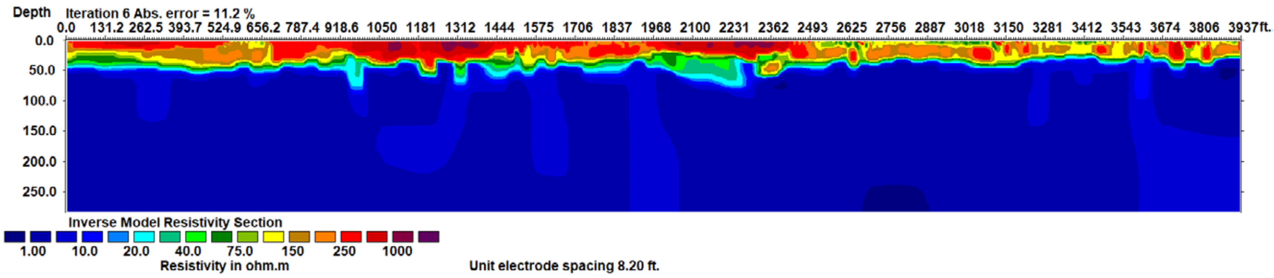
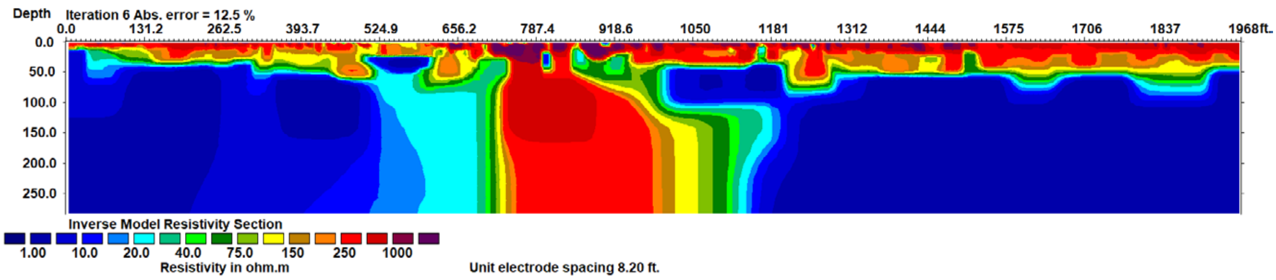
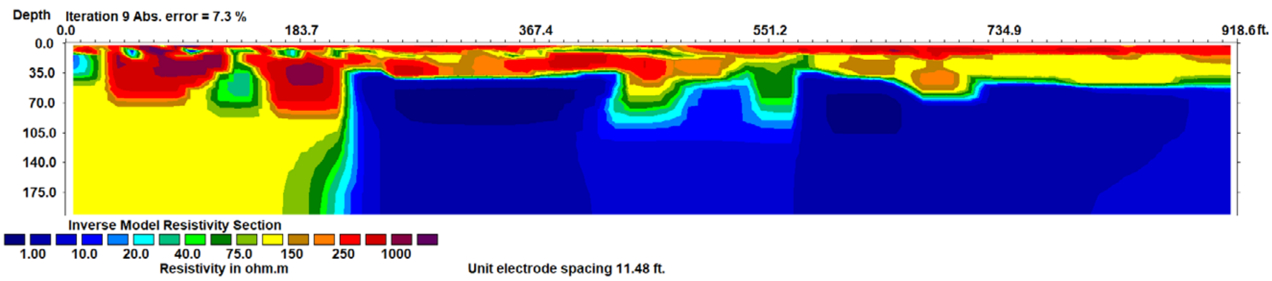


PALAU PEL08

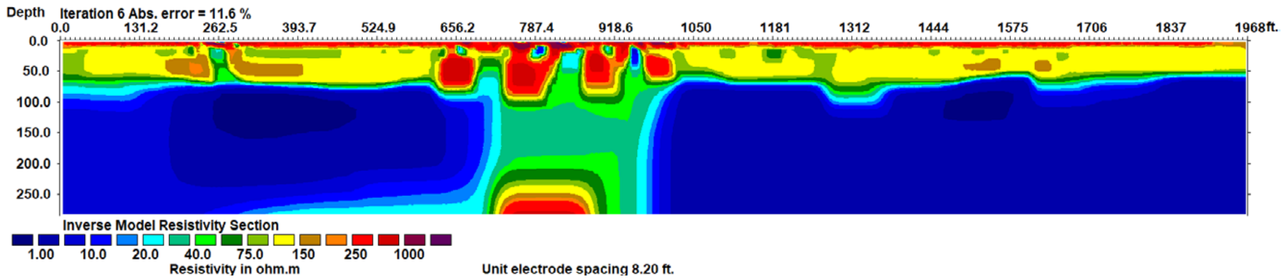


PALAU PEL09

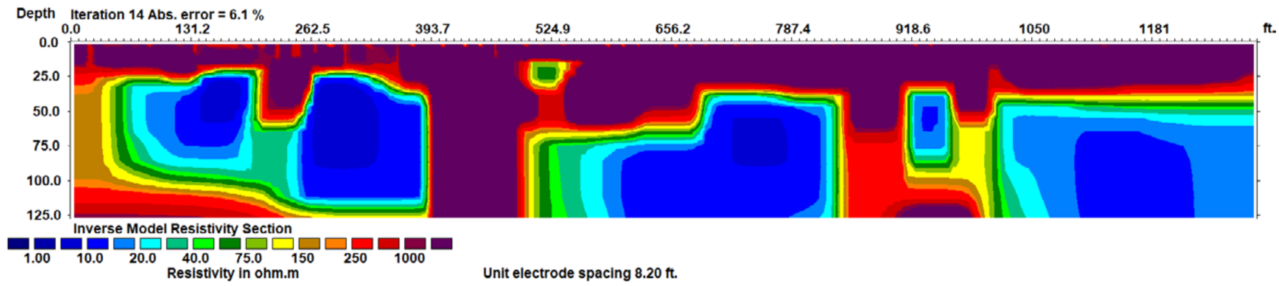


Angaur

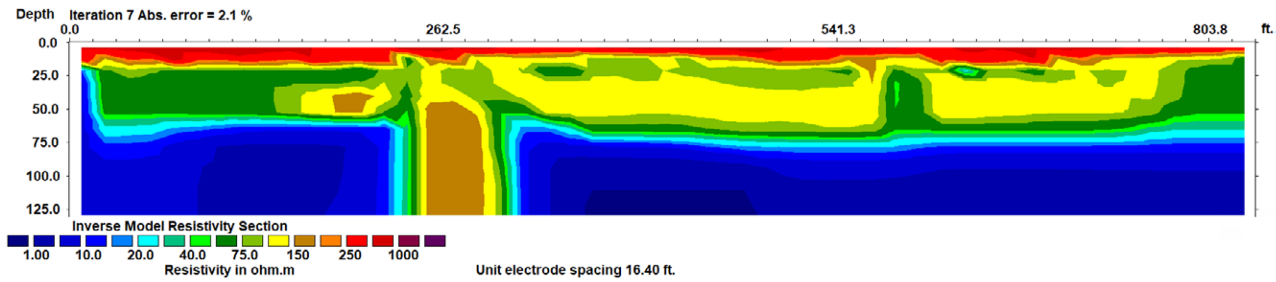
PALAU ANG01



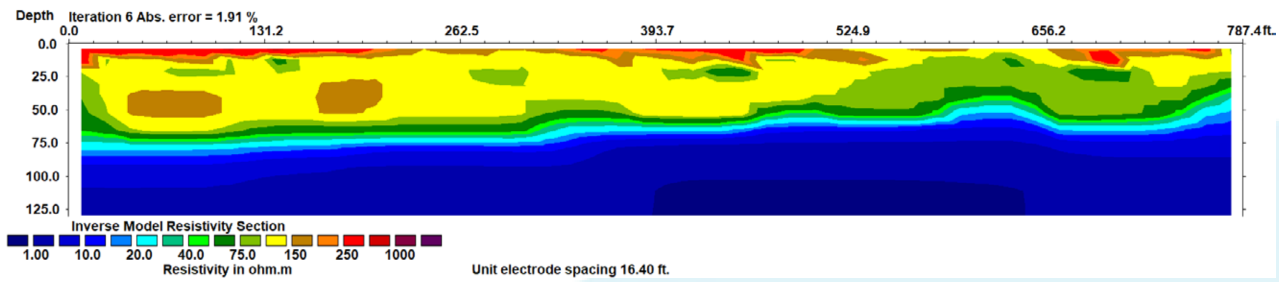
PALAU ANG02



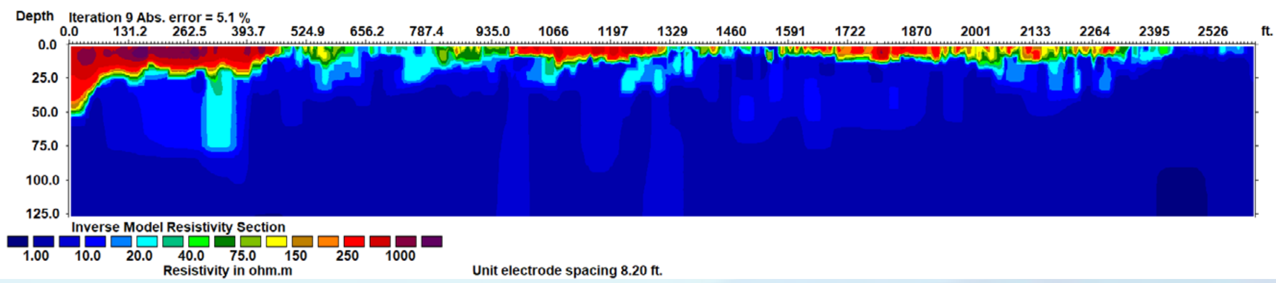
PALAU ANG03



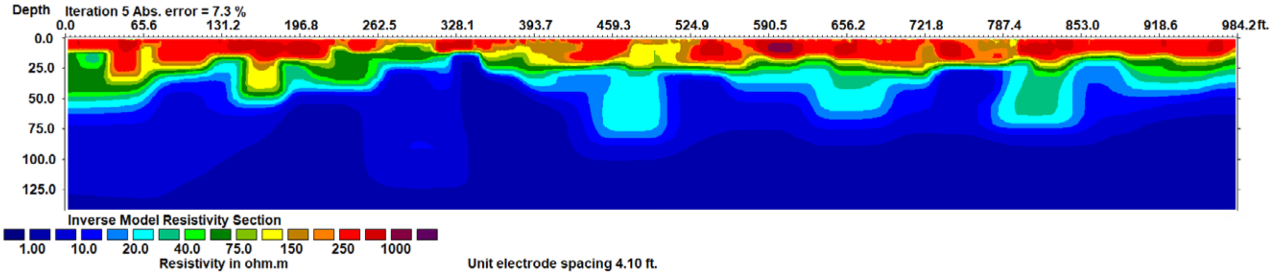
PALAU ANG04



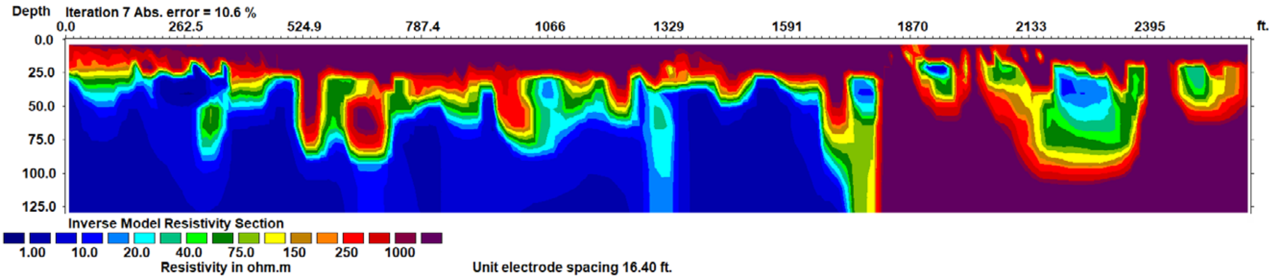
PALAU ANG05



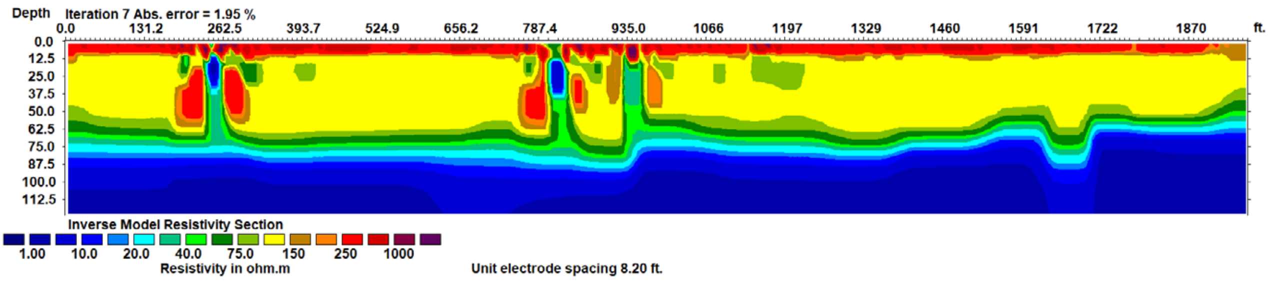
PALAU PEL06



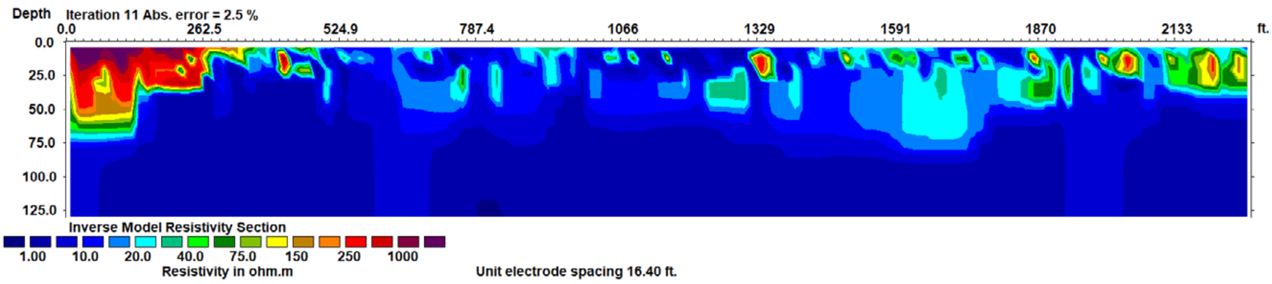
PALAU ANG07



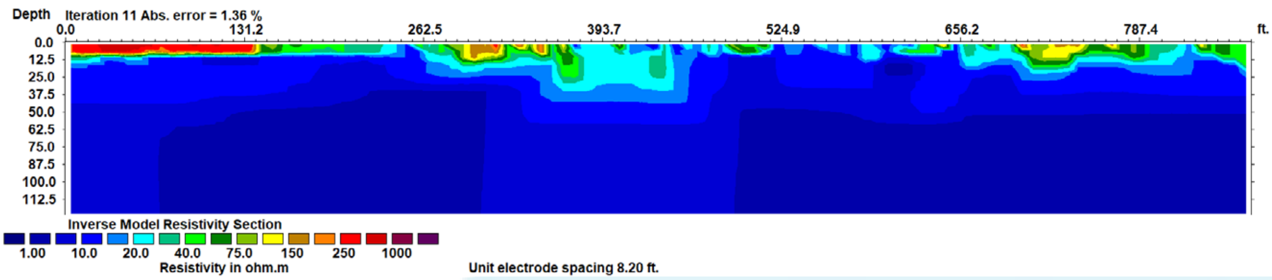
PALAU ANG08



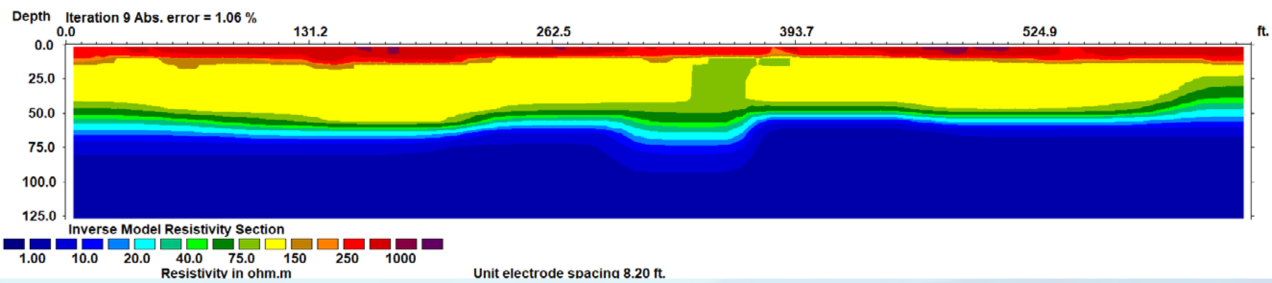
PALAU ANG09



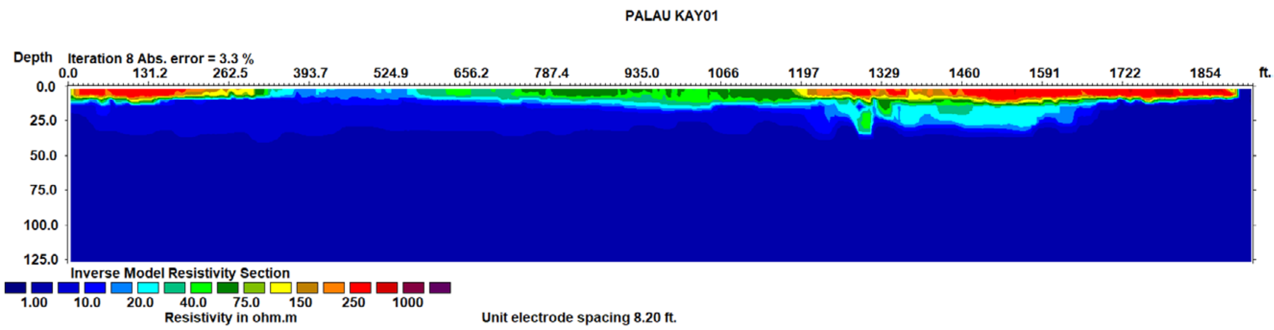
PALAU ANG10



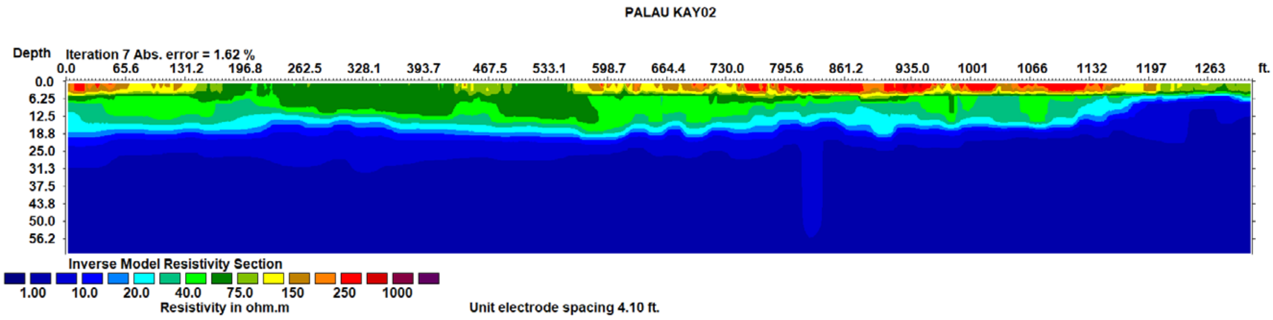
PALAU ANG11



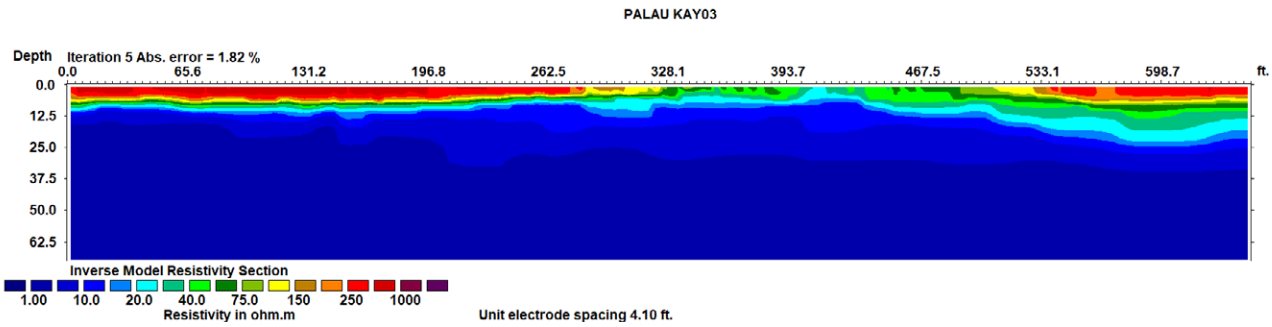
Kayangel



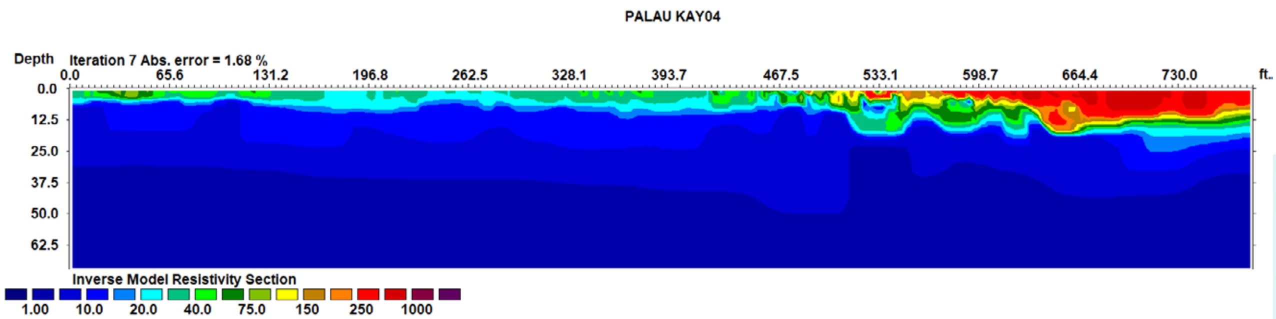
PALAU KAY01
Depth
Iteration 8 Abs. error = 3.3 %
0.0 131.2 262.5 393.7 524.9 656.2 787.4 935.0 1066 1197 1329 1460 1591 1722 1854 ft.
0.0 25.0 50.0 75.0 100.0 125.0
Inverse Model Resistivity Section
1.00 10.0 20.0 40.0 75.0 150 250 1000
Resistivity in ohm.m
Unit electrode spacing 8.20 ft.



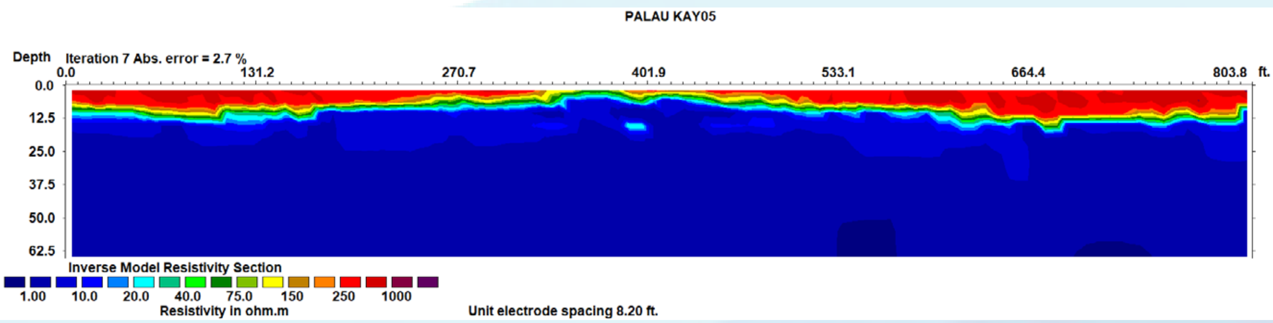
PALAU KAY02
Depth
Iteration 7 Abs. error = 1.62 %
0.0 65.6 131.2 196.8 262.5 328.1 393.7 467.5 533.1 598.7 664.4 730.0 795.6 861.2 935.0 1001 1066 1132 1197 1263 ft.
0.0 6.25 12.5 18.8 25.0 31.3 37.5 43.8 50.0 56.2
Inverse Model Resistivity Section
1.00 10.0 20.0 40.0 75.0 150 250 1000
Resistivity in ohm.m
Unit electrode spacing 4.10 ft.



PALAU KAY03
Depth
Iteration 5 Abs. error = 1.82 %
0.0 65.6 131.2 196.8 262.5 328.1 393.7 467.5 533.1 598.7 ft.
0.0 12.5 25.0 37.5 50.0 62.5
Inverse Model Resistivity Section
1.00 10.0 20.0 40.0 75.0 150 250 1000
Resistivity in ohm.m
Unit electrode spacing 4.10 ft.



PALAU KAY04
Depth
Iteration 7 Abs. error = 1.68 %
0.0 65.6 131.2 196.8 262.5 328.1 393.7 467.5 533.1 598.7 664.4 730.0 ft.
0.0 12.5 25.0 37.5 50.0 62.5
Inverse Model Resistivity Section
1.00 10.0 20.0 40.0 75.0 150 250 1000



PALAU KAY05
Depth
Iteration 7 Abs. error = 2.7 %
0.0 131.2 270.7 401.9 533.1 664.4 803.8 ft.
0.0 12.5 25.0 37.5 50.0 62.5
Inverse Model Resistivity Section
1.00 10.0 20.0 40.0 75.0 150 250 1000
Resistivity in ohm.m
Unit electrode spacing 8.20 ft.

Annex B – Historical data

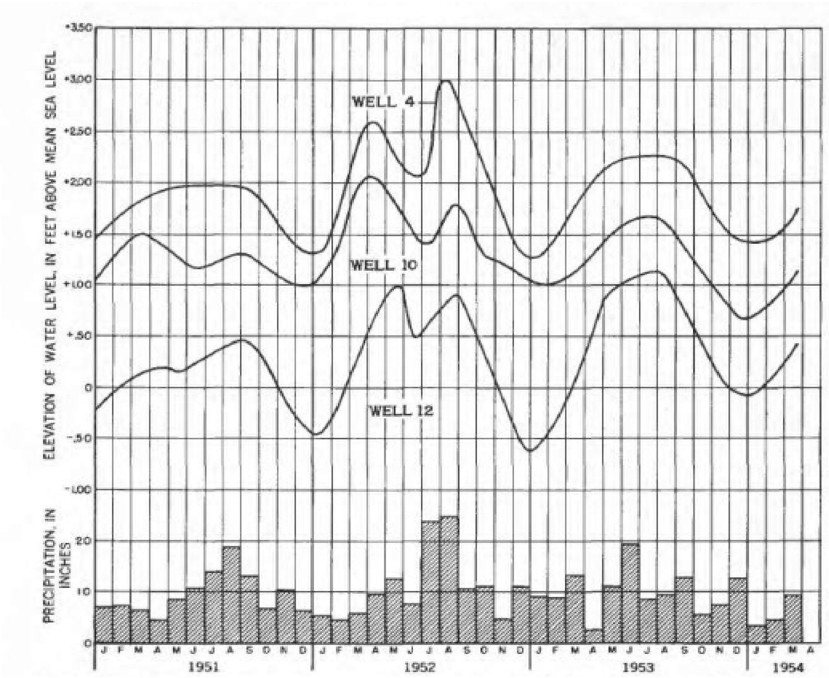


Figure 33. Water level fluctuations in wells 4, 10, and 12, and rainfall on Angaur, 1951–1954. Source: Arnow 1961

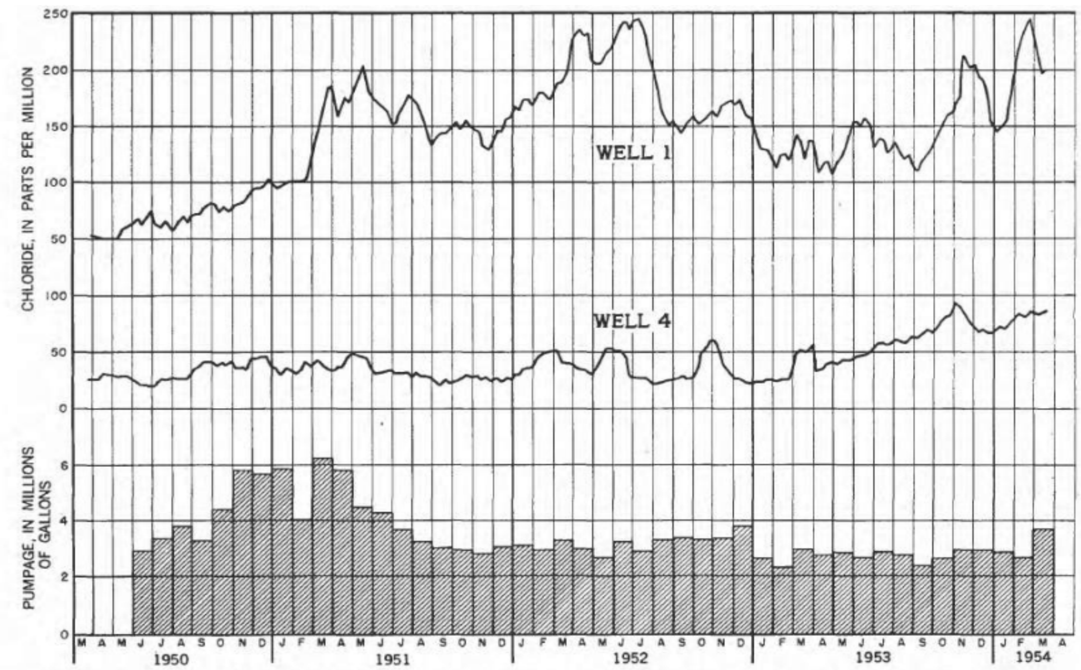


Figure 34. Five-week moving average of chloride content in wells 1 and 4, and combined abstraction from wells 1 and 2, 1950–1954. Source: Arnow 1961

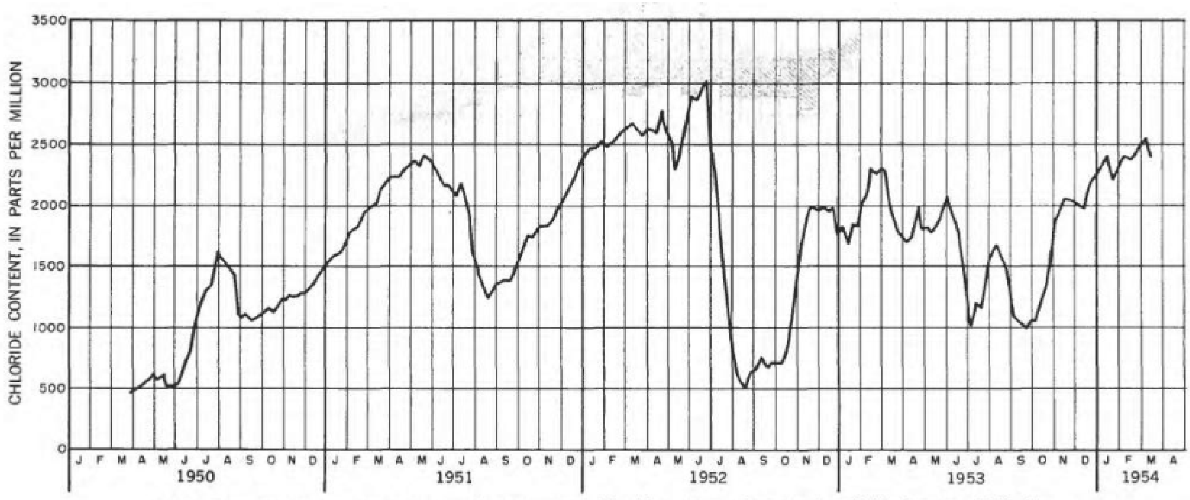


Figure 35. Five-week moving average of chloride content in well 10, 1950–1954.
Source: Arnow 1961

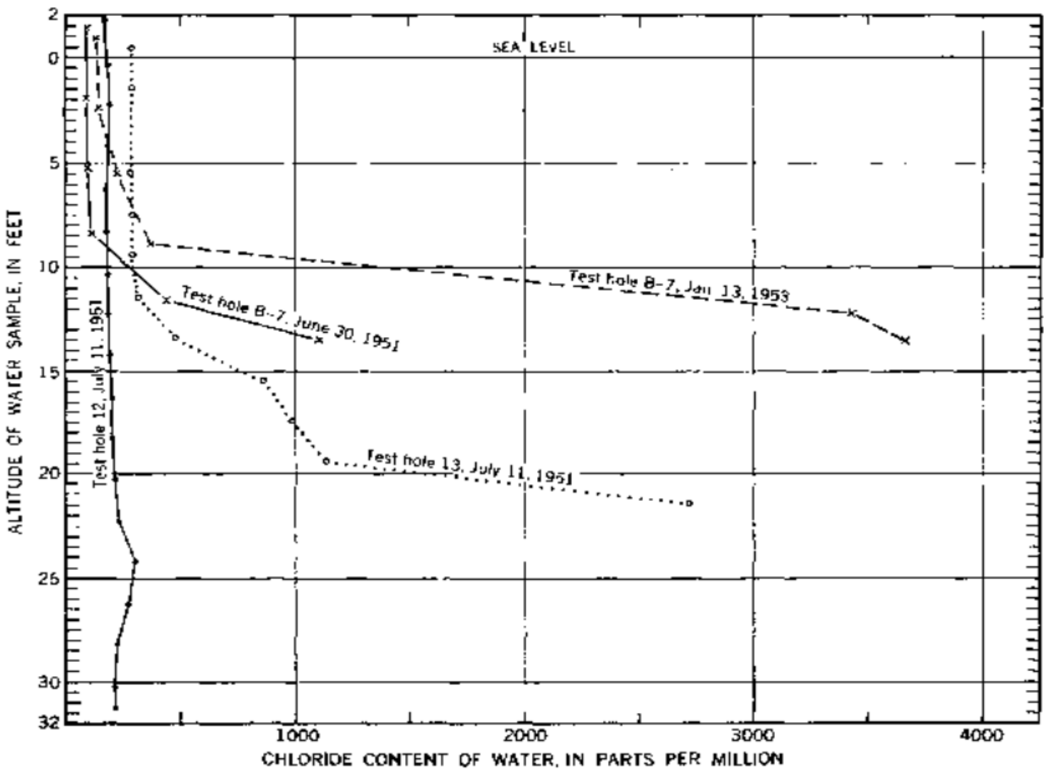


Figure 36. Vertical variation in chloride content of groundwater in test holes 12, 13 and B7.
Source: Arnow 1961

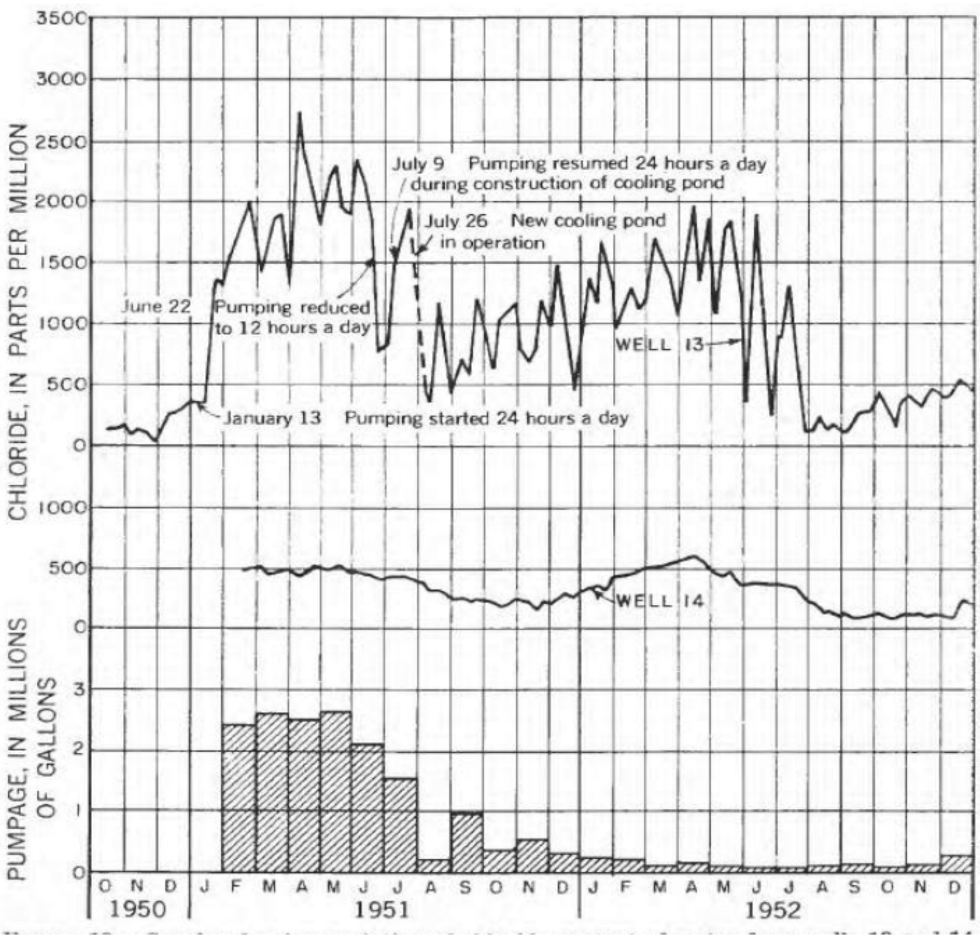


Figure 37. Variation of chloride content in wells 13 and 14, and abstraction from well 13, 1950–1952.
Source: Arnow 1961

Annex C – Chemical quality analysis of water samples

Quality Analysis ... ***Innovative Technologies***

Report No.:	**A22-08859-ReAssay**
Report Date:	**30-Dec-22**
Date Submitted:	**27-Jun-22**
Your Reference:	**MCAP-PALAU**

SPC
SPC-Private Mail Bag
Suva
Fiji

ATTN: Carlos M. Ordens

CERTIFICATE OF ANALYSIS

16 Water samples were submitted for analysis.

The following analytical package(s) were requested:		Testing Date:
6 Natural Waters (1-50)	QOP HYDROGEO (Natural Waters with low TDS - Hydrogeochemistry ICPMS)	2022-10-19 10:27:36
6-Acidify samples	Acidify	
6-Filter samples	Filter	
6B	QOP Anions, EPA 300.1 (Ion Chromatography)	2022-07-08 08:46:35
6C-Alkalinity	QOP Alkalinity	2022-07-11 12:53:34

REPORT **A22-08859-ReAssay**

This report may be reproduced without our consent. If only selected portions of the report are reproduced, permission must be obtained. If no instructions were given at time of sample submittal regarding excess material, it will be discarded within 90 days of this report. Our liability is limited solely to the analytical cost of these analyses. Test results are representative only of material submitted for analysis.

Notes:

Nitrate and nitrite results may be semi-quantitative when analyzed more than 48 hours after collection.

Note: This is a potentiometric method. Alkalinity (CaCO3) is the volume of 0.020 N H2SO4 acid required to reach a pH of 4.5. The components of the water requested for testing, alkalinity, carbonate and bicarbonate, are not stable when exposed to the atmosphere. Therefore, significant air space above samples impacts on data accuracy. If the temperature of the sample at the time of collection is different than that of the testing temperature, then a different CO2-HCO3-CO3 equilibrium and pH will result.

Values which exceed the upper limit should be analysed by Code 6 ICPOES/MS. Samples showing dilution factor had to be diluted for analysis due to high total dissolved solids content. This dilution is taken into account. Detection limits will be elevated on these samples by the dilution factor.

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LAB
LAB
Accrédité CCN
TM

LabID: 266

ACTIVATION LABORATORIES LTD.
41 Bittern Street, Ancaster, Ontario, Canada, L9G 4V5
TELEPHONE +905 648-9611 or +1.888.228.5227 FAX +1.905.648.9613
E-MAIL Ancaster@actlabs.com ACTLABS GROUP WEBSITE www.actlabs.com

Mark Vandergeest
Quality Control Coordinator

Results **Activation Laboratories Ltd.** **Report: A22-08859**

Analyte Symbol	F	Cl	NO2 (as N)	Br	NO3 (as N)	PO4 (as P)	SO4	Alk.	CO3(2-)	HCO3(-)	OH(-)	Na	Li	Be	Mg	Al	Si	K	Ca	Sc	Ti	V	Cr
Unit Symbol	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	mg/L CaCO3	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.01	0.03	0.01	0.03	0.01	0.02	0.03	2	1	1	1	5	1	0.1	2	2	200	30	700	1	0.1	0.1	0.5
Method Code	IC	IC	IC	IC	IC	IC	IC	TITR	TITR	TITR	TITR	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
1												2860	< 1	< 0.1	897	2	200	50	56000	< 1	< 0.1	< 0.1	0.8
2												117000	3	< 0.1	16900	3	1200	5160	84300	< 1	< 0.1	0.3	0.7
3												14600	< 1	< 0.1	364	12	< 200	580	3400	< 1	0.1	< 0.1	< 0.5
4												34900	< 1	< 0.1	5730	6	600	1360	91300	< 1	0.3	0.2	0.8
5												55900	1	< 0.1	9000	3	1100	1960	75100	< 1	< 0.1	0.6	0.5
6												6770000	110	< 5	791000	< 100	< 10000	262000	219000	< 50	< 5	< 5	< 30
7												25600	< 1	< 0.1	5400	3	< 200	1100	70200	< 1	< 0.1	< 0.1	< 0.5
8												22400	1	< 0.1	12300	8	400	2620	83100	< 1	< 0.1	0.3	< 0.5
1 ANIONS	0.03	5.96	< 0.02	< 0.06	0.06	0.04	0.86	163	< 1	163	< 1												
2 ANIONS	< 0.1	214	< 0.1	0.76	0.24	0.22	31.6	205	< 1	205	< 1												
3 ANIONS	< 0.01	18.0	< 0.01	< 0.03	0.05	< 0.02	0.76	20	< 1	20	< 1												
4 ANIONS	< 0.04	59.8	< 0.04	0.20	0.11	0.13	10.0	249	< 1	249	< 1												
5 ANIONS	0.10	82.8	< 0.04	0.33	0.06	0.25	14.1	219	< 1	219	< 1												
6 ANIONS	< 2	10600	< 2	32.3	< 2	< 3	1470	137	< 1	137	< 1												
7 ANIONS	0.10	41.1	< 0.03	0.14	0.07	0.11	5.28	200	< 1	200	< 1												
8 ANIONS	0.19	37.3	< 0.03	0.91	0.07	< 0.06	5.96	258	< 1	258	< 1												

Results **Activation Laboratories Ltd.** **Report: A22-08859**

Analyte Symbol	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Rb	Sr	Y	Zr	Nb	Mo	Ag	Cd	In	Sn	Sb	Te	Cs
Unit Symbol	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.1	10	0.005	0.3	0.2	0.5	0.01	0.01	0.03	0.2	0.005	0.04	0.003	0.01	0.005	0.1	0.2	0.01	0.001	0.1	0.01	0.1	0.001
Method Code	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
1	< 0.1	< 10	0.012	0.4	< 0.2	5.2	< 0.01	< 0.01	0.07	< 0.2	0.030	111	0.031	0.03	< 0.005	< 0.1	< 0.2	0.13	< 0.001	< 0.1	3.40	< 0.1	0.001
2	1.2	< 10	0.011	< 0.3	0.3	3.5	< 0.01	< 0.01	0.27	< 0.2	1.39	273	0.012	0.03	< 0.005	0.2	< 0.2	0.22	< 0.001	< 0.1	1.12	< 0.1	0.007
3	0.4	< 10	0.007	< 0.3	15.5	23.3	< 0.01	< 0.01	0.12	< 0.2	0.199	15.6	0.003	0.01	< 0.005	< 0.1	< 0.2	0.01	< 0.001	< 0.1	0.04	< 0.1	0.007
4	0.6	30	0.011	< 0.3	0.6	3.2	< 0.01	< 0.01	0.22	< 0.2	0.368	169	0.032	0.05	< 0.005	< 0.1	< 0.2	0.06	< 0.001	< 0.1	0.19	< 0.1	0.003
5	0.1	< 10	0.008	< 0.3	1.5	24.3	< 0.01	< 0.01	1.65	< 0.2	0.534	691	< 0.003	0.04	< 0.005	0.3	< 0.2	0.02	< 0.001	< 0.1	0.60	< 0.1	0.011
6	< 5	< 500	< 0.3	< 20	< 10	< 30	< 0.5	< 0.5	1.80	< 10	64.9	4300	< 0.1	1.17	< 0.3	< 5	< 10	< 0.5	< 0.05	< 5	< 0.5	< 5	0.150
7	0.6	< 10	0.012	0.5	0.7	4.9	< 0.01	< 0.01	0.15	< 0.2	0.330	372	0.005	0.08	< 0.005	< 0.1	< 0.2	0.02	< 0.001	< 0.1	0.15	< 0.1	0.004
8	0.5	< 10	0.018	< 0.3	0.4	4.1	< 0.01	< 0.01	0.38	< 0.2	0.758	846	0.007	0.11	< 0.005	< 0.1	< 0.2	0.01	< 0.001	< 0.1	0.03	< 0.1	0.007
1 ANIONS																							
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3 ANIONS																							
4 ANIONS																							
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6 ANIONS																							
7 ANIONS																							
8 ANIONS																							

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Results **Activation Laboratories Ltd.** **Report: A22-08859**

Analyte Symbol	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Hg	Tl	Pb	Bi	Th
Unit Symbol	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.02	0.2	0.001	0.01	0.3	0.001
Method Code	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
1	0.8	< 0.001	< 0.001	0.003	0.009	< 0.001	< 0.001	0.002	< 0.001	0.002	< 0.001	0.002	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.02	< 0.2	< 0.001	0.14	< 0.3	< 0.001
2	6.6	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.02	< 0.2	< 0.001	0.19	< 0.3	< 0.001
3	0.9	0.002	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.02	< 0.2	< 0.001	0.88	< 0.3	< 0.001
4	1.3	0.006	0.005	0.002	0.004	0.002	< 0.001	0.002	< 0.001	0.002	< 0.001	0.002	< 0.001	0.001	< 0.001	0.001	< 0.001	< 0.02	< 0.2	0.012	5.55	< 0.3	< 0.001
5	1.1	0.017	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.02	< 0.2	< 0.001	0.29	< 0.3	< 0.001
6	< 5	0.051	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 1	< 10	< 0.05	3.79	< 20	< 0.05
7	0.8	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001	< 0.02	< 0.2	< 0.001	0.05	< 0.3	< 0.001
8	1.8	0.004	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.003	< 0.001	< 0.02	< 0.2	< 0.001	0.55	< 0.3	< 0.001
1 ANIONS																							
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8 ANIONS																							

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Analyte Symbol	U
Unit Symbol	ug/L
Lower Limit	0.001
Method Code	ICP-MS
1	0.097
2	0.157
3	0.010
4	0.133
5	0.311
6	0.348
7	0.209
8	0.204
1 ANIONS	
2 ANIONS	
3 ANIONS	
4 ANIONS	
5 ANIONS	
6 ANIONS	
7 ANIONS	
8 ANIONS	

QC　　Activation Laboratories Ltd.　　Report: A22-08859

Analyte Symbol	F	Cl	NO2 (as N)	Br	NO3 (as N)	PO4 (as P)	SO4	Na	Li	Be	Mg	Al	Si	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni
Unit Symbol	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.01	0.03	0.01	0.03	0.01	0.02	0.03	5	1	0.1	2	2	200	30	700	1	0.1	0.1	0.5	0.1	10	0.005	0.3
Method Code	IC	IC	IC	IC	IC	IC	IC	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
IC Ref Std Meas	1.98	15.4	3.16	10.3	3.08	5.04	15.3																
IC Ref Std Cert	2.00	15.0	3.01	10.0200	3.01	5.01	15.0																
IC Ref Std Meas	1.82	15.4	3.16	10.3	3.09	5.05	15.3																
IC Ref Std Cert	2.00	15.0	3.01	10.0200	3.01	5.01	15.0																
IV-STOCK-1643 (ICP/MS) Meas								20800	16	13.0	7700	135		1940	31200			37.4	19.5	38.8	90	26.2	62.8
IV-STOCK-1643 (ICP/MS) Cert								21000	17.0	14.0	8000	142		2000	32000			38.0	20.0	39.0	98.0	27.0	62.0
8 Orig								22400	1	< 0.1	12300	10	400	2630	82900	< 1	< 0.1	0.3	< 0.5	0.6	10	0.018	< 0.3
8 Dup								22400	1	< 0.1	12300	6	400	2610	83300	< 1	< 0.1	0.3	< 0.5	0.4	< 10	0.017	< 0.3
6 ANIONS Orig	< 2	10600	< 2	31.6	< 2	< 3	1470																
6 ANIONS Dup	< 2	10600	< 2	33.1	< 2	< 3	1470																
Method Blank	< 0.01	< 0.03	< 0.01	< 0.03	< 0.01	< 0.02	< 0.03																
Method Blank	< 0.01	< 0.03	< 0.01	< 0.03	< 0.01	< 0.02	< 0.03																
Method Blank								< 5	< 1	< 0.1	< 2	< 2	< 200	< 30	< 700	< 1	< 0.1	< 0.1	< 0.5	< 0.1	< 10	< 0.005	< 0.3

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Analyte Symbol	Cu	Zn	Ga	Ge	As	Se	Rb	Sr	Y	Zr	Nb	Mo	Ag	Cd	In	Sn	Sb	Te	Cs	Ba	La	Ce	Pr
Unit Symbol	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.2	0.5	0.01	0.01	0.03	0.2	0.005	0.04	0.003	0.01	0.005	0.1	0.2	0.01	0.001	0.1	0.01	0.1	0.001	0.1	0.001	0.001	0.001
Method Code	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
IC Ref Std Meas																							
IC Ref Std Cert																							
IC Ref Std Meas																							
IC Ref Std Cert																							
IV-STOCK-1643 (ICP/MS) Meas	22.5	76.8			54.5	12.3	14.0	329				121	0.9	6.72			55.6	1.1		580			
IV-STOCK-1643 (ICP/MS) Cert	23.0	79.0			60.0	12.0	14.0	323				121	1.00	7.00			58.0	1.00		544			
8 Orig	0.4	4.7	0.01	< 0.01	0.37	0.2	0.766	849	0.009	0.10	< 0.005	< 0.1	< 0.2	0.01	< 0.001	< 0.1	0.03	< 0.1	0.006	1.9	0.005	< 0.001	0.001
8 Dup	0.3	3.5	< 0.01	< 0.01	0.39	< 0.2	0.750	843	0.005	0.11	< 0.005	< 0.1	< 0.2	0.01	< 0.001	< 0.1	0.02	< 0.1	0.008	1.8	0.003	< 0.001	< 0.001
6 ANIONS Orig																							
6 ANIONS Dup																							
Method Blank																							
Method Blank																							
Method Blank	< 0.2	< 0.5	< 0.01	< 0.01	< 0.03	< 0.2	< 0.005	< 0.04	< 0.003	< 0.01	< 0.005	< 0.1	< 0.2	< 0.01	< 0.001	< 0.1	< 0.01	< 0.1	< 0.001	< 0.1	< 0.001	< 0.001	< 0.001

QC **Activation Laboratories Ltd.** **Report: A22-08859**

Analyte Symbol	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Hg	Tl	Pb	Bi	Th	U
Unit Symbol	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L	ug/L
Lower Limit	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.02	0.2	0.001	0.01	0.3	0.001	0.001
Method Code	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
IC Ref Std Meas																				
IC Ref Std Cert																				
IC Ref Std Meas																				
IC Ref Std Cert																				
IV-STOCK-1643 (ICP/MS) Meas																6.76	19.2	13.9		
IV-STOCK-1643 (ICP/MS) Cert																7.00	20.0	14.0		
8 Orig	0.003	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.003	< 0.001	< 0.02	< 0.2	0.002	0.57	< 0.3	< 0.001	0.204
8 Dup	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002	< 0.001	< 0.02	< 0.2	< 0.001	0.53	< 0.3	< 0.001	0.204
6 ANIONS Orig																				
6 ANIONS Dup																				
Method Blank																				
Method Blank																				
Method Blank	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.02	< 0.2	< 0.001	< 0.01	< 0.3	< 0.001	< 0.001

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