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Provisional Hydrogeologic Data and Recommendations for Sustainable Groundwater Management, Tutuila American Samoa

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1.0 Introduction

Throughout the 20th century, groundwater management has progressed from being an unknown term to becoming a highly prioritized function of any society dependent on this resource. This is a result of a dramatic global increase in the ratio of groundwater usage to groundwater availability (Kalf and Woolley, 2005). Tutuila Island in American Samoa is almost completely dependent on groundwater resources and therefore faces very real consequences due to overexploitation of their limited water supplies.

Sustainable management of groundwater relies upon accurate quantification of supply, in the form of rainfall then recharge, and the factors that control aquifer storage and subsurface flow. Groundwater withdrawals must always remain as a fraction of groundwater recharge; the magnitude of which is dependent on local hydrogeologic conditions and the efficiency of well design. In an island setting, a significant portion of the freshwater recharge needs to escape development in order to provide a hydraulic buffer to keep seawater from encroaching on pumping wells. Additionally, we now understand the long-term economic benefits of maintaining the ecosystem services delivered by functioning riparian systems and coastal environments. Thus, it is prudent to consider how withdrawals may affect stream baseflow and submarine groundwater discharge, and to factor these effects into calculations of groundwater availability.

Quantification of groundwater availability has been approached in various ways. However, numerical models that integrate diverse sets of hydrologic observation data are generally considered to be the most reliable tools in estimating the effects of groundwater withdrawals. Regardless, the amount of groundwater that can be sustainably pumped is fundamentally dependent on the consequences a community is willing to accept. Any extraction of groundwater will result in some form of consequence, which may include water-table decline, saltwater intrusion, diminished flow to streams, and/or reduction of submarine groundwater discharge (SGD). Although the concept of sustainable groundwater yield has been discussed for over 100 years (Lee, 1915), there is still no universal formula for its calculation. Ultimately, sustainable yield criteria should be developed through a process involving input from local stakeholders. Numerical models can then be used to test the criteria with current or forecasted conditions based on future climate predictions, once sufficient calibration and parameterization data are collected.

This provisional compilation of groundwater information and management recommendations represents a status update on current progress toward the ultimate goal of determining rates of sustainable yield for Tutuila, American Samoa. Interim management recommendations based on these data are presented, and existing data gaps in the progress towards the goal of sustainability are identified. A majority of the information presented in this report is focused on preparation of the development of water budget and numerical groundwater models that can then be applied to assess sustainable yield scenarios, once a comprehensive process to determine these criteria is undertaken.

This report first presents a summary of the updated conceptual hydrogeological model in Section 2.0. The conceptual model is the foundation for future numerical modeling efforts. Existing calculations of recharge are summarized in Section 3.0, although these estimates are intended to be updated through future work. As of this writing, the University of Hawaii Water Resources Research Center (WRRC) is developing a water budget model with recently collected datasets to provide an up-to-date island-wide recharge coverage. In order to assess the sustainability of groundwater supplies in distinctive aquifer regions throughout Tutuila, all known well locations, available groundwater data, and historical water development information is compiled and organized by wellfield in Section 4.0 This information will be used in the future to parameterize numerical models, but in its current form can be qualitatively used to provide interim groundwater management recommendations for each wellfield (Section 4.0). Recommendations on maximizing hydrogeologic data collection during drilling and for performing aquifer tests are provided in Section 5.0. The report concludes with a list of existing data gaps in Section 6.0, which need to be addressed in order to develop sustainable yield estimates. It is hoped that future updates to this report will be used as preliminary decision support tools, and to encourage future work in developing more targeted tools for informing best-management practices for using Tutuila's limited groundwater resources.

1.1 Regional Setting

Tutuila is the third largest, and third oldest (1.5–1.0 Ma), island in the Samoan hot-spot island chain (Fig. 1.1) where two phases of volcanism, —a shield building phase and a rejuvenated phase — created Tutuila and the islands of Western Samoa. Due to this geologic history, Tutuila consists of two distinct regions: a highly-permeable rejuvenated-phase lava delta, (the Tafuna-Leone Plain), which is favorable for groundwater development but is susceptible to anthropogenic contamination; and a mountainous assemblage of lower-permeability Pleistocene age shield volcanoes that make up the bulk of the island and are generally less-favorable for groundwater development (Stearns, 1944). While some water development has occurred in the Pleistocene Shields, existing wells primarily tap basal groundwater and are located near coastal areas. Very little groundwater exploration has occurred in higher-elevation areas or in the island's most westerly region, the Taputapu Shield. However, some recently compiled information suggests that the Taputapu Shield region may be more favorable to water development than the other Pleistocene Shields.

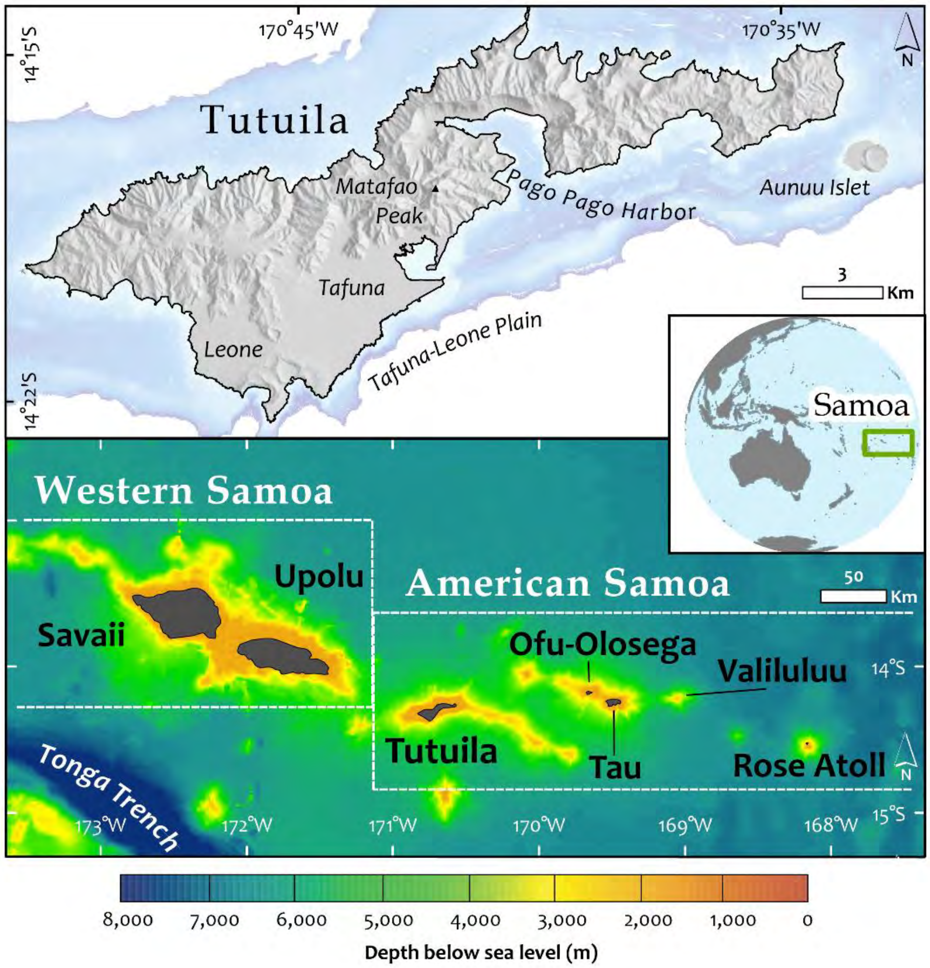
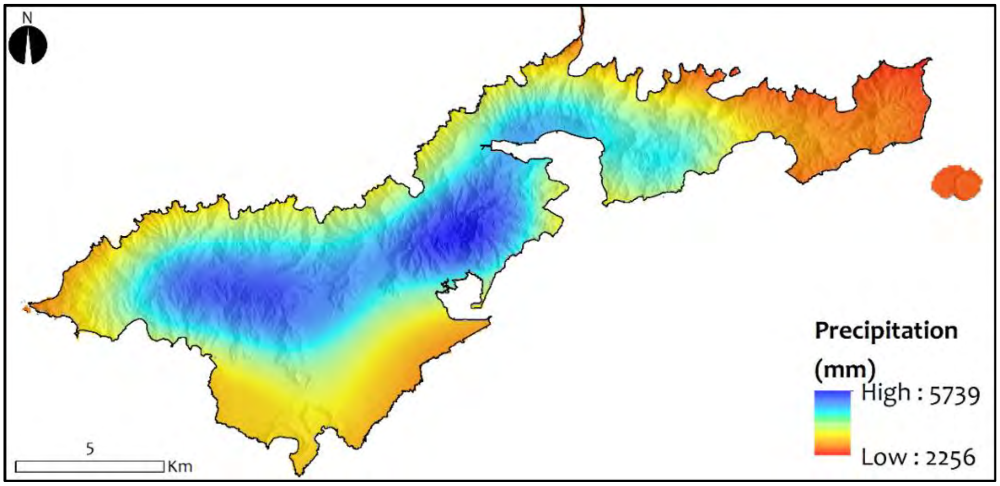


Figure 1.1 Map of Tutuila island (top) and bathymetric map of Samaoan archipelago (bottom). Divisions between Western and American Samoa are drawn to show political jurisdictions and do not constitute actual territorial boundaries. Regional location map shown in center-right inset.

Tutuila lies within the South Pacific Convergence Zone, thus there is abundant rainfall year round. The region experiences some seasonality in precipitation, with a wet season and a relatively less-wet season. Monthly average rainfalls in November to March are roughly twice that of May to August's still significant rainfall amounts. Rainfall varies considerably with location and elevation (Fig. 1.2) and ranges between 1,800 to 5,000 mm/yr. (70–200 in./yr.) (NWS, 2000). Strong tropical storms and hurricanes also influence the region about once every other year, and an average of 25 to 30 significant thunderstorms affect the island annually (Kennedy et al., 1987). Recharge estimates for the island generally follow rainfall patterns, whereas the western portion of Tutuila receives substantially more recharge than the eastern portion (Eyre and Walker, 1991; ASPA 2013).



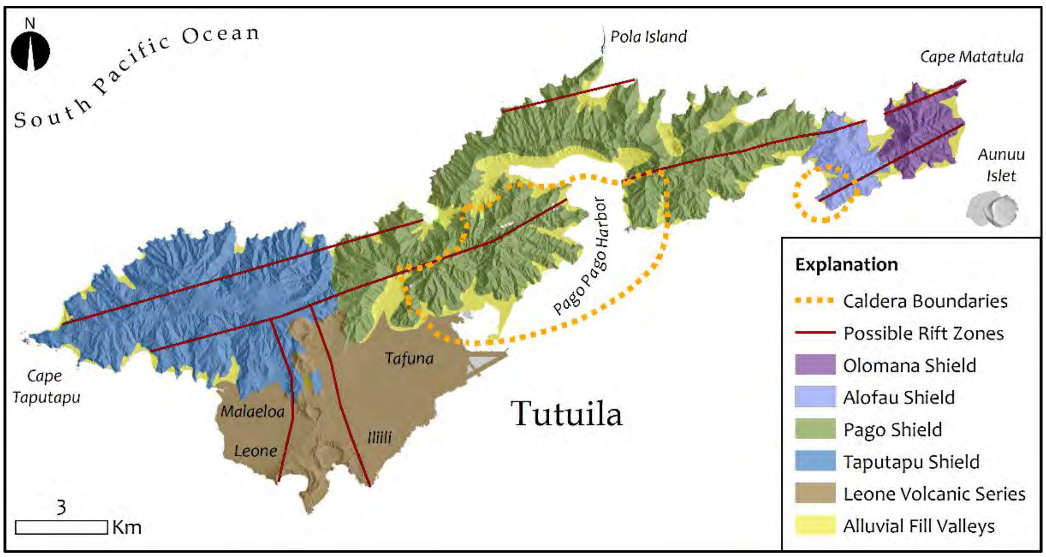
Data from Daly et al., 2006.

Figure 1.2. Average annual precipitation interpolated from climate data recorded from 1971 to 2000.

2.0 Conceptual Hydrogeologic Model of Groundwater Occurrence

On Tutuila and other oceanic islands, the primary groundwater resource is contained in a lens-shaped body near sea level, within saturated rock. This basal freshwater lens is supported by underlying seawater due to the density contrast between fresh water and salt water. The transition between fresh and salt water is marked by a zone of brackish water (the transition zone) that can vary in thickness and depth. A second groundwater resource described in basaltic island settings is high-level groundwater, which is distinctive from basal-lens groundwater as it is supported by low-permeability features, such as dikes, perching layers, or low-conductivity country rock and is often disconnected from underlying seawater. High-level groudwater has been observed and developed for use on other islands, such as the Hawaiian Islands. However, on Tutuila no existing wells have definitively tapped high-level groundwater and its occurrence remains generally unconstrained. Examination of high-level stream and spring flows throughout the island indicates locations where high-level resources might be found (Wong, 1996, Shuler et al. 2014). It is likely that multiple types of groundwater bodies such as perched water, dike-impounded water, and basal water exist and flow within Tutuila's Pleistocene rocks.

Observations of Tutuila's geologic structure from hard-rock outcrops (Eyre and Walker, 1991; Knight Enterprises Inc., 2014) and borehole logs (Bently, 1975; Geologica Geothermal Group, Inc., 2016) show a heterogeneous distribution of pahoehoe and a'a lava flows with associated rubble or clinker layers, as well as small and large pockets of talus breccia, debris flow material, cinders, or intrusive bodies. This complex geology results in a heterogeneous permeability fabric, the specifics of which are difficult to predict. On small scales, it may be reasonable to interpret the high degree of heterogeneity within Tutuila's subsurface as a bi-modal system with higher-conductivity water bearing zones or 'pockets' interspersed within an arrangement of fairly prevalent lower-conductivity barriers. While this description is academically interesting, it is not very useful as limitations in subsurface data density, and distribution make locations of these features generally unknown. On regional scales, it is probably sufficient to characterize these individual features within the realm of pore-scale heterogeneity and to assume that at this scale Darcy's equation is valid, meaning the island's aquifers might be approximated as a kind of grand scale porous media. Under this assumption, regional scale groundwater transport would be primarily controlled by the connectivity between water bearing pockets. It is not unreasonable to suppose this connectivity would vary significantly between hydrogeologic units due to differing geologic histories; and indeed, different units on Tutuila are observed to have very different water bearing properties, with the starkest contrast seen between the younger Tafuna-Leone Plain and the older Pleistocene Shields (Fig. 2.1).



Modified from Stearns (1941) and Knight Enterprises Inc. (2014).

Figure 2.1. Simplified geology of Tutuila showing volcanic shields and inferred volcanic structures such as rift-zones and caldera boundaries.

Various conceptual hydrogeologic models have been proposed to explain the occurrence of groundwaters on Tutuila. These models generally fall into two categories: Hawaiian and Canary Islands models (Join et al., 2016) (Fig. 2.2). The Hawaiian Model describes groundwater occurrence in two distinct and hydraulically disconnected systems: (1) basal water, and (2) high-level, water which is generally envisioned to be dike impounded. On the other hand, the Canary Islands Model, also termed a 'fully saturated vertically extensive freshwater body' model (Izuka and Gingerich, 2003) describes a single hydraulically connected basal groundwater body extending from sea level and supported to high elevations by low-conductivity aquifer material. The average hydraulic conductivity distribution in this model decreases with depth, which is justified by an assumed loss of porosity due to compaction and secondary mineralization, as well as increased age and weathering with depth.

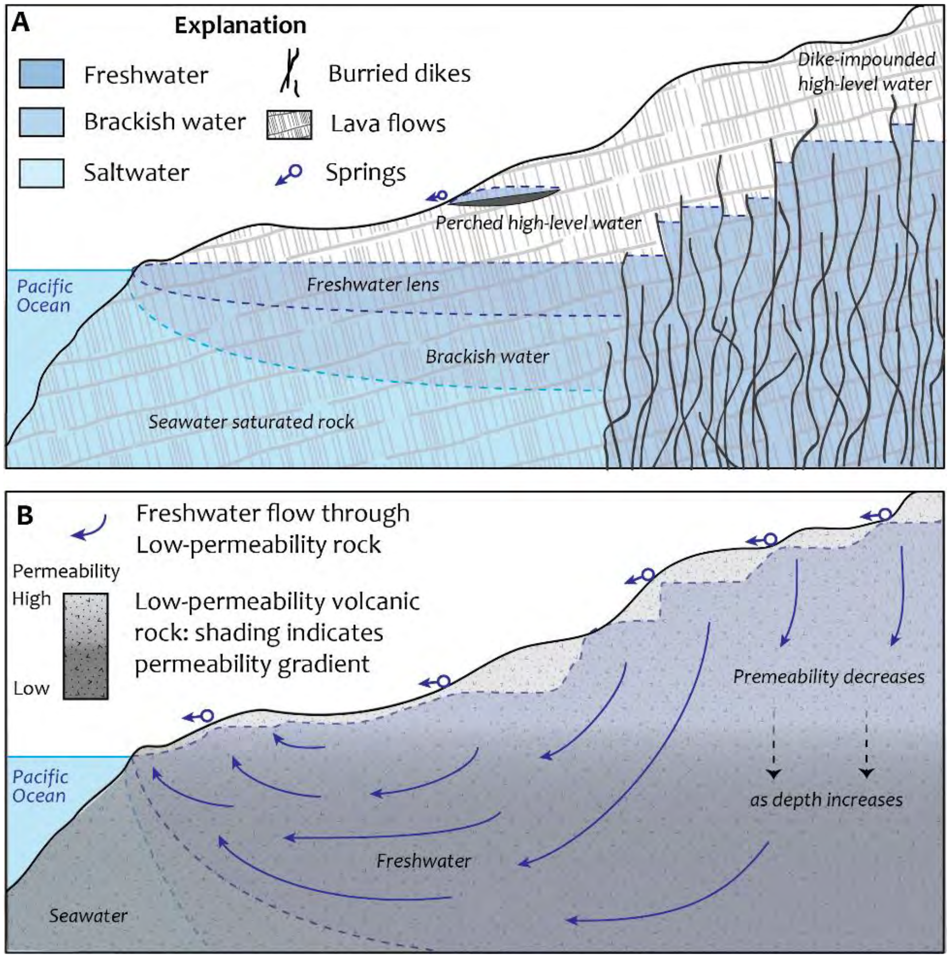
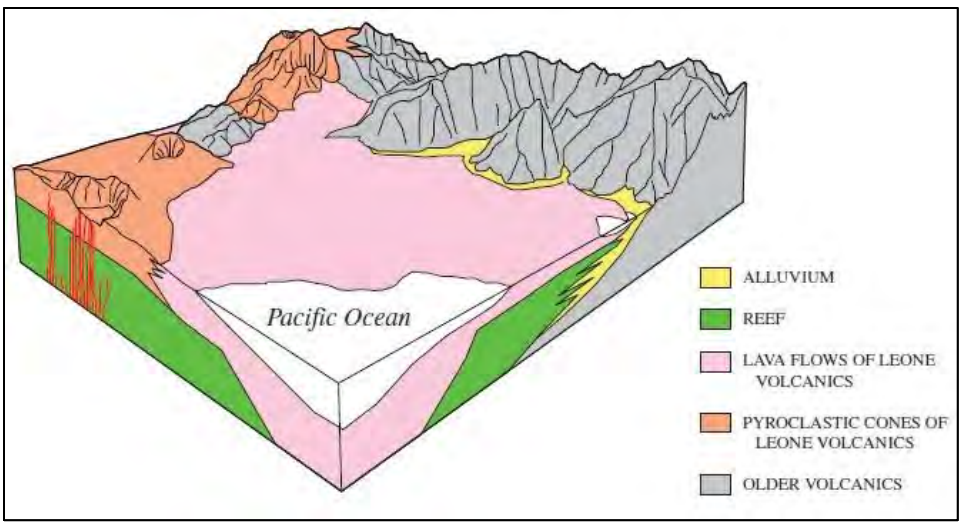


Figure 2.2: Two different conceptual models of groundwater occurrence on Tutuila have been previously proposed: (A) the Hawaiian Model (Lau and Mink, 2006) consisting of two disconnected groundwater systems (high-level and basal) and (B) the Canary Island Model (Join et al., 2016) where both elevated groundwater and basal groundwater are hydraulically connected as a single system contained in low-permeability rock.

Neither of these models have been definitively invoked to describe groundwater occurrence on Tutuila. However, they are not necessarily incompatible. Taken in perspective, a conceptual model is a simplification of reality, used to inform predictions or parameterization of numerical models. Real world subsurface conditions that control groundwater movement and storage on Tutuila are heterogeneous and poorly constrained, thus it is possible and even likely, that different regions with distinct geologic histories may be more effectively parameterized on a regional scale by different conceptual models. This emphasizes the importance of interpreting data from different aquifers or hydrogeologic units on an individual basis, as attempted in this report. Therefore, exploratory drilling or additional subsurface geophysical exploration in the island's mountainous interior would help to constrain the occurrence of Tutuila's high-level water, and fill a significant data gap in our understanding of subsurface hydrologic conditions in Tutuila's priority recharge areas.

2.1 Hydrogeologic Units

Izuka et al. (2007) delineated seven hydrologic units for Western Tutuila, based on what is known of the island's geologic construction (Fig. 2.3). The Taputapu and Pago Shields were consolidated into one low-conductivity unit—the Pleistocene Older-Volcanic shields—as lack of data precluded their differentiation into separate units. The Leone Volcanics were separated into the more hydrologically conductive Tafuna Unit on the eastern side of the plain and a less conductive Leone Unit on the western side. The rift zone running through the middle of the plain was classified as a Pyroclastic Unit with simulated dikes, and a wedge shaped Reef Unit was located between the Leone Units and the Pleistocene Older-Volcanic Unit. The boundaries and characteristics of these units comprise the foundation of the hydrogeological conceptual model of Tutuila. However, new geologic and hydrogeologic data may provide new evidence for updates to this conceptual model, such as considering each shield in the lower-conductivity unit separately.



Reprinted from Izuka et al. 2007 with permission.

Figure 2.3. Hydrogeological conceptual model of the Tafuna-Leone Plain region showing distinctive hydrological units.

2.1.1. Groundwater Occurrence in Pleistocene Volcanic Shields

The Pago, Taputapu, Alofau, and Olomoana Shields make up what has been previously referred to as the Older-Volcanic Hydrogeologic Unit, the Pleistocene Unit, or the Low-Permeability Unit (Eyre, 1994; Izuka et al., 2007). These shields are constructed of gently dipping a'a lava flows organized as an alternating sequence of more-permeable rubble zones and less-permeable massive sections. This sequence is complicated by the presence of cross-cutting dikes, interbedded pyroclastic sections, clay rich paleohorizons, and products of mass wasting or caldera collapse that all serve to disrupt the continuity of the lava-flow structures. This complex geology results in a heterogeneous permeability fabric where it is likely that variably sized compartments of high-permeability rubble or cinders sit adjacent to beds or tongues of massive lavas and other low-permeability features that act as perching layers or barriers to water movement.

Although previous workers have classified Tutuila's older shields as a single hydrogeologic unit with uniform properties, a number of recent observations suggest that there may be cause to subdivide this region into different hydrogeologic units. Within the Pago Shield there are two distinctive geological units, the Inner-Caldera and the Outer-Caldera. The Outer-Caldera Unit contains thin and thickly bedded a'a lava flows, numerous dikes, vitric tuff beds, and potentially buried cinder beds; whereas the Inner-Caldera Unit is composed primarily of ponded basalts, trachyte plugs and flows, as well as a relatively high fraction of volcaniclastics, brecias, and other products of mass wasting (Sterns, 1944; Knight Enterprises Inc., 2014). Both of these units contain numerous dikes and are thought to impound small quantities of high-level water behind these barriers (Keating, 1992). In general, the composition and structure of the Outer-Caldera Unit would suggest that it should have better water transmitting properties than the Inner-Caldera Unit (Shuler et al., 2014). However, the available hydrological data does not show a clear difference in the performance of wells drilled in either unit, which is probably due to local scale heterogeneities.

Although there has been little groundwater development, and thus few available data points to assess groundwater development in the Taputapu Shield region, measured aquifer parameters and geologic information suggests that this area may have higher water development potential than the island's other shields. This hypothesis is supported by observations of lower intrusive density (Machesky, 1965; Walker and Eyre, 1995) and recent aquifer tests showing specific capacities and hydraulic conductivities that are significantly higher than those measured in the other shields (Shuler, unpublished data, 2014).

2.1.2 Perched or Dike Impounded Aquifer at Aoloau

The 4.1 km^2 summit area at Aoloau is blanketed by layers of high-permeability Holocene-age cinders. The permeable nature of this formation is shown by observations of coarse cinder outcrops, domed topography, and a lack of runoff despite a high average rainfall (5,250 mm/yr). Aquitards within and below this unit are thought to consist of beds of fine ash, thermally welded tuff, lava flows, or paleo-horizons on the surface of the Taputapu Shield (Eyre and Walker, 1991). A known reservoir of elevated water has already been developed in the village of Aasu, and its large size makes it unique on Tutuila. The perched reservoir is inferred to be the source of multiple perennial springs that discharge from the margins of the subdued topography that define the unit. These springs are well documented and probably served as a source of village water prior to groundwater development. Geophysical cross sections from geothermal exploration efforts (Geologica Geothermal Group, Inc., 2014) indicate the potential for shallow perched aquifers of similar occurrence in both the eastern (Aoloau Village) and the western (undeveloped) portions of the cinder cap. The thickness of the cinder is likely to be variable and dependent on the underlying topography of the Taputapu Shield and the distance to source vents. A driller's log from Aasu Well 127, in the eastern portion of the unit, indicates the thickness of cinder deposits to be greater than

50 m (Eyre and Walker, 1991).

Approximately six million gallons per day of water recharges this area (Eyre and Walker, 1991). Since the subsurface geology of the Taputapu Shield underneath this unit has not been explored, it is also possible that the Aoloau aquifer is supported by dike-impounded groundwater from within the shield below. Further groundwater exploration in this unit will help to constrain the quality and the quantity of the available resource.

2.1.3 Groundwater Occurrence in the Tafuna-Leone Plain

The young aquifers of the Tafuna-Leone Plain region are primarily composed of pahoehoe and a‘a lava flows, with localized interfingerings of ash beds and/or sedimentary carbonate layers. These materials sit above the weathered edifice of the Taputapu Shield, though the degree of water movement between the Leone and Taputapu Units is unknown. Due to their young age and lack of weathering, the Leone Volcanic aquifers are generally, on average, extremely hydraulically conductive and contain a thin basal lens. The region has a high secondary porosity due to prevalent fractures, clinker zones, and lava tubes —which make it favorable for groundwater development (Bentley 1975). However, these features also make the Tafuna-Leone Plain susceptible to groundwater contamination (Kennedy et al., 1987). Currently, 24 wells in the plain region produce about 70% of the island’s municipal water (RCWW, 2002). Wells in this area are generally designed to skim the top of the unconfined basal lens that floats, due to its lower density, on salt water within saturated rock. Because the plain’s geologic units are so conductive, the water table in the region is generally about 1 to 3 m above sea level (Izuka, 1999). The unsaturated zone above the water table is typically less than 35 m deep, allowing only minimal travel time for contaminant attenuation. The plain has three sub-regions or hydrogeological units: (1) the Tafuna Plain, (2) the Leone Plain, and (3) the Leone Pyroclastics. Each of these units probably has a large degree of heterogeneity, as shown by the quickly alternating sequences of variably textured lavas and different types of pyroclastic materials in cores from boreholes. Although the materials in both boreholes are still predominantly basaltic lava, visual inspection of the deep borehole cores from each side of the plain (Geologica Geothermal Group, Inc. 2016) shows that the Leone side generally has a higher proportion of volcanoclastics (ash and cinder) than the Tafuna side.

The Tafuna-Leone Plain is uniquely situated below the steeper slopes of the Taputapu Shield, which provides additional water from mountain front recharge (MFR). Streams flowing off the flanks of the less permeable Taputapu rocks quickly infiltrate and add to the area’s recharge total (See Section 3.0). This additional recharge likely acts to increase the thickness of the basal lens in this area, as well as providing an added water supply for the lens downgradient from the MFR zone (Fig. 2.4) . The elevated lens thickness has the potential to act as a freshwater fence, not only reducing the potential for saltwater upconing in the MFR zone, but upgradient as well in areas like Malaeimi Valley.

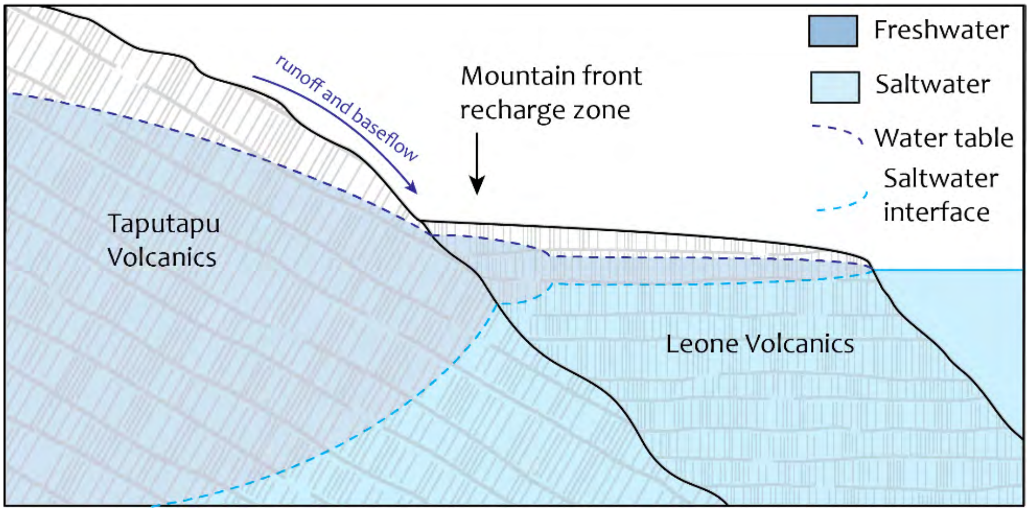


Figure 2.4: Diagram showing possible interaction of the basal lens in the mountain front recharge zone at the margin of the less-permeable Taputapu Shield and the more-permeable Tafuna-Leone Plain.

The hydrogeology in the MFR zone is further complicated by subsurface geologic structures, where more permeable alluvium and Leone Volcanics lie unconformably on the eroded and probably less permeable rocks of the Taputapu Shield. This arrangement may create a condition that Meinzer (1923) describes as a semi-perched groundwater system, where an elevated water table is observed, but is still physically connected through a continuous zone of saturation to the main (basal) water body. This system is theoretically distinct from basal groundwater, as semi-perched water is at least partially supported by underlying rock, as opposed to underlying seawater. While this condition would not necessarily serve to increase the below-sea-level thickness of the basal lens, it may decrease the hydraulic connectivity to saltwater and reduce the chances of groundwater salinization. With these factors in mind, further exploration and groundwater development in the MFR zone may be beneficial.

3.0 Recharge Calculations

Tutuila's drinking water supply is primarily derived from groundwater, which is fed by the infiltration of rainfall into the land. The water that reaches the saturated zone is termed recharge. In general, the spatial distribution of recharge on Tutuila seems to follow a similar pattern as rainfall, where higher elevations contribute more water to the subsurface than lower elevations. Existing recharge estimates indicate that the eastern part of the island receives significantly lower amounts of recharge than the west.

Most precipitation falling on the Tafuna-Leone Plain infiltrates before it has a chance to runoff due to the high permeability of the Holocene-age lavas. There are few well developed stream channels on the plain and no perennial streams (Izuka et al., 2007). In contrast, the older volcanic shields that lie above the plain have much lower permeabilities and contain perennial streams and springs that drain to the sea or to the Tafuna-Leone Plain. The recharge on the Tafuna-Leone Plain is enhanced by the process of MFR, where runoff from mountain streams infiltrates into the streambed once water flows from less to more permeable geologic formations. This process is analogous to the MFR frequently observed in arid climates (Wilson and Guan, 2004). The actual point of infiltration of each stream varies depending on stream discharge rate and occurs within an MFR zone (Perreault, 2010). This process is most significant in the Tafuna-Leone Plain where low-permeability rocks are positioned directly above and adjacent to high-permeability rocks, although it has also been observed to a limited extent in alluvial-fill valleys.

Recharge is usually calculated with water-balance/budget models, which can incorporate varying degrees of detail. These models generally calculate groundwater recharge as a residual term after other water budget components are subtracted from a measured amount of precipitation (Fig. 3.1). In the most simplified model, Thornthwaite and Mather (1955) stipulated that:

$$\text{RECHARGE} = \text{RAINFALL} - \text{RUNOFF} - \text{ACTUAL EVAPOTRANSPIRATION}$$

Although simple in theory, some site specific complications add uncertainty to recharge estimates. During periods when rainfall and soil moisture storage are not sufficient to supply the demands of plants, actual evapotranspiration (***AET***) is less than potential evapotranspiration (***PET)***. However, on Tutuila, Perreault (2010) determined that ***AET*** is generally about 92% of ***PET***. Of the recharge estimates presented below, only the Izuka et al. (2007) model accounts for the difference between ***AET*** and ***PET***. Tutuila has over 140 perennial streams, therefore runoff cannot be directly constrained for every basin. Thus the estimates presented below use a runoff to rainfall ratio, based on measurements in gaged basins to estimate runoff on ungauged streams. Other factors that add uncertainty to groundwater recharge estimates on Tutuila are strong spatial and temporal gradients in precipitation, runoff, or evapotranspiration. In addition, anthropogenic activities such as subsurface additions from on-site wastewater disposal systems or leaky water delivery lines likely change the distribution of groundwater recharge, yet these effects are difficult to constrain.

3.1 Existing Recharge Estimates

Because of data limitations, the Tutuila recharge estimates presented here consider only basic hydrologic variables, which include precipitation, evapotranspiration, MFR, and runoff. Despite this limitation, it is still useful to consider the three existing recharge estimates developed and detailed in Eyre and Walker (1991), Izuka et al. (2007), and ASPA (2013). Methods of calculation and input datasets used for these estimates vary between each study, and are described in the respective publications. The Izuka et al. (2007) coverage was focused only on the Tafuna-Leone Plain region and thus Eastern Tutuila was excluded from the result. The American Samoa Power Agency calculation (ASPA 2013) does not consider the process of MFR. Recharge calculations made by Izuka et al. (2007) and ASPA (2013) are given in the form of recharge depth over an area in vector polygon and raster formats, respectively. In contrast Eyre and Walker (1991) calculated recharge with a basin total volume approach. For comparison, each estimate was converted to a region standardized format based on the boundaries of twelve geographic regions defined by the surface expressions of inferred subsurface geologic features, such as rift zones or dense trachyte plugs. This was done by calculating recharge volume in cells, polygons, or basins; intersecting these units with regional boundaries; and summing the result for each geographic region. This produced maps of total regional recharge in million gallons per day (Mgal/d) for each of the three estimates (Fig. 3.2).

The use of this method does not imply groundwater availability within each region is limited to the calculated recharge amount. Groundwater flow is not necessarily constrained by topographic boundaries, and wells on Tutuila might draw water from other regions or topographic basins. The total amount of sustainably developable groundwater on any island is fundamentally limited by the rate of groundwater recharge available to developable areas. Total groundwater withdrawals must always remain as a fraction of total recharge to maintain a buffer against seawater encroachment. The magnitude of this fraction will be primarily dependent on local hydrogeologic conditions.

Presently, a new hydrological monitoring network is currently collecting updated data, which fills a significant need and will be used in water budget modeling designed to constrain groundwater recharge at a high temporal and spatial resolution. While this is currently a data gap, it is anticipated to be filled soon.

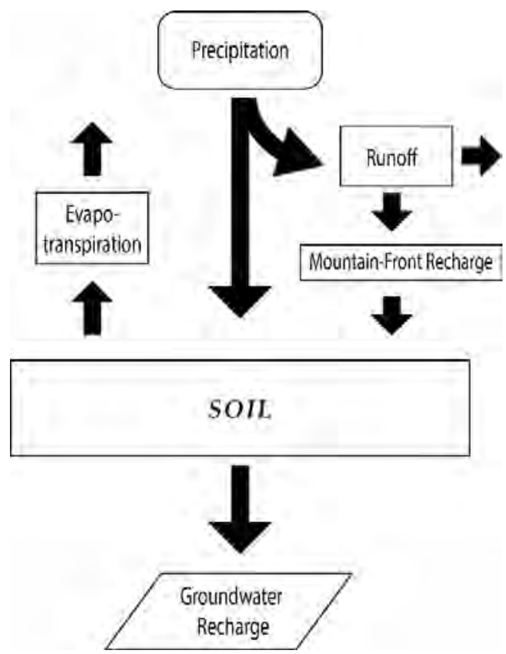
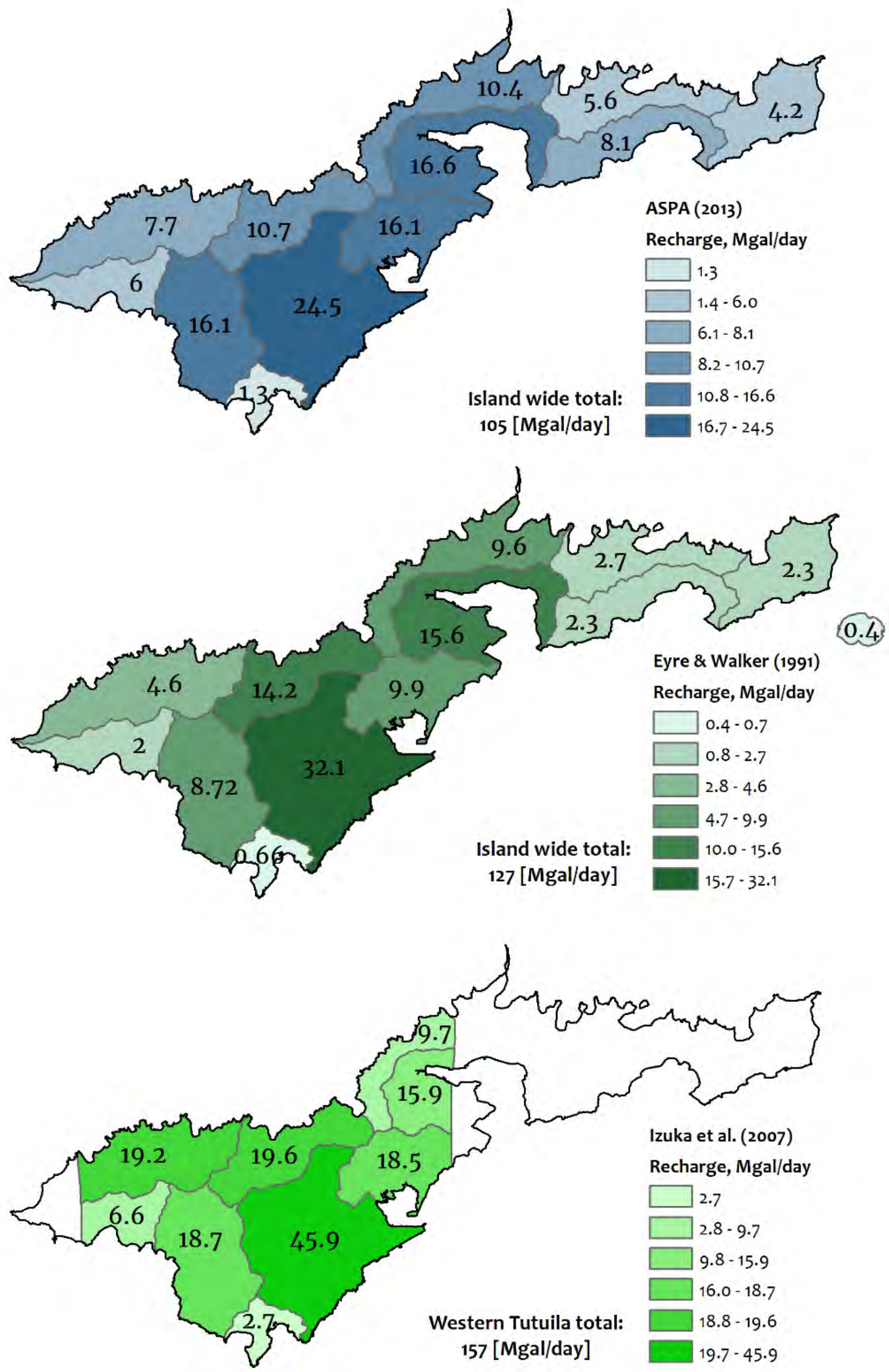


Figure 3.1. Diagram illustrating factors used to calculate water balance for Tutuila.



Sources: Eyre and Walker (1991), Izuka et al. (2007), and ASPA (2013).
Note: Izuka et al. did not calculate recharge for eastern or far western Tutuila.

Figure 3.2. Comparison of Tutuila's recharge estimates by ASPA (2013), Eyre and Walker (1991), and Izuka et al. (2007). Each estimate was converted to a region-standardized format.

4.0 Consolidated Well Data

Data obtained from existing wells is a key resource for understanding the condition of aquifers and assessing future groundwater development potential. This section (4.0) organizes available well data by wellfields (Fig. 4.1), that are generally defined by existing groupings of wells, topographic basins, geologic units, or geographic regions throughout Tutuila. Three subsections group these wellfields based on a qualitative determination of current aquifer conditions and the perceived viability of future groundwater development. The first subsection presents data for areas with a minimal amount of groundwater development in comparison to their likely potential for groundwater development capacity, as well as areas where data limitations preclude a confident assessment of capacity. The second subsection includes areas where moderate to extensive groundwater resources are currently developed, yet aquifer data does not show trends suggesting withdrawal rates are unsustainable. The third subsection includes heavily developed wellfields with water level and chloride trends suggesting groundwater withdrawals may already exceed the aquifer's capacity to sustainably supply water.

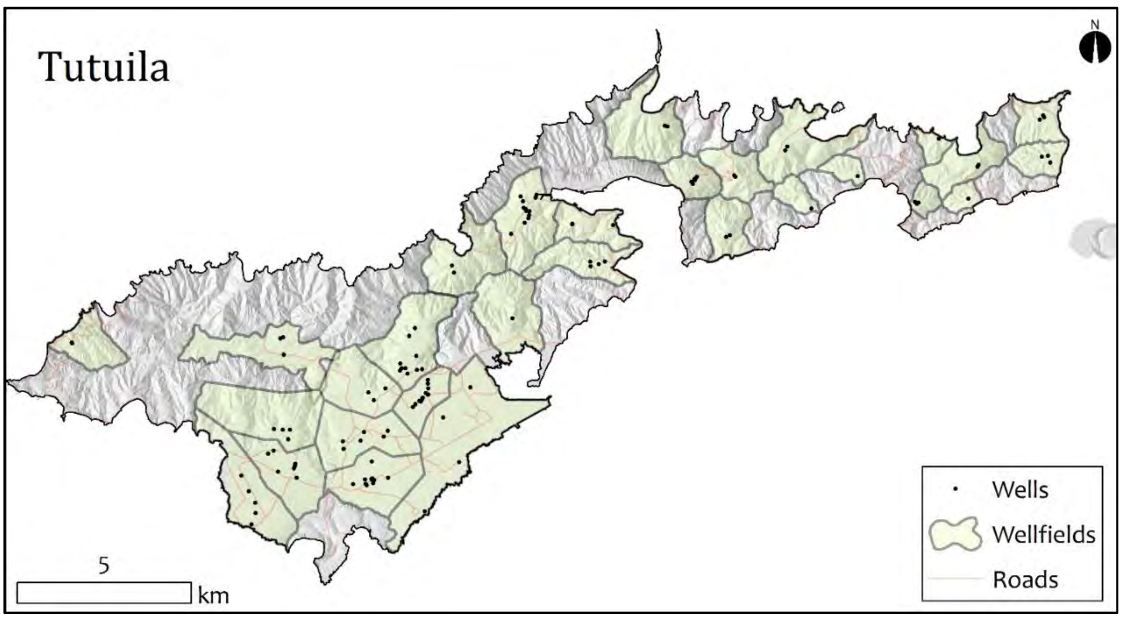


Figure 4.1: Map of existing wellfield boundaries on Tutuila

Aquifer data included in this section are intended to inform a dialog about past and present groundwater conditions on Tutuila. Additionally, assessment of temporal trends may be useful for understanding the current trajectory that may occur for future groundwater resources, should controlling factors remain as they are. For example, measured chloride concentrations in many of the island's wells have been increasing for the last three years. The sustainability of Tutuila's groundwater supply is limited by the effects of saltwater upconing and intrusion, which may be a warning sign that the rate of groundwater extraction in these areas exceeds the sustainable supply. However, these trends are not in themselves predictive of future conditions as numerous factors may affect their magnitude and direction.

Currently available groundwater datasets include: well locations and elevations, pumping rates, pre-production and pumping water levels, chloride (Cl^-) concentrations, specific capacity values, and transmissivity (***T***) and hydraulic conductivity (***K***) values from aquifer tests. Although not all wells have records available for each of these parameters, every effort was made to compile as much of this information from as many sources as possible. These sources include published reports, values obtained through fieldwork, and unpublished datasets or reports. Because multiple sources were compiled to develop these datasets, some wells have multiple values from different sources for a given parameter. The values presented here were selected based on the trustworthiness and completeness of the available sources and a source-preference ranking for each parameter is described below.

Chloride concentrations reported here are from the following sources in the preferred order of (1) average Cl- from ASPA records spanning January 2015 to April 2017, (2) discrete Cl- measurements as directly sampled by WRRC from 2013 to 2017, and (3) discrete Cl- measurements as reported by Bentley (1975). An existing data gap to fill is obtaining higher resolution Cl^- information from production wells. Aquifer test values, such as specific capacity, ***K,*** and ***T***, are reported from the following sources in the preferred order of: (1) WRRC recovery tests, (2) values of ***K*** derived by Zangar's equation from Eyre and Walker (1991), (3) values of ***T*** reported by Bentley (1975), and (4) values of ***K*** that were calculated with ***T*** values from Bentley and records of the well's open interval thickness. Some existing wells have no documented aquifer test information and this is a data gap that could be filled through performing pumping and recovery tests in the future.

Water levels can vary dramatically through time and during different hydrologic conditions. Documented pre-development water levels are here reported from the following sources in the preferred order of: (1) actual drillers logs or pre-development pump test reports, (2) water levels reported by Bentley (1975), and (3) drilling water levels from Eyre and Walker (1991, 1993). Pumping water levels, are distinct from static water levels as they are recorded while a well is operational. These water levels are subject to both aquifer and well losses. Pumping water levels are here reported as an average of monthly ASPA data spanning the period January 2008 to September 2013. When water level records for wells were not available in the ASPA files, pumping water levels from the observed discrete production drawdown measurements taken during WRRC recovery tests done in 2014 are reported.

Water level elevations are reported relative to mean sea level and are calculated as the difference of the depth to water measurement and the well's measuring point elevation. Unknown accuracy of measuring point elevations adds uncertainty to the water level elevation, so every attempt was made to determine the most accurate measuring point elevations. The preferred order of the sources for the measuring point elevations are (1) ASPA wellhead survey information, (2), land-surface altitude reported in Bentley (1975), (3) well elevations reported by Eyre and Walker (1991, 1993), and (4) when documented elevations were not available elevations were taken from a 1 m resolution digital elevation mode.

Well ID numbers on Tutuila have been documented in two different systems. The USGS developed a well ID system that consists of a four digit map quadrant identifier with a dash separating a separate well number (e.g., 1642-01). ASPA well ID numbers are one to three digit numeric identifiers, (e.g. Well 179) and do not have any relation to USGS well IDs. In general, older wells have only USGS IDs, newer wells only have an ASPA ID number, and many wells have both. Data tables are indexed by both ID's where available.

As mentioned earlier, recharge is the source of all groundwater on the island, thus recharge rate is a fundamental control on groundwater availability. Determining the ratio of recharge rate to extraction rate (referred to here as the use ratio) in each region can be a helpful metric for assessing the relative development potential of different regions throughout the island. Extraction is measured as a volume of water per time, while recharge is generally calculated as a volume per unit area per time. Therefore, to determine the amount of recharge available for extraction, a boundary delineating the area that supplies groundwater to the region's wells must be specified. Since aquifer boundaries have not been conclusively delineated, the island was partitioned into twelve geographic zones based on surface expressions of inferred subsurface geologic features. Recharge estimates from three sources, Eyre and Walker (1991), Izuka et al. (2007), and ASPA (2013), were summed for each geographic zone and the area weighted portion of recharge in each wellfield region was determined by dividing the wellfield region area by the geographic zone area. Wellfield region boundaries were delineated with topographic watershed boundaries in the Pleistocene unit, or as the consolidated area of Thiessen polygons defined for all wells in each wellfield on the Tafuna-Leone Plain. Estimates based on these calculations have an inherent amount of uncertainty because it cannot be assumed that true aquifer boundaries conform to the wellfield region boundaries. However, they may be useful for making some very rough assessments of groundwater availability. This methodology could be greatly improved by developing improved recharge coverages and also by improved assessments of aquifer boundaries.

4.1 Underutilized or Unexplored Areas

These areas are characterized as having a minimal amount of groundwater development in comparison to their potential for groundwater storage capacity (Fig. 4.2). Some of these areas have been subject to more extensive groundwater development in the past, such as the Pago Inner-Caldera region, but currently experience extraction rates that are significantly lower than their expected extraction potential, based on a qualitative assessment of recharge quantities and aquifer parameters. It should be noted that any future groundwater development in these areas is likely to be more successful if it is carried out farther from present and past extraction sites, and as far inland as possible. Also included in this section are relatively unexplored regions where a limitation in data precludes a confident assessment of the area's capacity, such as the Taputapu Shield.

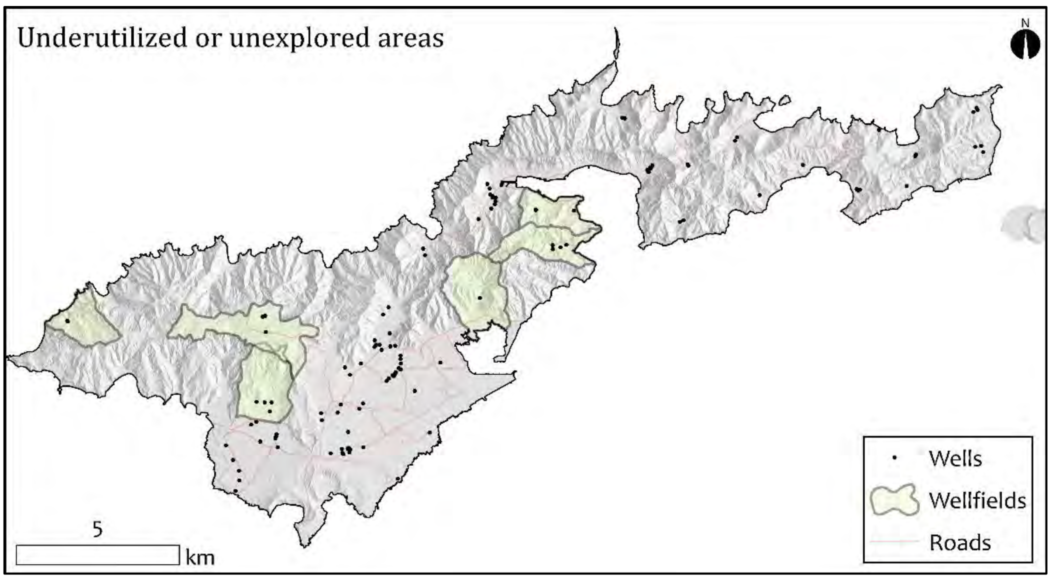


Figure 4.2: Map of wellfields with minimal amount of groundwater development in Tutuila

4.1.1 Aasu and Aoloau Region

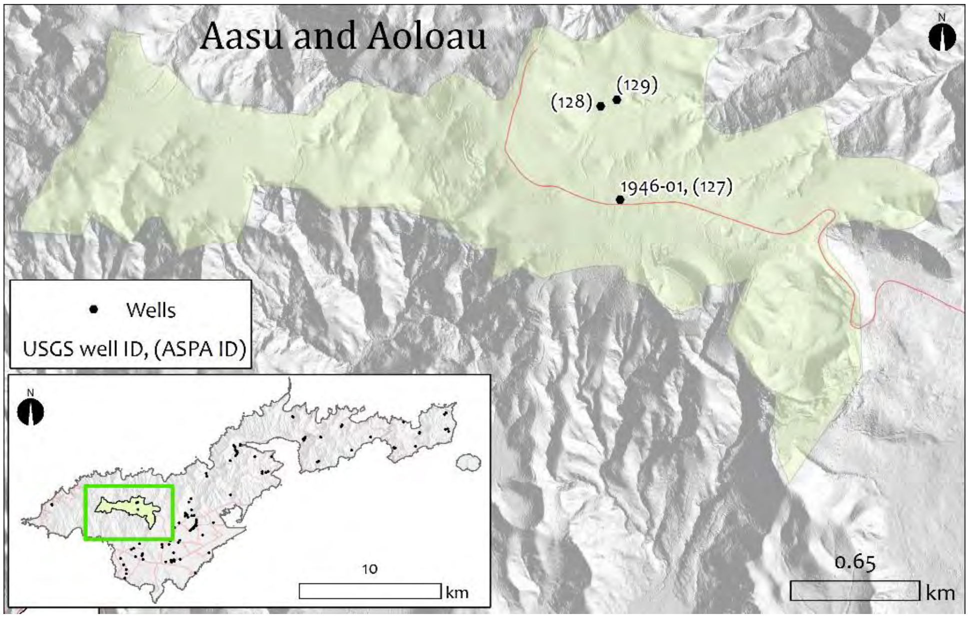


Figure 4.3: Location map of the Aasu and Aoloau region. Green shading denotes the inferred area of cinder deposits that may contain a potentially perched aquifer.

In the Aasu-Aoloau aquifer (Figs. 4.3, 4.4, and 4.5) only Well 128 is currently active. This well extracts about 0.03 Mgal/d (22 GPM). Section 2.1.2 provides a description of the region's geology and groundwater occurrence. Eyre and Walker (1993) estimate this area receives about 6 Mgal/d of recharge, which suggests that regional withdrawal rates could be sustainably increased. It should be noted however, that an increase in groundwater development in this region is likely to reduce flow at springs on the unit's periphery and subsequently reduce streamflow to the perennial streams that flow across the flanks of the Taputapu Shield and to the Tafuna-Leone Plain below (Table 4.1).

The region is estimated to receive about 6 mgal/d of recharge (Eyre and Walker, 1991), whereas the extraction at well 128 averages 0.03 Mgal/d (22 GPM). The roughly estimated area weighted recharge use ratio for Aasu-Aoloau is 0.4%

Table 4.1: Aasu and Aoloau region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
1946-01	127	382.2	-	-	-	-	-	-	-
-	**128**	**-**	**345.5**	**22**	**-**	**-**	**-**	**21**	**↑, 2**
-	129	-	343.6	40	-	-	-	23	-

* Pump rates and Ave. Cl^- values are taken from 2015-2017 ASPA data, ↓ denotes decreasing Cl^- trend, ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

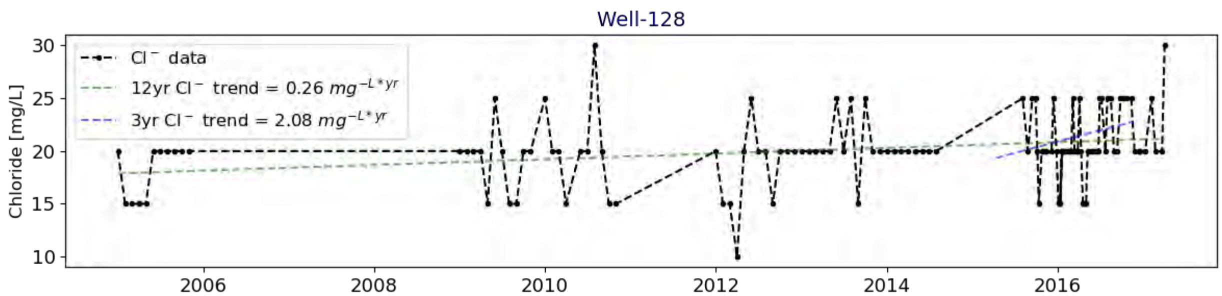


Figure 4.4: Cl^- concentrations for most recent 3-year period, 2015-2017 at Well 128. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Pumping water levels from the period of 2008 to 2013 as reported by ASPA (ASPA unpublished data) indicate that the aquifer tapped by Wells 128 and 129 is fairly stable at current pumping rates. Since these wells most likely tap a perched high-level aquifer, saltwater intrusion is not a concern. To assess the viability of additional withdrawals from Wells 128 and 129 measurements of specific capacity or pumping tests would be very useful for developing numerical or analytical estimates of sustainable withdrawal rates.

Future development: It is unclear as to why Wells 127 and 129 were decommissioned. However, it does appear that additional water could be withdrawn from the aquifer without significantly affecting the sustainability of groundwater supplies in this area. A possible issue with developing water from this likely unconfined aquifer is the existence of high numbers of On-Site Wastewater Disposal Systems and piggeries located within the villages of Aoloau and Aasu. These villages are, however, concentrated within the eastern side of the unit, whereas the western side currently has no development on it. Despite these potential sources of contamination, the well in Aasu Village, does not show levels of contaminants (including bacteriological indicators) that are above Environmental Protection Agency limits. Additionally, withdrawals in this region are likely to reduce discharge from the numerous natural springs that are located on the margins of the cinder unit. These springs feed perennial streams that in turn create aquatic habitats. It is unknown if springs serve village water systems. Springs and subsurface flows feed basal aquifers, primarily in the Malaeloa and Pavaii wellfields, and if withdrawals are significant enough, basal water supplies may be affected.

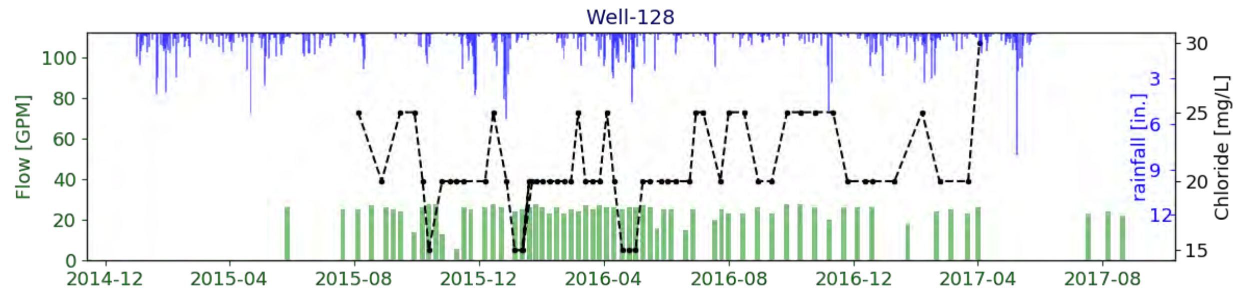


Figure 4.5: Plot of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for Well 128 for the period 2015-2017.

4.1.2 Taputapu Shield Including Upper Malaeloa Wellfield

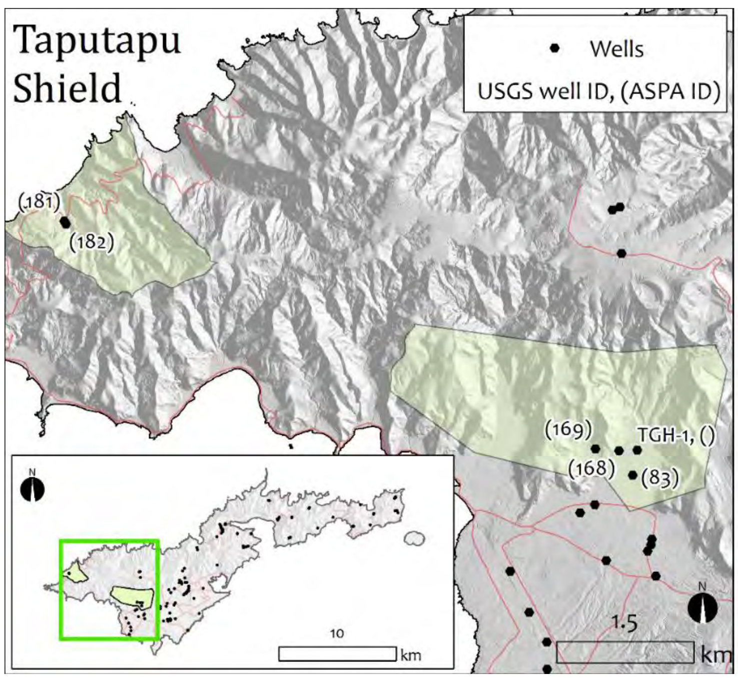


Figure 4.6: Location map of wellfields in the Taputapu region with locations of active and abandoned wells. *Green shading* denotes local watershed or wellfield boundaries, which do not necessarily delineate aquifer extent. Labels indicate well ID numbers.

Although the Taputapu Shield Region (Figs. 4.6, 4.7, and 4.8) is quite extensive, only a limited amount of groundwater development has occurred throughout the region. One well (Well 182) on the shield's northwestern flank and two wells on its southern margin (Wells 169 and 168) likely tap the Taputapu rocks. Well 83 lies to the southeast of Well 168 and probably penetrates alluvial sediments for much of its depth, although it may also be partially completed in Taputapu Volcanics.

Existing wells are generally drilled with a substantial buffer in distance or elevation from the coast, and thus show very low Cl^- concentrations. Extraction rates in these wells are not insignificant, yet

Cl^- trends are stable, possibly due to the thickness of the freshwater lens at these locations, and the high amount of recharge that feeds the area. Only about 0.5 to 1 m of pumping drawdown is seen in the few wells with complete records, indicating reasonably high conductivities and further supporting the idea that these wells draw from an aquifer that is supported by ample recharge (Table 4.2).

The Northern Taputapu Region is estimated to receive between 4.6 and 19.2 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 182 averages 0.15 Mgal/d (105 GPM). The roughly estimated area weighted recharge use ratio for the Fagalii Watershed is between 6 and 24% (average of 15%).

The Leone Plain Region is estimated to receive between 8.7 and 18.7 Mgal/d of recharge (range of all estimates), whereas the extraction at wells 169, 168, and 83 averages 1.2 Mgal/d (815 GPM). The roughly estimated area weighted recharge use ratio for the Upper Malaeloa region is between 19 and 41% (average of 25%).

Table 4.2: Taputapu Shield region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
-	181	-	-	-	-	-	-	-	-
-	**182**	**5.5**	**5.0**	**105**	**202**	**5700**	**312**	**31**	**-**
-	**83**	**-**	**0.8**	**270**	**-**	**-**	**-**	**24**	**→, 0**
-	**168**	**-**	**2.4**	**245**	**471**	**4100**	**147**	**25**	**→, 0**
-	**169**	**3.5**	**2.5**	**300**	**1154**	**5600**	**199**	**25**	**→, 0**
-	15	14.2	-	-	-	-	-	-	**↑, 1**
-	TGH-1	3.6	-	-	-	-	-	-	**-**

* Pump rates and Ave. Cl^- values are taken from averages of the last 3 years of ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

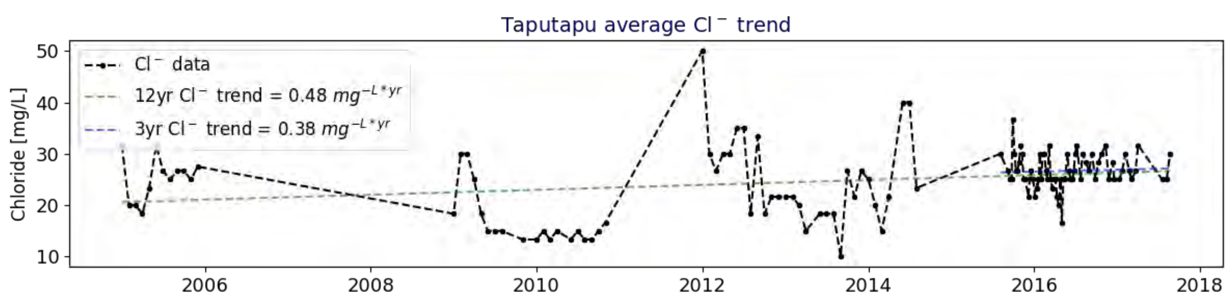


Figure 4.7: Averaged Cl^- concentrations for most recent 3-year period, 2015-2017 at Taputapu wells. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells:

Flat trends in water levels and Cl^- concentrations suggest the few existing wells in the Taputapu Region are being sustainably managed at their current extraction rates. Well 15 was recently drilled just to the south of Well 169, and will soon be online in the Upper Malaeloa Valley area. Regardless, the behavior of existing wells suggests this well should be able to extract a significant quantity of water without affecting the water levels or Cl^- concentrations at the nearby wells. Presently the well in Fagalii Valley has not been put into heavy production and the low water demand in the area keeps extraction rates at this well quite low.

Future development:

Although previous conceptual models have combined all of Tutuila's older shields into a single hydrologic unit with uniform properties, some recent observations suggest that the Taputapu Shield may have better water development potential than the island's other shields. Groundwater recharge is significantly higher over the Taputapu Region and specific capacities and $\boldsymbol{K}$ values measured in the Taputapu wells are generally higher than in the other older shield rocks. The distribution of geologic features throughout the island suggests that the Taputapu Shield contains less impermeable intrusive bodies, such as dike complexes that would serve to reduce permeability and aquifer connectivity. There remains significant exploration potential for groundwater resources in the Taputapu region. Primary recommendations for exploration and development in this area are to (1) drill new wells as far inland as possible to avoid saltwater intrusion, and (2) to spread development centers out to avoid excessive drawdown caused by overlapping cones of depression.

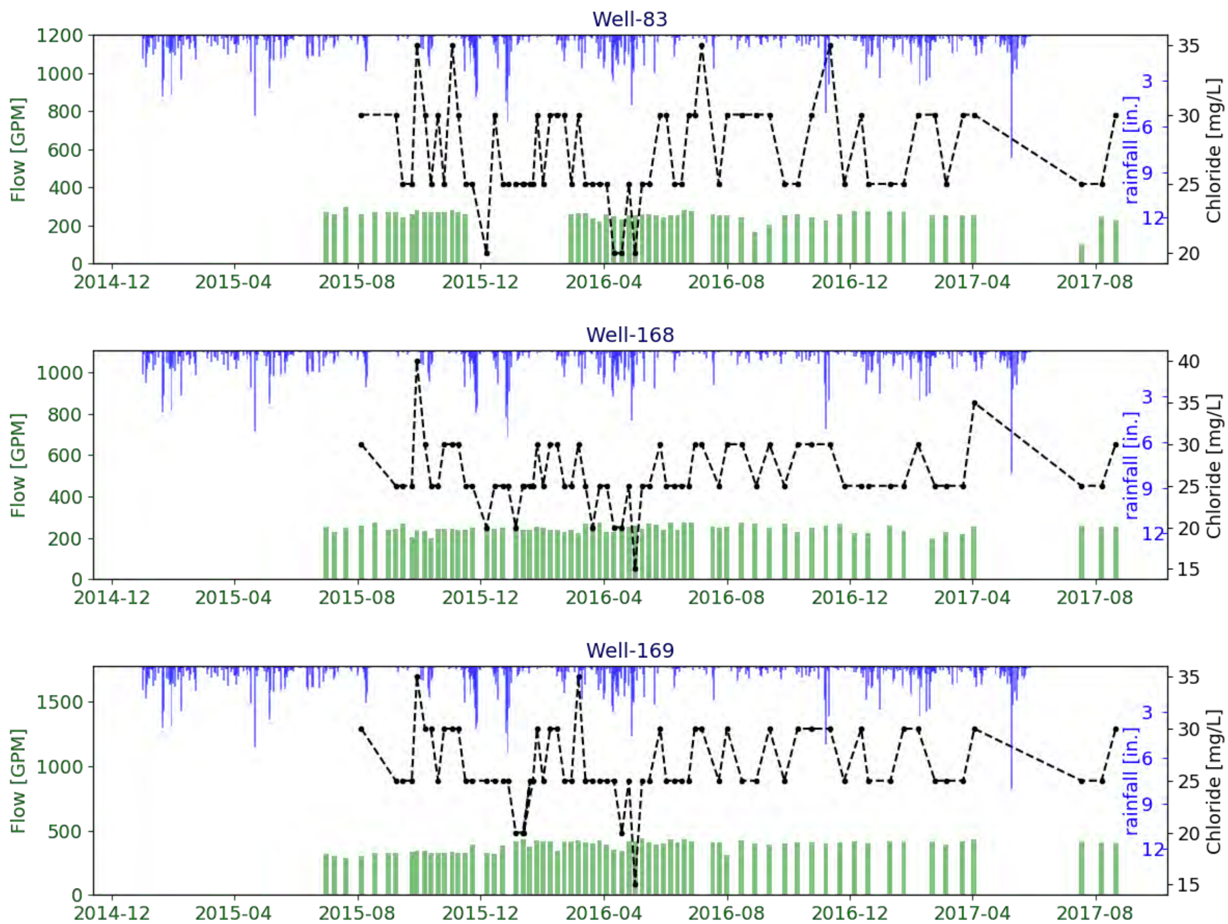


Figure 4.8: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for Taputapu region wells during the period 2015-2017.

4.1.3 Mesepa Wellfield

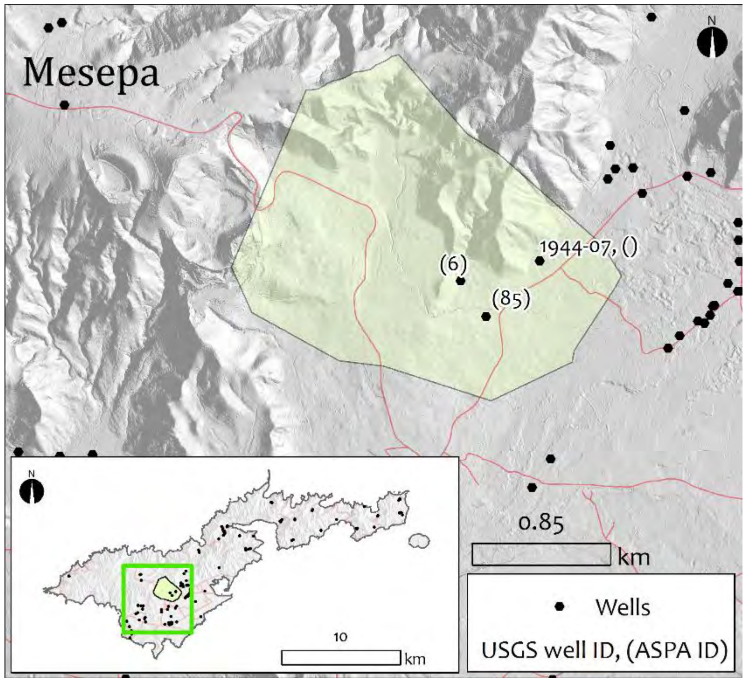


Figure 4.9: Location map of the Mesepa wellfield with locations of active and abandoned wells. *Green shading* denotes wellfield boundary, which does not necessarily delineate aquifer extent. Labels indicate well ID numbers.

The Mesepa wellfield (Figs. 4.9, 4.10, and 4.11) lies on the northwesterly portion of the Tafuna Plain. This area is geologically distinctive in that it has a steeper slope and is likely to be composed of lava flows lying upon the flanks of the Taputapu Shield below. This geology suggests that semi-perched conditions may be possible, though a geophysical survey (Geologica Geothermal Group, Inc., 2014) suggests that the basal lens under the surface may be similar in size to the lens on the Tafuna Plain. There are only two wells drilled in the area, Well 85 is active and Well 6 has not yet been connected to the system. Well 85 is relatively new and is located near the boundary of the Malaeimi area. The Pavaiai wells are located to the south of the Mesepa area, but are located on the flatter portion of the plain. No published documentation is available regarding wells in this area. Existing data for Well 85 shows low Cl^- values that are not affected by rainfall and seem to be increasing slightly through time. Values of T and K from two relatively new wells in the area indicate that the aquifer probably shares some characteristics with the Tafuna Aquifer to the southeast, but likely there are lower conductivity and Cl- concentrations due to the proximity to denser lava flows in the nearby Pleistocene unit (Table 4.3).

The Tafuna Plain Region is estimated to receive between 24.5 and 45.9 Mgal/d of recharge (range of all estimates), whereas the extraction at the only active well in Mesepa area averages 0.4 Mgal/d (280 GPM). The roughly estimated area weighted recharge use ratio for the current wellfield is between 7 and 13% (average of 10%). However, this value is likely to increase once the newly drilled Well 6 is put into production.

Table 4.3: Mesepa Wellfield aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl- [mg/L]	Cl- trend [mg/L/yr.]
1944-07	-	3.0	-	-	-	-	-	23	
-	**85**	**-**	**0.8**	**280**	**1244**	**9195**	**647**	**28**	**↑, 4**
-	6	0.0	-43.9	130	3	3810	18	25	

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

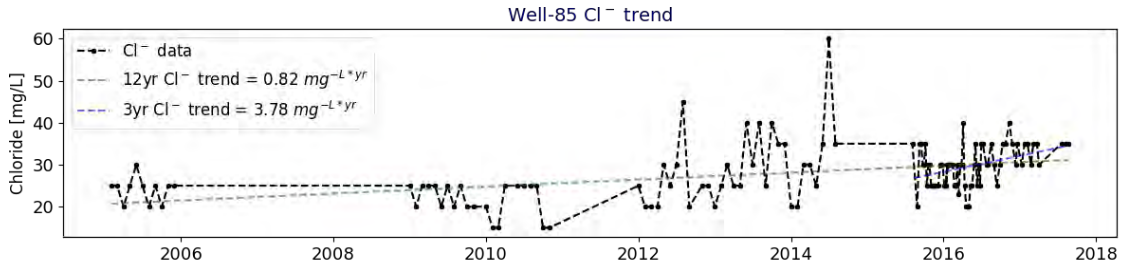


Figure 4.10: Averaged Cl^- concentrations for most recent 3-year period, 2015-2017 at Well 85. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells:

Since only one well is currently active in this area, and this well seems to be producing water with relatively low Cl^- concentrations, it appears that this extraction rate can be sustainably maintained. Once Well 6 is put into production it will be useful to reassess the effects of increased pumping in this area.

Future development:

The recharge use ratio of this well averages around 10%, which is not insignificant for a single well. Thus drastic increases in extraction rates in this area may quickly overwhelm the area's natural storage potential. Nonetheless, the upgradient portion of the Mapasagafou area remains fairly unexplored, and likely hosts rock with a relatively high ***K*** distribution, as is indicated by geophysical cross-sections (Geologica Geothermal Group, Inc., 2014). This certainly warrants further groundwater exploration within the Mesepa and Mapasagafou areas.

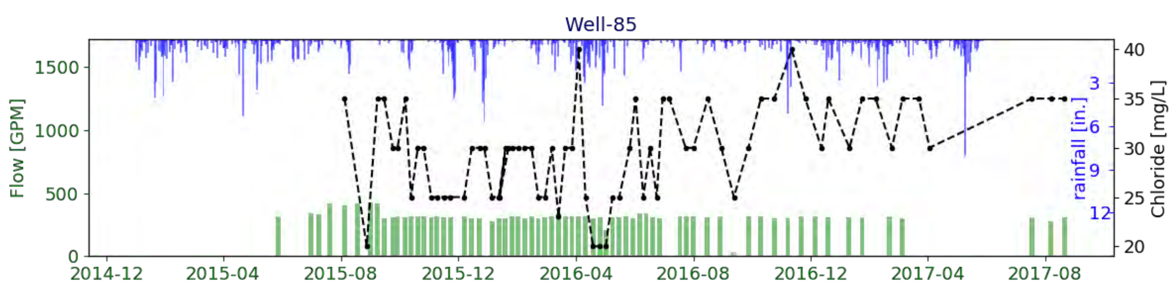


Figure 4.11: Plot of pump rate (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for Well 85 during the period 2015-2017.

4.1.4 Pago Inner-Caldera Geologic Unit

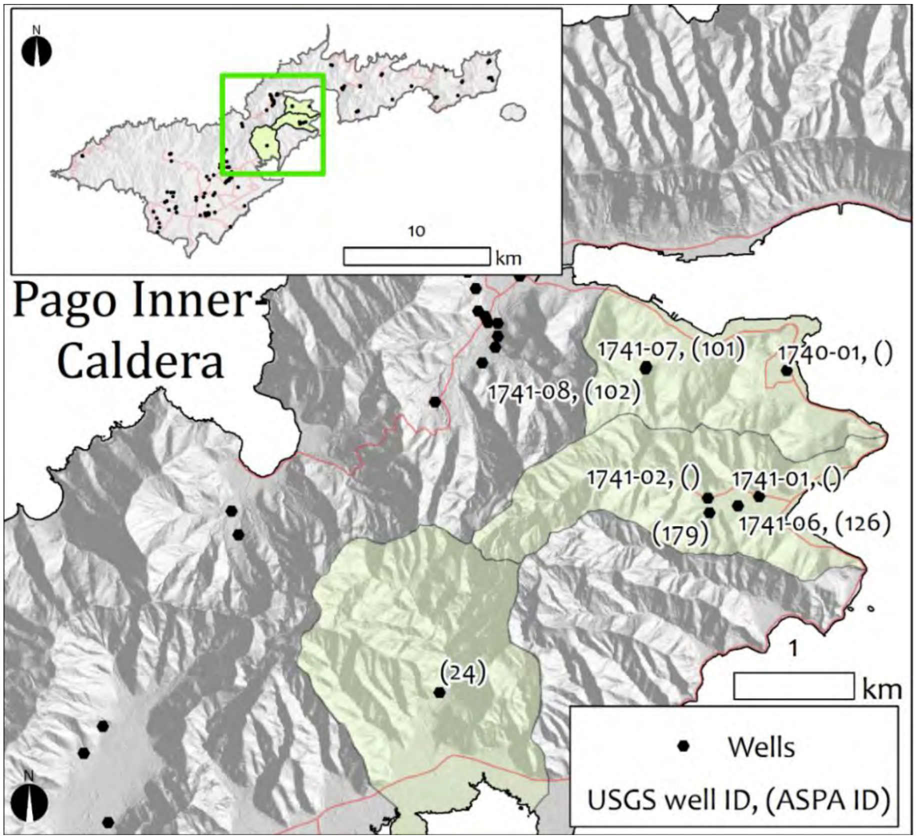


Figure 4.12: Location map of distinct watersheds in the Pago Inner-Caldera unit with locations of active and abandoned wells. *Green shading* denotes local watershed boundaries, which do not necessarily delineate aquifer extent. Labels indicate well ID numbers.

Although a number of wells have previously been developed in this geologic unit (Figs. 4.12, 4.13, and 4.14), only two wells are currently active. In Fagaalu Valley Well 179 produces an average of 19 GPM and has a pumping water level drawdown of 2 to 4 m. At the head of Fagaalu Valley is an exceptionally large high-level spring was recorded to have been used by the U.S. Navy in recent historical times (Davis, 1963). This spring was said to have a flow rate of 0.5 Mgal/d. The large spring feeds the headwaters of Fagaalu Stream and its flow has long since been captured by a reservoir located at the base of Mt. Matafao. Use of the reservoir has been discontinued, although it and the dam remain intact. Groundwater behavior observed in this area indicates how geologic features such as faults and low-permeabiltiy layers can control subsurface water flow on Tutuila. These conditions were described by Eyre and Walker (1991) as,

> "*The fault separating these two formations is visible at the base of the dam. The occurrence of the large spring is controlled by the interrelations of infiltrating rainwater, the trachyte plug, the Pago volcanic rocks, and the location of the fault.*"

A number of now abandoned moderately producing (30-60 GPM) wells have been drilled in Fagaalu Valley and their development histories are described in greater detail in Eyre and Walker (1991) (Table 4.4).

Groundwater development in the Fagatogo/Utulei Region has an enigmatic history. The aquifer in this area currently yields a significant amount of water from Well 101 (520 GPM) while showing only a moderate pumping drawdown, and maintaining stable long-term Cl^- concentrations. Eyre and Walker (1991) noted that upon drilling of the Fagotogo wells, artesian conditions below hard basalt were encountered at -3 m below sea level with water rising to about 7 m above sea level. Wells 101 and 102 have been used in alternating cycles of pumping and observation in the past. The producing zone was said to be about 6 m thick. Also a now abandoned well, (1740-01), was drilled in Utulei, the valley south of Fagatogo. This well was shallow, 4 m deep, and pumped at 90 GPM. The Cl- concentrations were reported to have ranged from 30 to 200 mg/L. It is unusual for a well so near to the shore to produce water this fresh, and it would seem that this area must receive a disproportionate share of recharge from nearby areas, and have aquifer properties that allow for a significant amount of storage. Geologically this unit would be expected to have a high-proportion of less-permeable material, and it has been hypothesized that the prevalence of fresh water, as well as the observed occurrence of marshes in this area, prior to being filled for urban development, may result from the discharge of an underlying artesian volcanic aquifer (Eyre and Walker, 1991).

Only recently have any known wells been developed in the Nuuuli area. Well 24 was drilled in 2015 and has not yet been pumped. This well is fairly shallow and may experience some hydraulic connection to the nearby stream.

The Pago Harbor Region is estimated to receive between 15.6 and 16.6 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 179 averages 0.03 Mgal/d (19 GPM). The roughly estimated area weighted recharge use ratio for the Fagaalu Watershed averages less than 1%.

The Pago Harbor Region is estimated to receive between 15.9 and 16.6 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 101 averages 0.8 Mgal/d (520 GPM). The roughly estimated area weighted recharge use ratio for the Fagatogo Watershed is between 30 and 32% (average of 31%).

Table 4.4: Pago Inner-Caldera Unit aquifer parameters

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl⁻ [mg/L]	Cl⁻ trend [mg/L/yr.]
-	24B	22.4	-	-	-	-	-	0	
1740-01	-	0.0	-	-	-	-	-	425	
1741-07	**101**	**6.9**	**-0.4**	**520**	**711**	**3270**	**244**	**50**	**↑, 7**
1741-08	102	6.4	5.5	310	363	3317	363	-	
1741-01	-	6.1	-	-	-	-	-	-	
1741-02	-	27.4	-	-	-	-	-	-	
1741-06	126	10.7	-	-	-	-	-	-	
-	**179**	**2.7**	**-1.1**	**19**	**19**	**561**	**18**	**38**	**↑, 1**
1741-09	-	7.5	-	-	-	-	-	-	

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

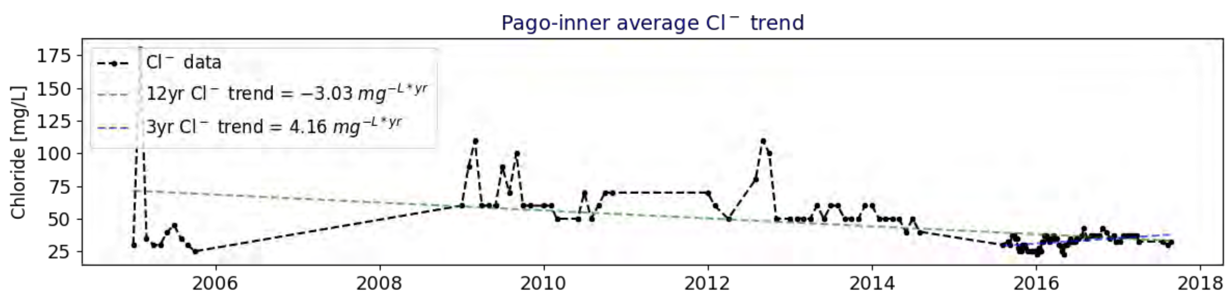


Figure 4.13: Averaged Cl^- concentrations for most recent 3-year period, 2015-2017 at Pago Inner-Caldera Unit wells. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Although this unit has contained numerous wells in the past, many have been abandoned. Considering the very favorable groundwater producing conditions reported and observed in the Fagatogo and Utulei Valleys it is unclear as to why additional development has not occurred in these areas. The wells in Fagatogo however, do pump at a fairly high rate, and although this rate appears to be sustainable, additional extraction has the potential to exceed the sustainability of the areas resources.

Future development:

Current production rates and Cl^- trends at active wells seem to indicate that it may be reasonable to explore new sites for future groundwater development. The geologic characteristics of this region would indicate that keeping an expectation for low to moderate extraction rates would be prudent, although Well 102 provides an example of how the island's heterogeneity can sometimes produce outliers from expectations. The Utulei Watershed currently has no active wells, and while the southern portion contains a fuel tank farm and a wastewater treatment plant, upgradient portions of the northern portion of the watershed may be viable locations to explore for groundwater. In general, a strategy of siting wells above development and farther from the coast should help to protect against issues related to contamination or salinization.

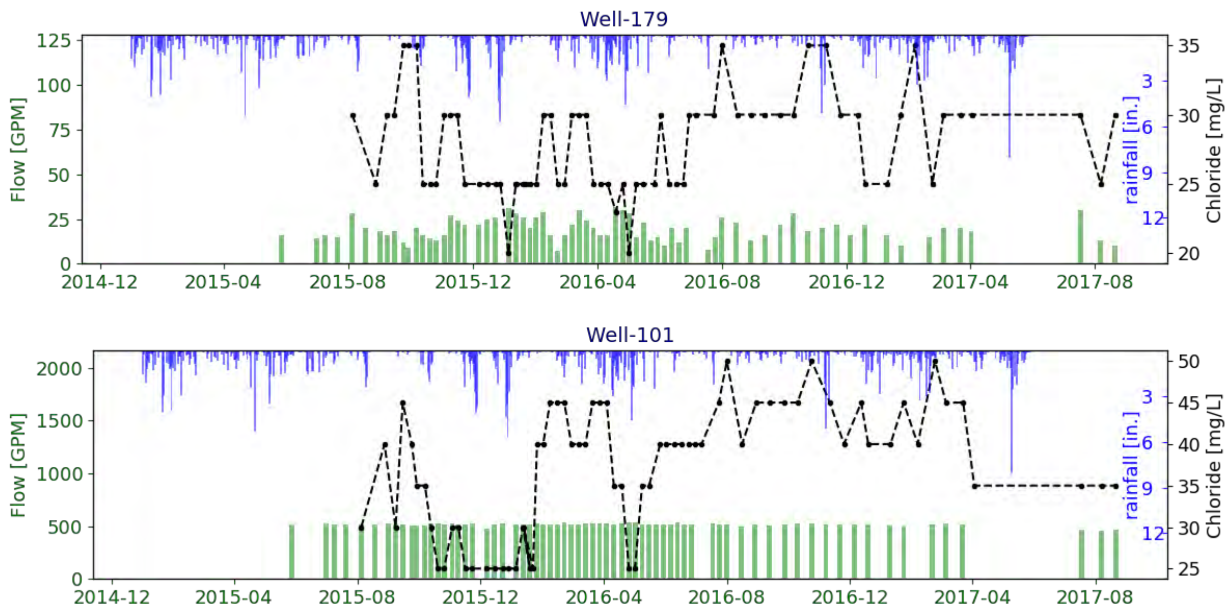


Figure 4.14: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for active Pago Inner-Caldera Unit wells during the period 2015-2017.

4.2 Moderately Utilized Areas

Moderately utilized areas have been grouped based on characteristics of a having light to moderate groundwater development in place, but where aquifer data for the most part does not show trends suggesting that extraction rates are clearly unsustainable (Fig. 4.15). While additional development may be possible without affecting water levels or Cl^- concentrations in existing wells, consideration of aquifer conditions at existing extraction sites should be informative for siting future wells. A number of these regions are fairly large and may contain some areas that already seem to experience extraction rates that exceed freshwater supply. In particular, the Pago Valley area has one well with a Cl^- concentration and trend that is dramatically higher than other upgradient wells. This could be due to tapping a different aquifer, or simply a different portion of the same basal lens. Regardless, abandonment of this well, and replacement with another in a different, more upgradient location, may allow for extraction of the same amount of water at a higher quality.

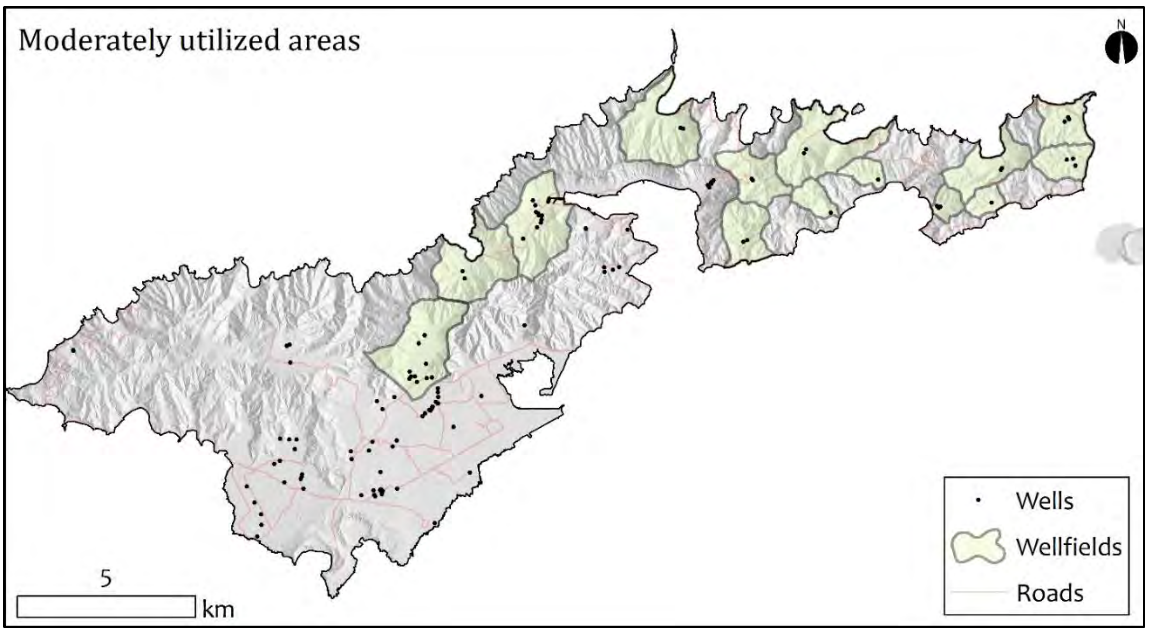
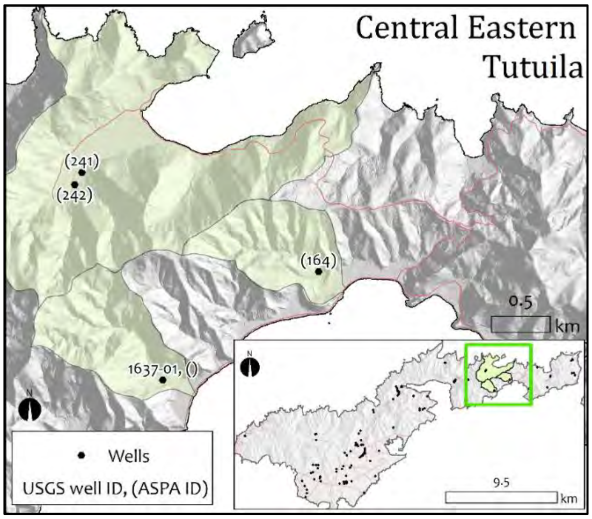


Figure 4.15: Map of wellfields that show characteristics suggesting current extraction rates may currently be close to water supply capacity.

4.2.1 Eastern Tutuila Region



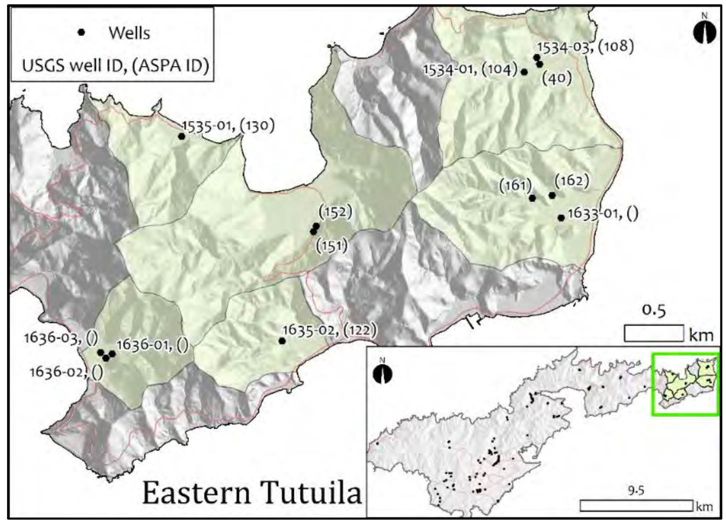


Figure 4.16: Location map of small distinct watersheds in the Eastern Tutuila Region with locations of active and abandoned wells. *Green shading* denotes local watershed boundaries, which do not necessarily delineate aquifer extent. Labels indicate well ID numbers.

Many wells have been completed in Eastern Tutuila (Figs. 4.16, 4.17, and 4.18). Most of these are connected to satellite systems and develop only small quantities of water for small localized population centers. The dispersed satellite system strategy is well suited to this region since groundwater development conditions, recharge rates, and storage volumes, are somewhat less favorable than in Western Tutuila. Many of the wells in this region tap small basal lenses in alluvial or marine sedimentary wedges that fill the mouths of valleys. The water quality from these alluvial aquifers is variable and often affected by saltwater intrusion or sometimes by excessive organic material within the shallow aquifer. Drilling water levels in these wells generally ranged from approximately 0 to 6 m above sea level; however, current pumping water levels are often below sea level indicating that even with low pump rates, aquifer yield would be expected to remain fairly small. Some wells do produce relatively fresh water, but most wells in this region are drilled close to the coast and in thin lenses, thus they are prone to producing high Cl^- water. However, this is not necessarily an indication that this region is overexploited, as these high Cl^- concentrations may be due to well placement rather than local groundwater availability (Table 4.5).

Eyre and Walker (1993) described developed groundwater resources in this region to be primarily derived from thin and sometimes brackish basal lenses:

> "*Flow into the well(s) may occur evenly along the submerged length of the well, but more commonly, flow occurs from a narrow water-producing zone. Pumping at rates of 50 gal/min or less yields water with chloride concentrations between l5O and 2,000 mg/L. These data indicate that thin fresh- to-brackish water lenses occur in this area in both sedimentary and volcanic rocks*."

While there are springs that feed a few perennial streams in this region, there are generally more intermittent streams than there are in Western Tutuila, which indicates that ground water supplies (high-level or otherwise) in the mountainous interior are typically limited in extent.

The total Eastern and Central Eastern Tutuila Regions are estimated to receive between 7.3 and 17.9 Mgal/d of recharge.

The North-Central Eastern Tutuila Region is estimated to receive between 2.7 and 5.6 Mgal/d of recharge (range of all estimates), whereas the extraction at Wells 241 and 242 averages 0.1 Mgal/d (69 GPM). The estimated area weighted recharge use ratio for Masefau Watershed is between 5 and 9% (average of 7%).

The South-Central Eastern Tutuila Region is estimated to receive between 2.3 and 8.1 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 164 averages 0.04 Mgal/d (28 GPM). The roughly estimated area weighted recharge use ratio for Fagaitua Watershed is between 5 and 21% (average of 13%).

The Eastern Tutuila Region is estimated to receive between 2.3 and 4.2 Mgal/d of recharge (range of all estimates), whereas the extraction at Wells 151 and 152 averages 0.04 Mgal/d (30 GPM). The roughly estimated area weighted recharge use ratio for Aoa Watershed is between 4 and 8% (average of 6%).

The Eastern Tutuila Region is estimated to receive between 2.3 and 4.2 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 104 averages 0.02 Mgal/d (13 GPM). The roughly estimated area weighted recharge use ratio for the Tula Watershed is between 2 and 4% (average of 3%).

Table 4.5. Eastern Tutuila Region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m^2/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
1637-01	-	-	-	-	-	-	-	-	
-	**164**	**-**	**-0.7**	**28**	**13**	**610**	**46**	**1113**	**↑, 83**
-	**241**	**-**	**0.9**	**33**	**-**	**-**	**-**	**30**	**↑, 3**
-	**242**	**-**	**2.2**	**36**	**10**	**51**	**1**	**28**	**↑, 4**
1633-01		5.7	-	-	-	-	-	38	
-	161	-	-0.7	-	-	-	-	-	
-	162	-	-4.9	-	-	-	-	-	
1635-02	122	5.3	3.8	25	16	325	16	-	
-	**151**	**-**	**-7.9**	**2**	**-**	**-**	**-**	**168**	**↓, 120**
-	**152**	**-**	**0.7**	**28**	**21**	**37**	**3**	**414**	**↓, 51**
1636-01	-	0.0	-	-	-	-	-	12	
1636-02	-	-	-	-	-	-	-	-	
1636-03	-	2.3	-	-	-	-	-	106	
1535-01	130	2.7	-	-	-	-	-	-	
1534-01	**104**	**3.1**	**-5.1**	**13**	**2**	**28**	**1**	**75**	**↑, 13**
1534-03	108	3.0	-	-	-	-	-	-	
	40		-	-	-	-	-	-	

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

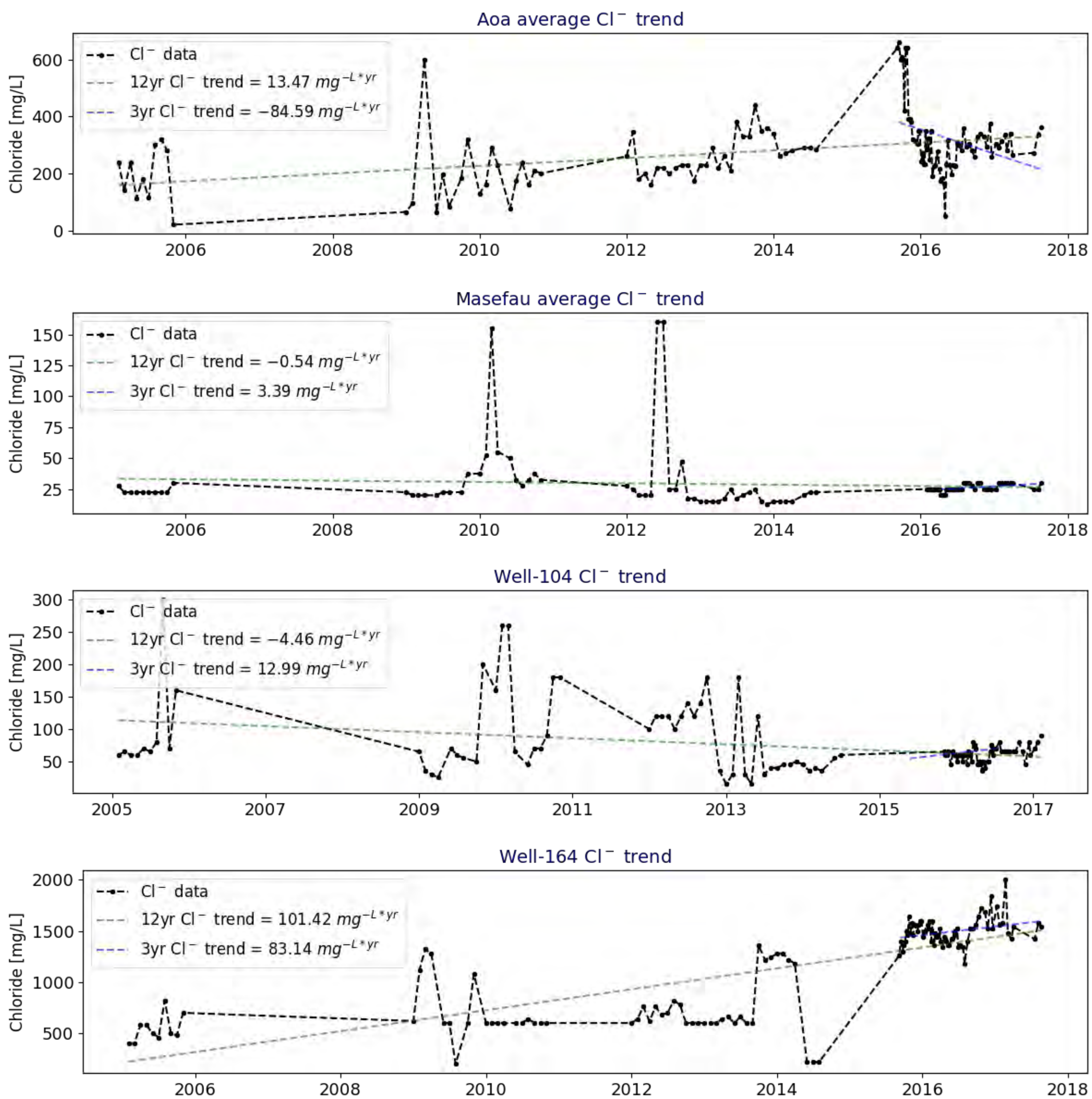


Figure 4.17: Cl^- concentrations and trends for active wells in the Eastern Tutuila Region. Tula (Well 104) and Fagaitua (Well 164) have only one active well each and Aoa and Masefau have two wells each, with averaged Cl^- concentrations presented here. *Green dashed lines* show the linear regression trend line for all data, generally about 12 years, and *blue dashed lines* show the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Many of the existing wells are located adjacent to the coast and are set to a depth where saltwater intrusion is a consistent problem. Where possible, abandonment of existing salty wells and replacement with wells that utilize the same aquifer, but are located farther inland in a thicker part of the freshwater lens may provide similar yields with lower Cl^- concentrations.

Future development: It appears that aquifers in this region have the potential to provide small yields (< 20 GPM) of groundwater. However, pumping in excess of this rate may easily cause saltwater intrusion. Continuing the strategy of developing multiple low-yield wells, dispersed to avoid concentrating the effects of drawdown or upconing, to supply a low-level of demand will likely be sustainable until population increases to the point where demand is increased beyond what the region can supply. Pumping in excess of this amount may not be feasible, due to apparently low ***K*** values combined with overall low recharge rates in this area.

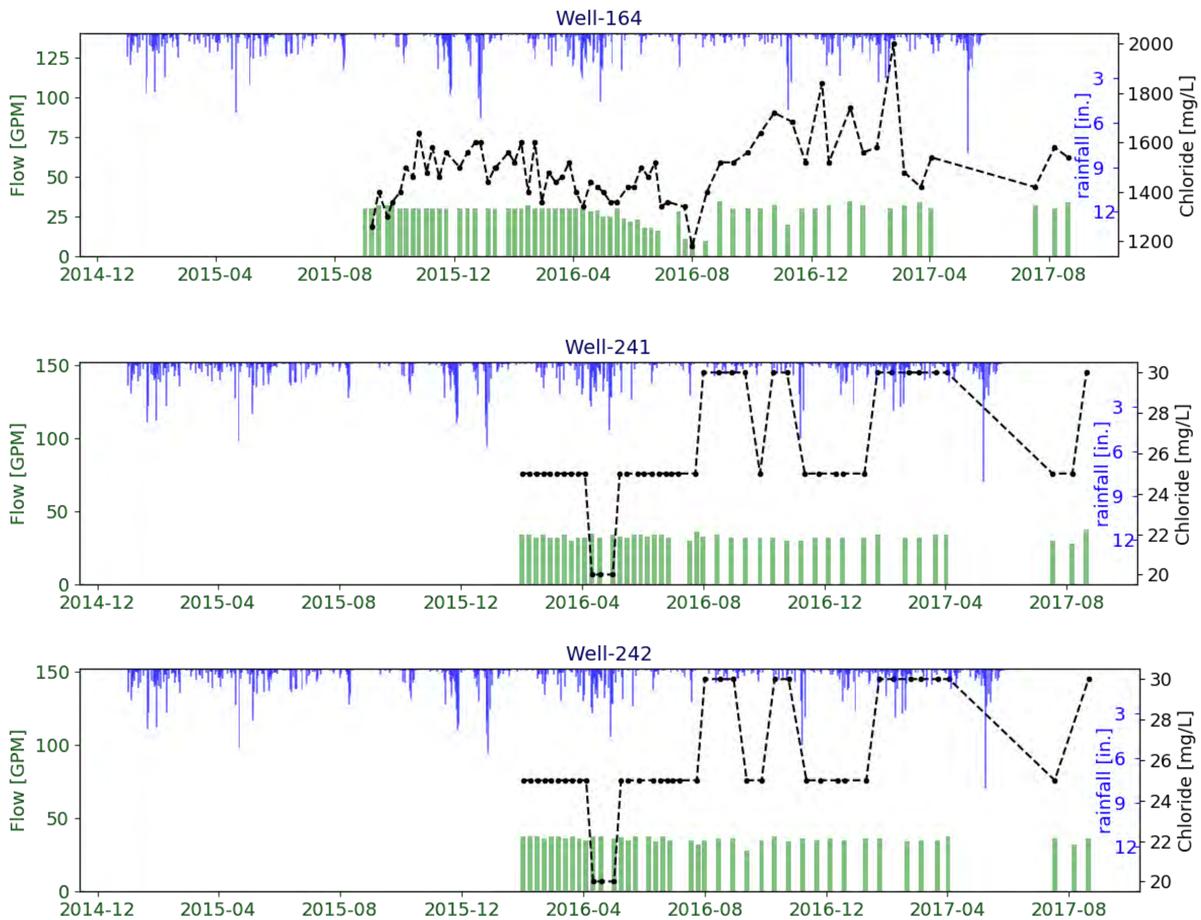


Figure 4.18: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Eastern Tutuila Region for the period 2015-2017.

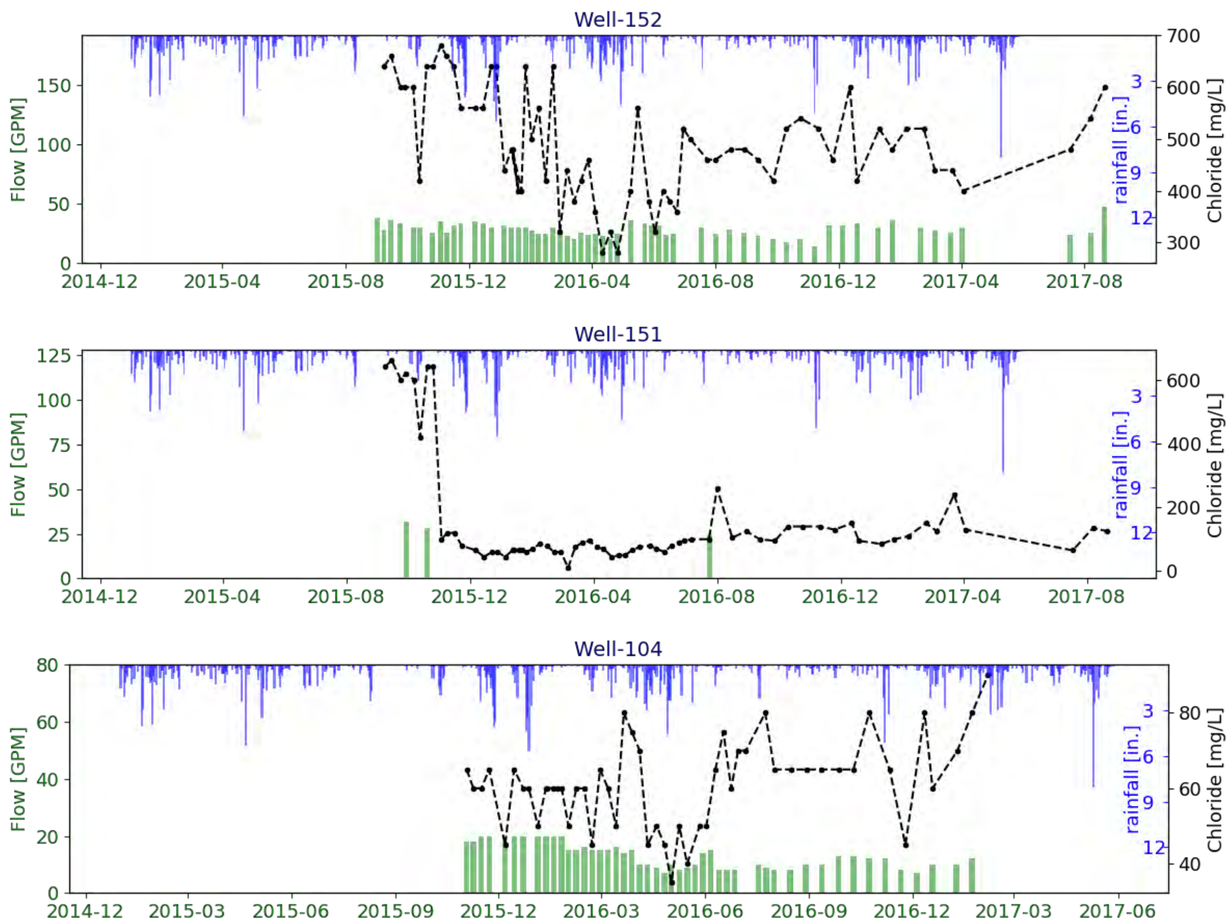


Figure 4.18 continued: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Eastern Tutuila Region for the period 2015-2017.

4.2.2 Pago Outer-Caldera Geologic Unit

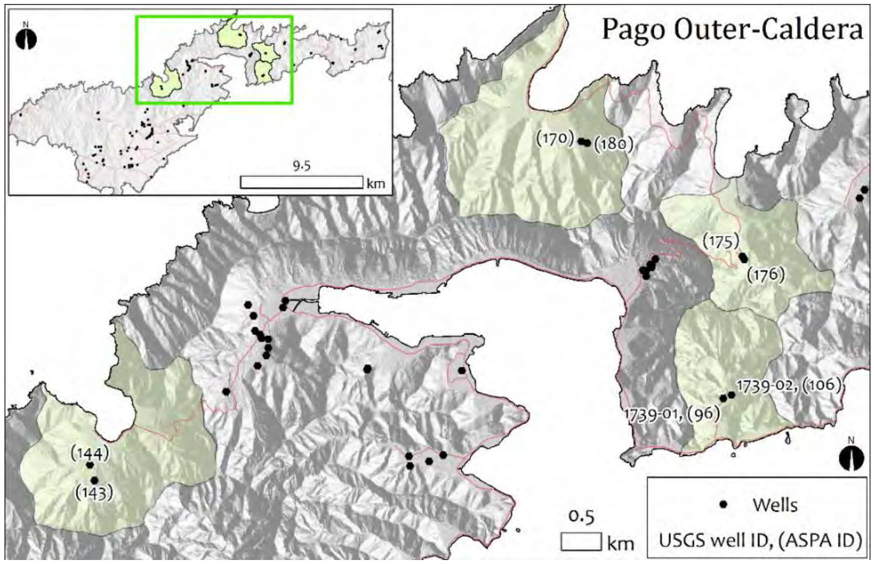


Figure 4.19: Location map of watersheds in the Pago Outer-Caldera Unit with locations of active and abandoned wells. *Green shading* denotes local watershed boundaries, which do not necessarily delineate aquifer extent. Labels indicate well ID numbers.

Wells drilled into the basalt aquifers of the outer-caldera region of the Pago Shield (Figs. 4.19, 4.20, and 4.21) generally show low ***K*** values, low specific capacity, and low Cl^- concentrations. This supports the idea that overall conductivities in the unit are low, which contributes to the development of a thick basal-lens. However, due to the low ***K*** values, these areas may be susceptible to high aquifer drawdowns. Water levels in each of the unit's wells are variable. However, it appears that local barriers to water movement may drastically control groundwater levels in the unit as is shown by the historical account of groundwater development in Laulii Village from Eyre and Walker (1991):

> "[Laulii] *well 96 entered the major water-producing formation at 150 feet below sea level. Water with a chloride concentration of 25 mg/L rose in the well to an altitude of 19 feet above sea level. Another well, 150 feet deep and drilled 400 feet to the north of well 96, encountered only massive rock, yielded no water, and was abandoned. Well 106 was drilled across the stream 500 feet to the east of well 96 to a depth of 320 feet below sea level. Prior to pumping well 96, water levels at well 106 ranged from 22 to 24 feet above sea level"* (pg. 36).

Interestingly there have been a few accounts of finding confined conditions during drilling of some, but not all, of the wells in Aua, Laulii, and the Pago Valley watersheds. This is shown by observations of pre-development heads in localized portions of these aquifers that are significantly above sea level and in some cases above the ground surface, encountered after drilling through dry often massive lava formations above (Eyre and Walker, 1991). Extraction of water from these wells subsequently produced large drawdowns, indicating the confined water bodies are likely to be limited in extent. This supports the conclusion that aquifer connectivity in the Pago Volcanics is typically low and may be controlled by the locations of low-conductivity formations such as massive lava flows, pyroclastics, or potentially dikes (Table 4.6).

The Central Northern Coast Region is estimated to receive between 9.6 and 10.4 Mgal/d of recharge (range of all estimates), whereas the extraction at Wells 170 and 180 averages 0.4 Mgal/d (31 GPM). The roughly estimated area weighted recharge use ratio for the Vatia Watershed averages less than 1%.

The North-Central Eastern Tutuila Region is estimated to receive between 2.7 and 5.6 Mgal/d of recharge (range of all estimates), whereas the extraction at Well 176 averages 0.14 Mgal/d (100 GPM). The roughly estimated area weighted recharge use ratio for Afono Watershed is between 12 and 25% (average of 18%).

The Western Central Northern Coast Region is estimated to receive between 10.7 and 19.6 Mgal/d of recharge (range of all estimates), whereas the extraction at well 143 averages 0.16 Mgal/d (110 GPM). The roughly estimated area weighted recharge use ratio for Fagasa Watershed is between 2 and 4% (average of 3%).

Table 4.6: Pago Outer-Caldera Unit aquifer parameters

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m^2/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
-	175	-	-	-	-	-	-	-	
-	**176**	**-**	**-1.3**	**100**	**-**	**-**	**-**	**23**	**↑, 2**
-	**143**	**-**	**25.3**	**110**	**-**	**-**	**-**	**35**	**↑, 2**
-	144	-	4.3	120	-	-	-	25	
1739-01	96	5.5	-7.5	47	4	38	1	-	
1739-02	106	7.3	-	-	-	-	-	-	
-	**170**	**8.1**	**-**	**14**	**1**	**13**	**7**	**24**	**↑, 5**
-	**180**	**7.9**	**-**	**17**	**9**	**461**	**18**	**24**	**↑, 5**

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

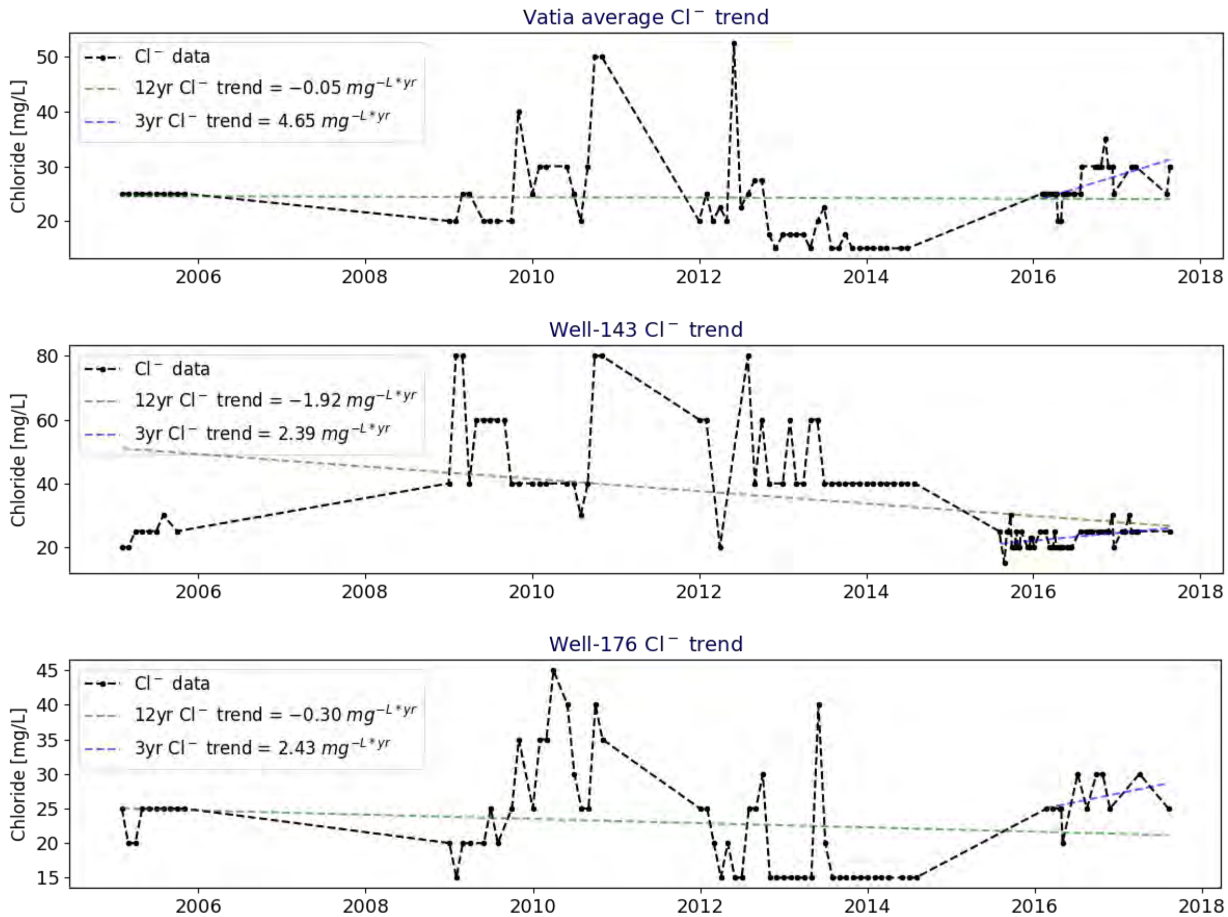


Figure 4.20: Cl^- concentrations and trends for active wells in the Pago Outer-Caldera unit. Fagasa (Well 143) and Afono (Well 176) have only one active well each and Vatia has two wells, with averaged Cl^- concentrations presented here. *Green dashed lines* show the linear regression trend line for all data, generally about 12 years, and *blue dashed lines* show the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: The satellite systems in Vatia, Afono, and Fagasa Villages appear to be maintaining stable Cl^- concentrations and water levels, based on data from ASPA records (from 2006 to 2017). This suggests these wells are currently pumped at a sustainable rate, and indeed, in general pump rates at these wells do not exceed 120 GPM and some pump at rates as low as 15 GPM. As long as demand does not increase, these wells are likely to be able to continue supplying high-quality water at current rates.

Future development: Since this is a large and diverse region, localized aquifer conditions are also likely to be diverse. However, as long as lower yielding wells are acceptable, it is likely that new wells could be sustainably developed. Individual site characteristics will be variable, in general targeting areas that are likely to encounter continuous water bodies near sea level will be the most conservative approach. As wells are deepened below sea level, the risk of dewatering a surficial aquifer of limited extent is exchanged for the risk of drilling through the basal lens and invoking saltwater intrusion via pumping. Both of these risks can be minimized by drilling as far inland as possible where the main groundwater body is expected to be thicker, or by utilizing angled drilling methods to further gain access to more inland parts of the lens. Based on available data, it would be conservative to expect wells in the Pleistocene shields to yield water at an order of magnitude less than wells in the Tafuna-Leone aquifers.

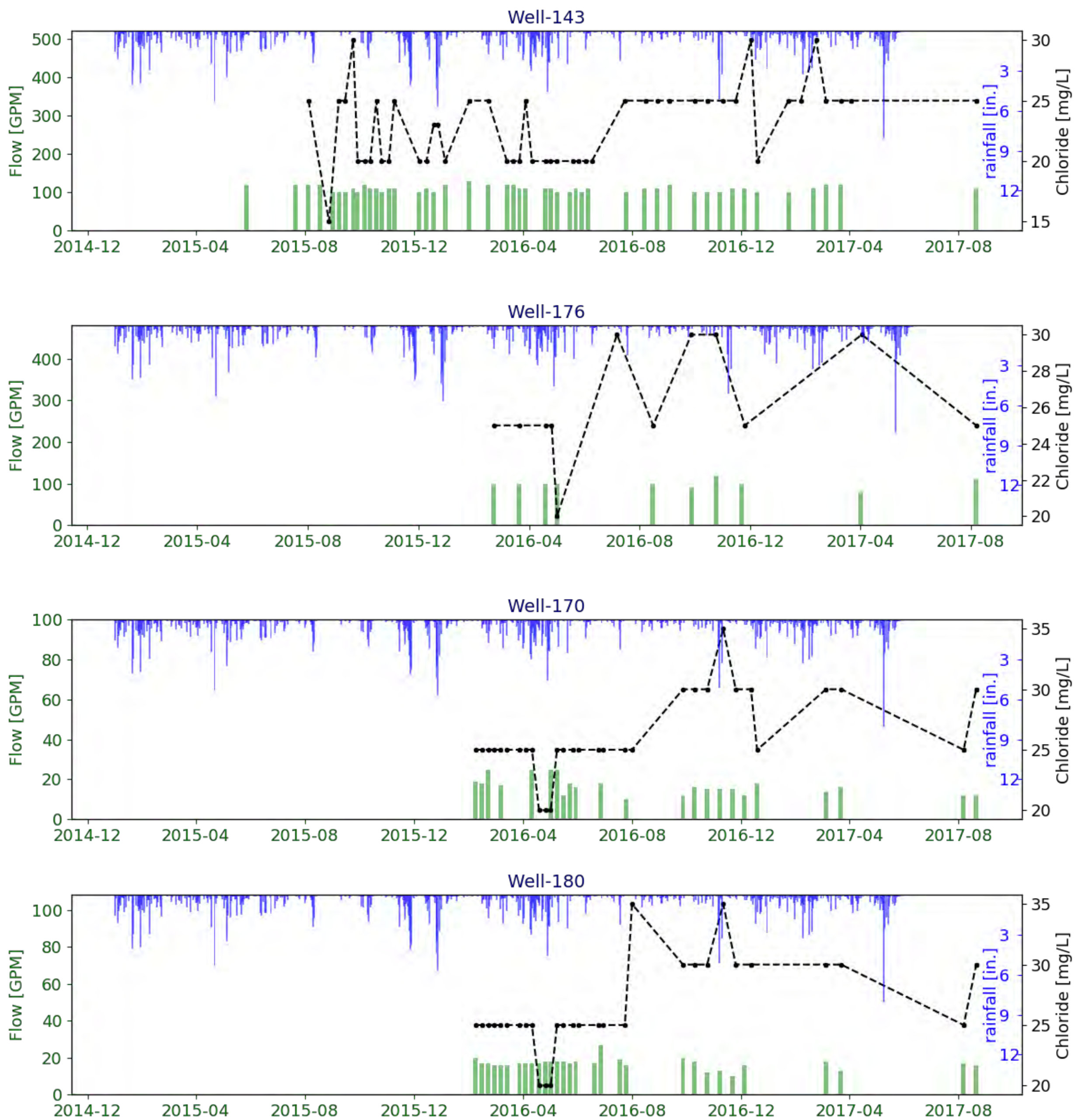


Figure 4.21: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Pago Outer-Caldera Unit for the period 2015-2017.

4.2.3 Malaeimi Watershed

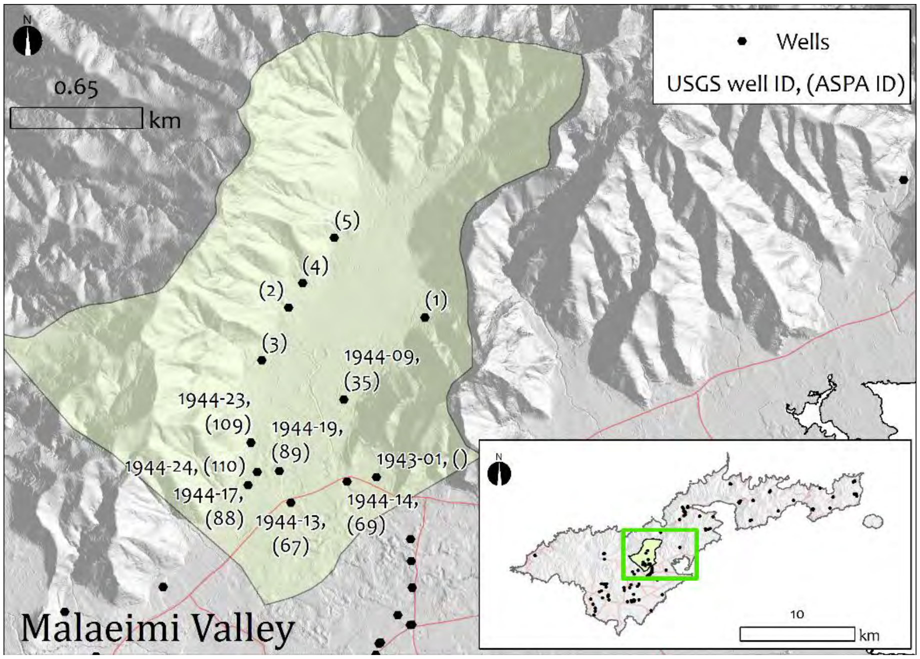


Figure 4.22: Location map of Malaeimi Watershed with locations of active and abandoned wells. *Green shading* denotes local watershed boundary, which does not necessarily delineate aquifer extent. Note, new well locations (Wells 1 to 5) are estimated, and are still awaiting surveyed locations from ASPA. Labels indicate well ID numbers.

The Malaeimi Valley area (Figs. 4.22, 4.23, and 4.24) has been widely recognized as having valuable water resource characteristics. This is due to underlying geologic features, as well as relatively high recharge rates for Tutuila. The valley is a primary recharge capture zone for the heavily utilized Tafuna Plain aquifer. Currently the valley's land use is mostly undeveloped and second growth forest. While some agro-forestry and light habitation exists in the valley, there are presently few residents. The valley has been recognized as possessing all three of the needed qualifications for designation an area as a "Special Management Area" under American Samoan Law. These qualifications include unique and irreplaceable habitat, products or materials offering beneficial functions, and products or materials affecting the cultural values or quality of life that are significant to the general population of the Territory of American Samoa and Fa'a Samoa. (ASAC 26.0221 A). Multiple studies to assess Malaeimi's water resources value have been performed, and in 2004 it was recommended that the watershed be legally protected as a special management area (Shuler et al. 2014, Pedersen Planning Consultants 2004). Unfortunately, this recommendation was not legislated upon and no management protections for Malaeimi Valley exist at this time (Table 4.7).

Geologically, the area is unique in that it lies at the boundary of two very hydrogeologically different rock units. Subsurface water flow and storage is affected by the physical structure of the Leone lava flow and the underlying topography of the valley carved into the Pleistocene Pago Inner-Caldera volcanics. Surface water draining off of the Pleistocene mountains has been observed to quickly infiltrate into the alluvial deposits that fill the valley bottom. These deposits are bounded to the south by Tafuna lavas, which are likely to be even more permeable than the alluvium, thereby increasing the proportion of MFR that occurs at the valley mouth.

The structure of less-permeable Pleistocene rocks underlying more permeable alluvium or Tafuna Lavas creates the potential for a semi-perched groundwater system to be present. Meinzer (1923) describes this condition as theoretically distinct from basal groundwater as the semi-perched water is at least partially supported by underlying rock, as opposed to underlying seawater, but is still physically connected through a continuous zone of saturation to the main (basal) water body. This hypothesis is supported by high observed drilling water levels in wells with reasonably high T and K values, such as those at Wells 1, 88, 89, 109, 110, that rapidly drop off further down the valley near Wells 67 and 69. Pumping shows that these high water levels are unstable and may decline rapidly when they are hydraulically connected to the underlying basal aquifer via a high permeability pathway such as a well. All of the Malaeimi wells show low Cl- levels, which also support the idea that these wells tap a thick freshwater lens with a potential partial disconnection from underlying seawater.

The Tafuna Plain Region is estimated to receive between 24.5 and 45.9 Mgal/d of recharge (range of all estimates), whereas the extraction at the two active well in Malaeimi averages 0.7 Mgal/d (460 GPM). The roughly estimated area weighted recharge use ratio for the current wellfield is between 9 and 16% (average of 12%). However, this value is likely to drastically increase once five new wells are put into production in this area.

Presently, Wells 1-5 are awaiting connection to the water distribution system, and available data should be considered to be provisional. Once these wells are connected, elevations can be more accurately surveyed, and pumping water levels can be monitored this analysis should be revisited.

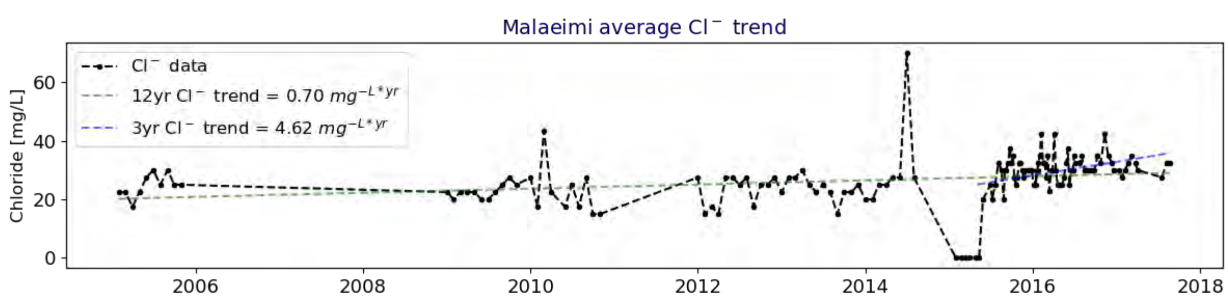


Figure 4.23 Cl^- concentrations averaged across active Malaeimi Wells 89 and 67. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management
Existing wells:
Presently, only two wells are producing water in the watershed. These wells have low Cl^- concentrations and do not appear to produce unsustainable drawdowns, therefore current extraction rates can be sustainably maintained. However, five new wells have been drilled in this area and once they are put into production it will be important to reassess the effects of increased pumping in this area.

Future development:

The recharge use ratio of this well averages around 12%, but it is unclear as to how well the recharge estimates incorporate the addition of MFR to the local aquifer. The area is soon to be subject to what are likely to be drastic increases in extraction rates from five new wells that are not yet online. It would be prudent to assess the effects of this recent development prior to planning any future groundwater development in the watershed.

Table 4.7: Malaeimi region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
1943-01	-	8.8	-	-	-	-	-	20	-
1944-09	35	25.4	23.9	15	10	-	-	-	-
1944-13	**67**	**3.2**	**-0.5**	**280**	**-**	**-**	**-**	**28**	**↑, 1**
1944-14	69	1.8	-	-	-	-	-	-	-
1944-17	88	19.2	-	300	-	-	-	-	-
1944-19	**89**	**30.7**	**-1.1**	**180**	**41**	**30000**	**1798**	**26**	**↑, 4**
1944-23	109	35.4	-	-	-	-	-	-	-
1944-24	110	23.5	-	-	-	-	-	-	-
-	1	20.3	-19.6	120	3	1107	5	-	-
-	2	8.0	2.8	300	58	2830	24	25	-
-	3	5.9	5.8	60	984	1301	637	-	-
-	4	16.5	-6.7	200	30	740	4	20	-
-	5	34.2	27.6	50	2	81	0.4	25	-

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

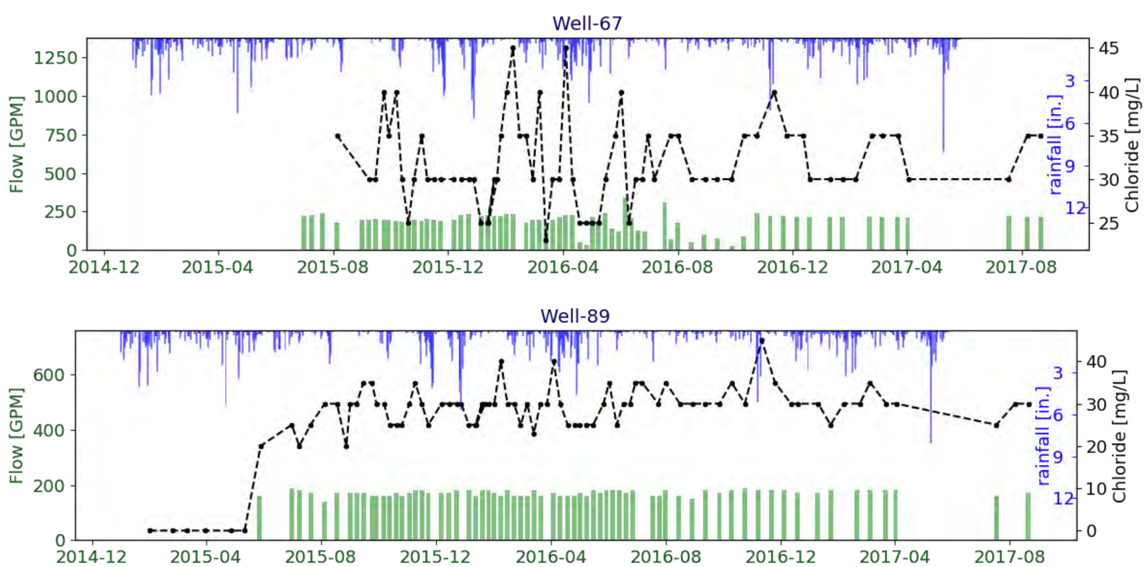


Figure 4.24 Plots of pump rates (green bars), Cl^- values (black line), and rainfall (blue bars) for each active well in the Malaeimi Valley Wellfield for the period 2015-2017.

4.2.4 Pago Valley Wellfield

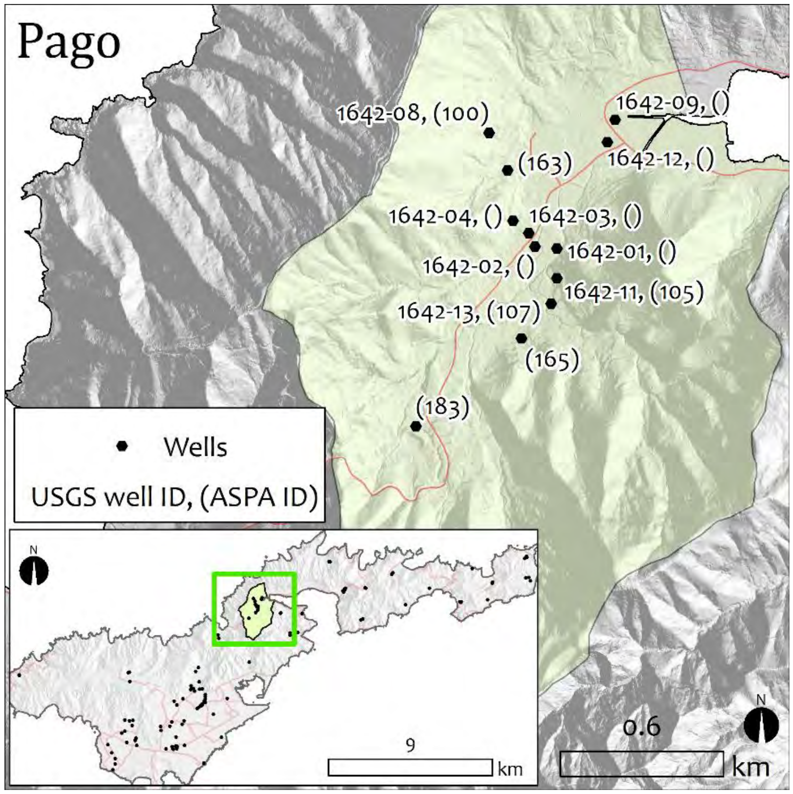


Figure 4.25: Location map of Pago Valley Watershed with locations of active and abandoned wells. *Green shading* denotes local watershed boundary, which does not necessarily delineate aquifer extent. Labels indicate well ID numbers.

The alluvial-fill valley of Pago Pago, also known as Vaipito Valley, is here referred to as Pago Valley (Figs. 4.25, 4.26, 4.27and ,4.28), is one of the largest and most populated on Tutuila. Groundwater development in this region dates back to the 1940's when Stearns selected a site for a water tunnel (Pago shaft, Well 1642-04) in a ridge of Pago inter-caldera rocks on the north side of the valley. Eyre and Walker (1993) provide an account of the construction and use of the Pago shaft:

> *"Pago shaft 2 is a water tunnel excavated at sea level and accessible through a vertical shaft 56 feet deep. The infiltration gallery is composed of several nearly horizontal tunnels that penetrate massive ponded lavas, volcanic ejecta, breccia, dikes, and faults, as well as a small amount of thin-bedded vesicular lava. The materials penetrated are typical of the rocks found in the central part of Tutuila. The artesian aquifer tapped by the tunnels had a head of 30 feet above sea level. Storage of 0.3 million gallons is available in the tunnels, only one of which contributes significantly to the gallery yield of about 60 gal/min."*

Numerous other wells have been drilled in the valley, generally through a relatively thick (15 to 30 m) veneer of alluvium into either the layered a'a flows of the Pago Outer-Caldera Unit or the massive flows of the Pago Inner-Caldera Unit. The fault boundary separating the inner and outer unit likely lies somewhere between Pago shaft 1642-04 and Well 1642-08 based on different lithologies documented in their driller's logs. Higher pre-development water levels and low $\boldsymbol{K}$ values in the more southerly of Pago valley's wells may indicate that they are located within the Pago Inner-Caldera Unit. Also an artesian aquifer was reported to have been found in 1985 very near to the shore at the Pago Plaza in Wells 1642-09 and 1642-12. The productive formation at about 20 m depth consisted of basalts overlain by 5 m of alluvium and scapolite. Drilling water levels were about 0.5 m above ground surface with low (10 mg/L) Cl^- concentrations (Eyre and Walker, 1993). With pumping, Cl^- concentrations in these wells rose to an average of 250 mg/L, though the eventual fate of these wells remains unreported. A number of other anecdotal reports of lithology and drilling conditions of wells in the Pago region are reported by Eyre and Walker (1991; 1993) (Table 4.8).

Currently five wells produce about 1.7 Mgal/d of water from the valley. While most wells in this area show low Cl^- concentrations, Well 163 has concentrations that are significantly higher. This is enigmatic as the other wells are drilled to similar depths and have similar extraction rates. It is possible that this discrepancy could be caused by heterogeneous subsurface structures that connect the location of Well 163 to coastal water more directly than other parts of the local formation. This hypothesis could be tested through the use of tidal efficiency tests at each of the wells in this region. Also the geologic unit boundary between the Pago Outer-Caldera Unit and the Inner-Caldera Unit, is thought to lie somewhere proximal to Well 163, thus the behavior of this well might be controlled by faulting or other types of fractures. Nonetheless Well 163 is only about 0.5 km from the Vaipito Stream estuary and may serve as an example of the risks involved in drilling in thinner portions of the freshwater lens.

Although pre-development water levels in the region were generally high (up to 10 or 20 m) pumping water levels are primarily below sea level. This indicates the low hydraulic conductivity of this area and the high risk of thinning of the freshwater lens. Water level and Cl^- concentration trends in the Pago area are similar to that of the Aua region, though not as dire. Because of this, and the already high Cl^- concentration in Well 163, the sustainability of additional water development in this area is questionable.

The Pago Harbor Region is estimated to receive between 15.7 and 16.6 Mgal/d of recharge (range of all estimates), whereas the extraction at the valley's active wells averages 1.5 Mgal/d (1045 GPM). The roughly estimated area weighted recharge use ratio for the Pago Valley Watershed is between 33 and 35% (average of 34%).

Table 4.8: Pago Valley aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m^2/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
1642-01	-	10.7	-	-	-	-	-	30	-
1642-02	-	8.2	-	-	-	-	-	-	-
1642-03	-	10.5	-	-	-	-	-	13	-
1642-04	-	7.3	-	-	-	-	-	-	-
1642-08	100	1.2	-	35	-	-	-	-	-
1642-09	-	3.0	-	-	-	-	-	250	-
1642-11	**105**	**12.4**	**-44.8**	**88**	**11**	**78**	**2**	**51**	**↑, 3**
1642-12	-	3.0	-	-	-	-	-	250	-
1642-13	**107**	**20.3**	**-21.2**	**380**	**-**	**-**	**-**	**91**	**↑, 2**
-	**163**	**7.3**	**-35.9**	**150**	**8**	**140**	**5**	**846**	**↑, 273**
-	**183**	**62.5**	**61.0**	**224**	**20**	**140**	**10**	**28**	**↑, 2**
-	**165**	**-**	**-31.5**	**203**	**-**	**-**	**-**	**41**	**↑, 2**

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

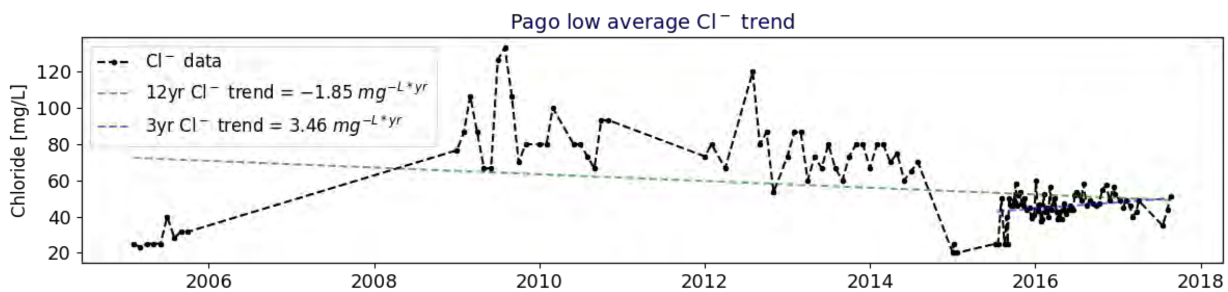


Figure 4.26: Cl^- concentrations averaged across active wells in the Pago Valley, except for Well 163, which has Cl^- concentrations that are significantly higher than other wells in the area. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

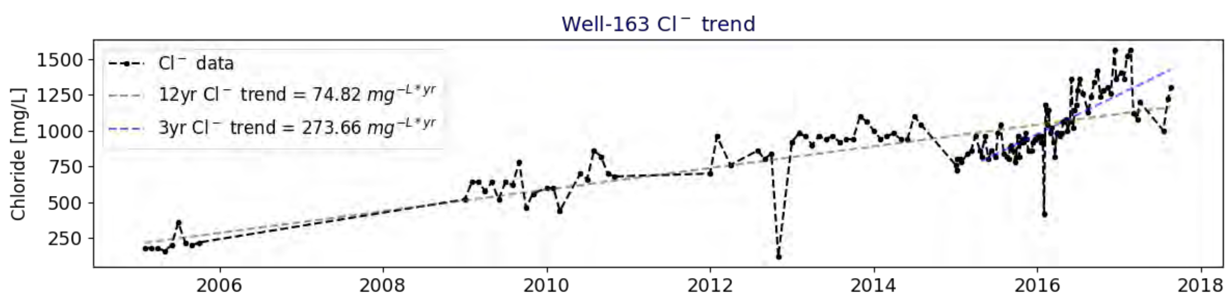


Figure 4.27: Cl^- concentrations for Well 163, which has distinctively higher Cl^- concentrations than the other Pago area wells. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: The wells in Pago Valley can be classified into three groups based on their potential sustainability: (1) Well 183, which utilizes a high-level (or potentially semi-perched) reservoir; (2) Well 163, which must develop a thin part of the basal aquifer or be drilled in a different lithology; and (3) all the other wells, which utilize a seemingly thicker part of the basal lens. Cl^- concentrations at Well 163 clearly indicate that this well is experiencing saltwater upconing and the issue is only being exacerbated with continued pumping. While this well is the closest of its neighbors to the coast, it is located only about 150 m closer to the Vaipito Stream estuary than Wells 105 and 107, and is drilled to a similar depth (-50 to -60 m) as nearby wells. Regardless, it is clear that Well 163 would benefit from a reduction in pumpage or in abandonment.

The other wells that utilize the basal aquifer (group 2 above) seem to have relatively low and stable Cl^- concentrations in comparison to Well 163, despite having production water levels that are similar and below sea level. These wells may tap an aquifer system that has less connectivity to coastal saltwater and more connectivity to freshwater recharge zones located above. These wells seem to have fairly stable Cl^- trends suggesting that if their pump rates are not increased current production levels may be maintained without detriment to local water quality.

Well 183, which is located at a higher elevation, seems to tap an aquifer that is significantly elevated above the basal water levels that are found at the Valley's other wells. This suggests the aquifer tapped by Well 183 is perched, semi-perched or elevated in some other manner. The water produced at this well has a Cl^- concentration that is not affected by underlying saltwater at all, further supporting the idea that it is disconnected from the basal system below.

Future development: Additional exploration could be undertaken in the upper sections of the watershed to assess the development potential of the elevated water system found at Well 183. Additional development in the lower watershed area is not recommended based on the already high extraction in this area.

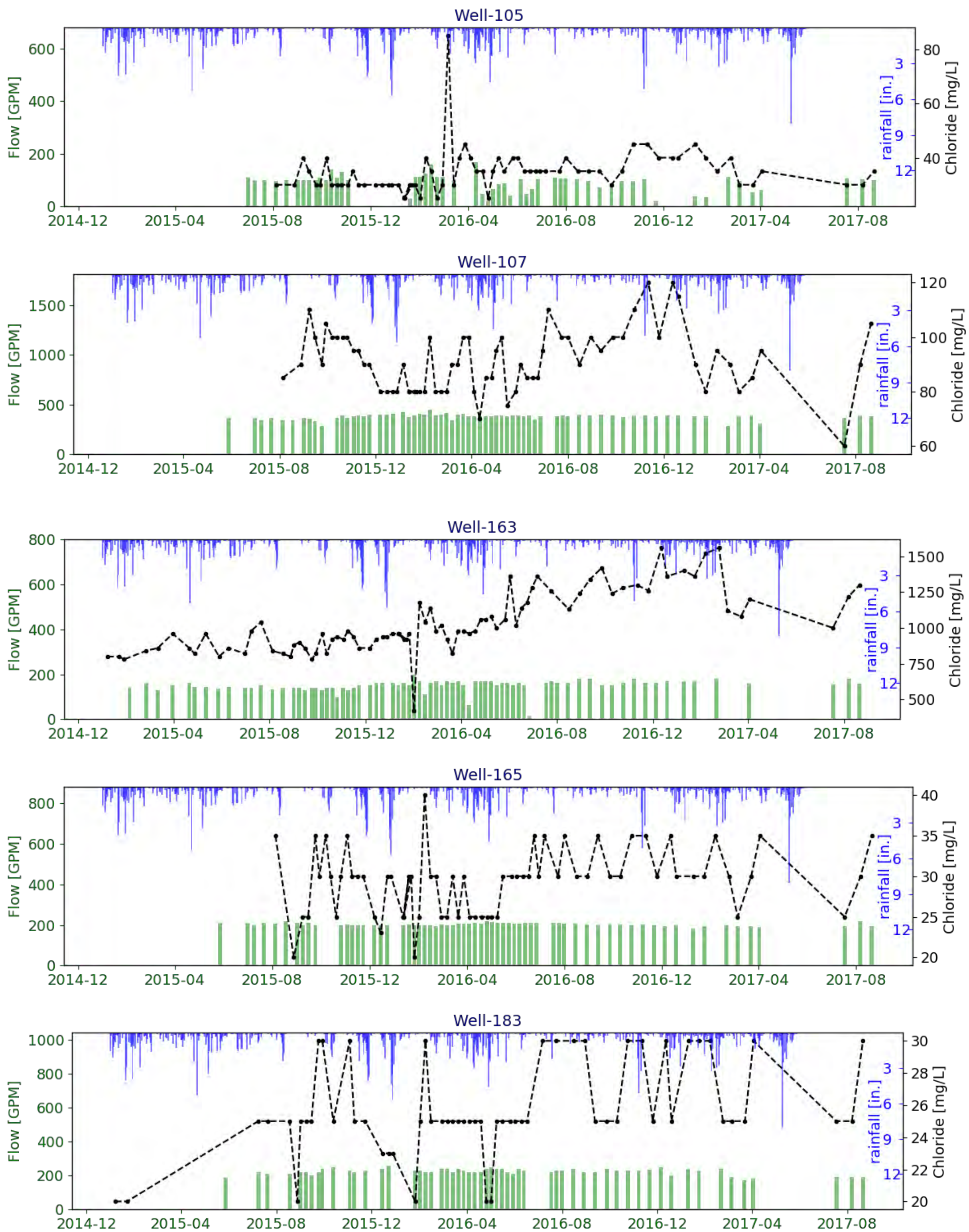


Figure 4.28: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Pago Valley Wellfield for the period 2015-2017.

4.3 Heavily Developed Areas

Regions or wellfields grouped in this section already have a significant amount of existing groundwater development in place. Many of these areas have increasing Cl^- trends or decreasing water level trends (Fig. 4.29). Additionally, groundwater recharge to extraction ratios in many of these areas are generally higher than the in areas in other sections. While each area is influenced by each these factors to a different degree, in general, these indicators suggest that groundwater withdrawals may be occurring at a rate exceeding the capacity of the aquifer to sustainably supply water. In consideration of these concerns future development of groundwater in these areas is generally not recommended.

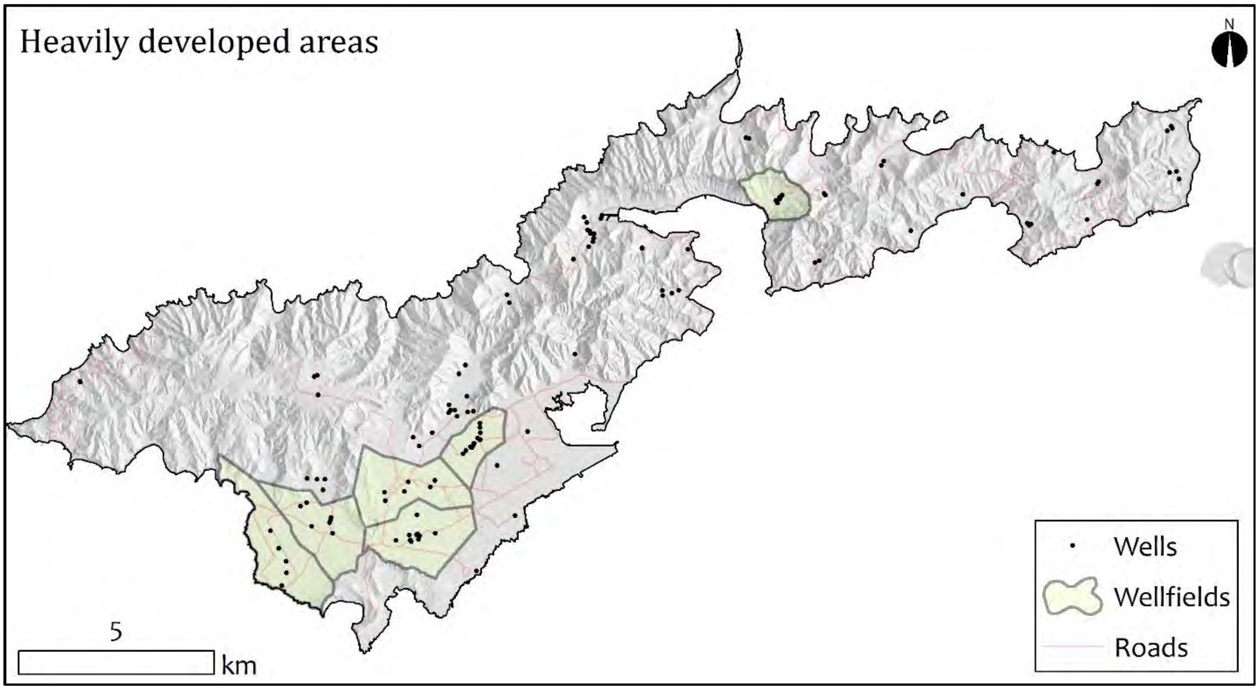


Figure 4.29: Map of wellfields showing characteristics where current extraction rates may exceed the water supply capacity in Tutuila.

4.3.1 Aua Watershed

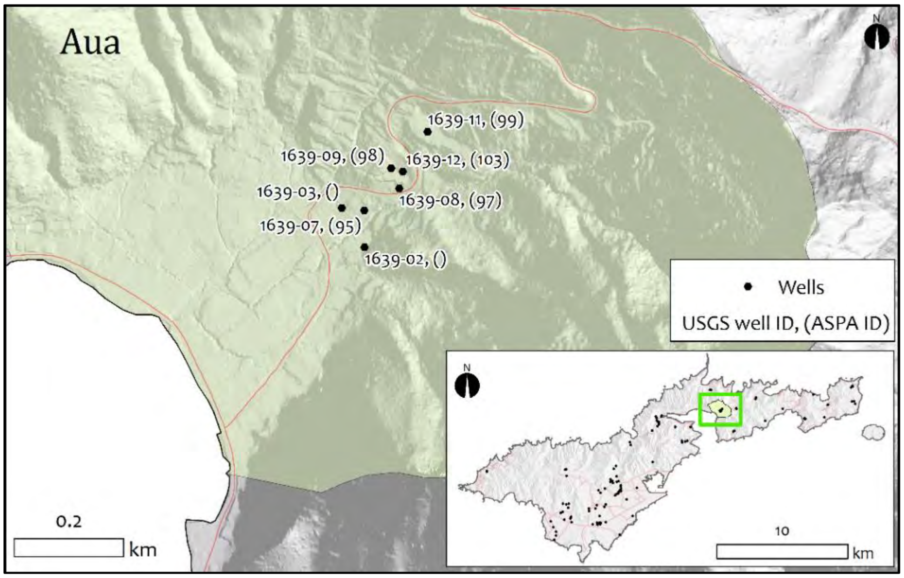


Figure 4.30: Location map of Aua Watershed with locations of active and abandoned wells. *Green shading* denotes local watershed boundary, which does not necessarily delineate aquifer extent. Labels indicate well ID numbers.

The Aua Region (Figs. 4.30, 4.31, and 4.32) provides a clear example of consequences that may be expected when rates of groundwater withdrawal exceed the sustainable capacity of an aquifer. In Aua, these consequences have taken the form of large water level drawdowns (up to 15 m) and progressively increasing Cl^- concentrations. In 1983 total extraction in this area was 0.28 Mgal/d (233.5 GPM), this rose to 0.93 Mgal/d (775.5 GPM) in 1985, and then in 1989 was scaled back to 0.22 Mgal/d (183.5 GPM), following a rise in chloride concentration. Currently only Wells 97 and 99, are active in this watershed and together they now produce an average of 0.39 Mgal/d (229 GPM). Present day Cl^- concentrations in these wells are some of the highest on the island, generally exceeding the USEPA recommended maximum level of 250 mg/L by 4 to 7 times. In addition to high Cl^- levels, these wells also show large pumping water level drawdowns, 11 m in Well 97, and 15 m in Well 99. While some of this drawdown can be attributed to well losses, the temporal trend in regional water levels clearly indicates that dewatering of the aquifer has taken place. This trend is evident in pre-development water level observations, which dropped from an average of about 5 m above sea level when the first wells were drilled in this area to over -7 m below sea level when now inactive Well 103 was drilled in 1985. At Well 99 a static water level of -1.2 m below sea level was recorded in 2014 after a 24-hour cessation in pumping. Eyre and Walker (1991) provide a summary of the area's hydrogeology and development history.

> *"The producing zone of the volcanic aquifer in Aua valley, west of Laulii, is overlain by approximately 100 feet of saturated sediments and several tens of feet of poorly permeable basalt. The alluvial aquifer has not been developed because of its generally low permeability and its susceptibility to contamination. By drilling to sufficient depths a productive artesian aquifer, with a potentiometric surface 20 feet above sea*

level, has been tapped. Apparently, recharge to the deep aquifer is by way of fractures in the overlying rock… The water level at the deeper of two adjacent alluvial wells was 18 feet above sea level, while the water level at the shallower well was 16 feet above sea level (Bentley, 1975). A source of this alluvial water is apparently upward flow from the deeper artesian volcanic aquifer….During the drilling of deep Aua wells 95, 97, 98, 99, a substantial flow of water was not found until productive zones between 40 and 140 feet below sea level were tapped. The water rose to 20 feet above sea level at well 95 when it was completed in 1981. Subsequent wells encountered progressively lower water levels. A single aquifer has been tapped by these wells, as evidenced by the decline of water levels at each well in response to pumpage from the others."

The similar water chemistry and water level behavior in the Aua wells indicates that the wells tap a common aquifer, which is probably fairly limited in extent and bounded by impermeable structures that do not provide a hydraulic connection to distant reservoirs. This idea is supported by the results of a pumping test performed in 1982 and documented in Eyre and Walker (1991):

"*When well 97 was pumped steadily at a rate of 263 GPM, water levels declined 38 feet in 27.7 hours and remained at that level, or rose slightly, for the next 44.3 hours (test data is in the files of the U.S. Geological Survey, Honolulu, Hawaii). …a step drawdown test shows that the aquifer loss was about 23 feet at that pumping rate. Because the cone of depression is generally steep in aquifers of low permeability, water levels several hundred feet from well 97 would be expected to be little affected. Certainly the static water levels of -6 and -20 feet relative to sea level, eventually reached at wells 99 and 103, respectively, could not have been predicted from the 72-hour pumping test. These large drawdowns, far from the pumping wells, were most likely be caused by dewatering of an aquifer of limited size."*

The Pago Harbor Region is estimated to receive between 15.6 and 16.6 Mgal/d of recharge (range of all estimates), whereas the extraction at wells 97 and 99 averages 0.3 Mgal/d (229 GPM). The estimated area weighted recharge use ratio for Aua Watershed is between 17 and 18% (average of 17%) (Table 4.9).

Table 4.9: Aua region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m^2/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
1639-02	-	5.5	-	30	1	-	-	-	-
1639-03	-	5.1	-	45	16	-	-	-	-
1639-07	95	6.1	-	-	-	-	-	-	-
1639-08	**97**	**5.5**	**-10.2**	**190**	**24**	**190**	**4**	**1586**	**↑, 114**
1639-09	98	4.3	-	-	-	-	-	271	-
1639-11	**99**	**1.2**	**-15.1**	**139**	**10**	**150**	**5**	**942**	**↑, 91**
1639-12	103	-7.6	-21.9	280	20	183	5	-	-

* Pump rates and Ave. Cl^- values are taken from 2015-2017 ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

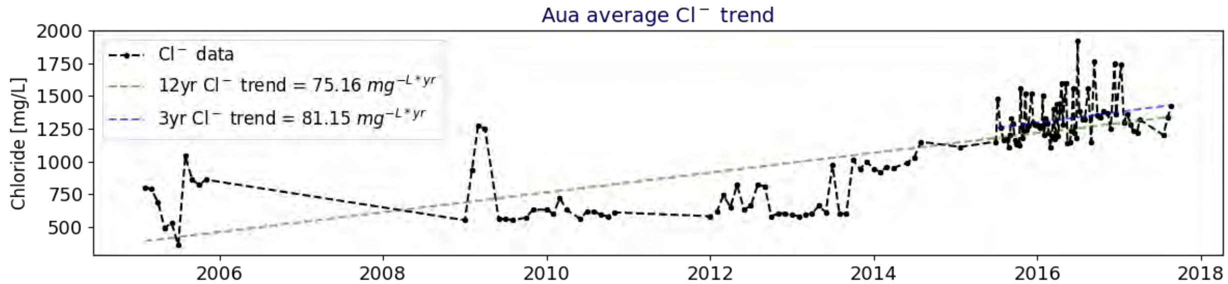


Figure 4.31: Cl^- concentrations averaged across all active wells in the Aua Region. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Considering high observed aquifer drawdown and chloride levels observed in Wells 97 and 99, the pumping rates in these wells could be reduced to allow recovery of the aquifer and reduction of Cl^- concentrations.

Future development: Due to the groundwater development history in the Aua area, drilling additional wells in the already over-utilized aquifer is not recommended. If additional wells are necessary in this area, they could be used to offset the pumpage of existing wells, thereby allowing all the wells in the aquifer to pump at lower rates. This may spread out the effects of withdrawals to a larger area, and potentially serve to reduce local drawdown and Cl^- at each well. This would require locating new wells as far from existing wells as possible.

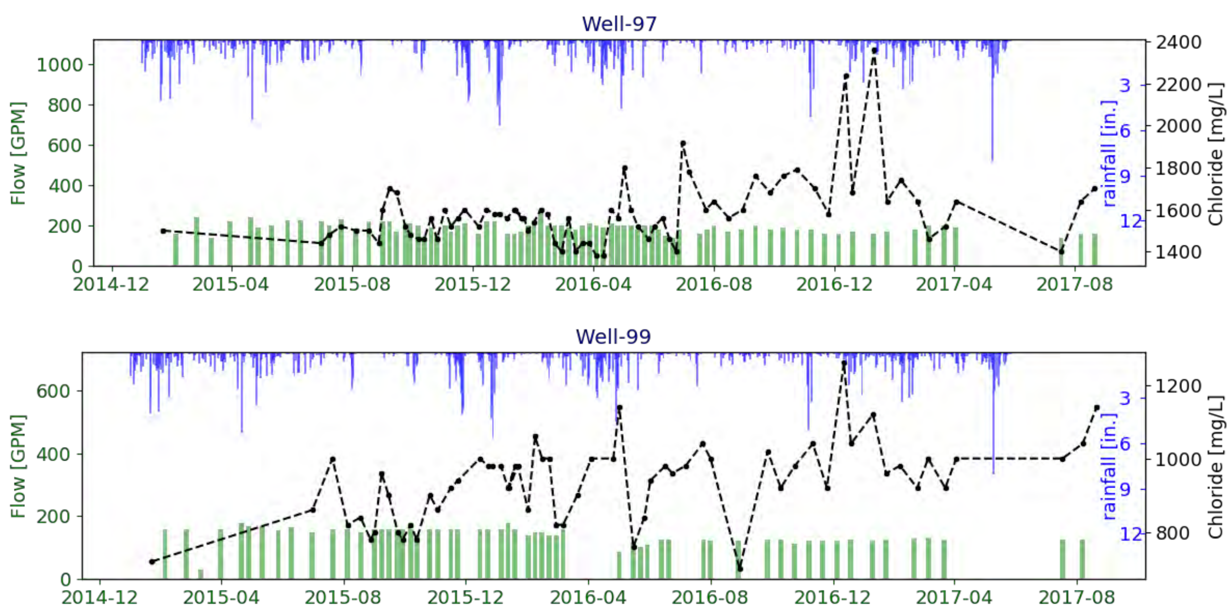


Figure 4.32: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Aua Region for the period 2015-2017.

4.3.2 Iliili Wellfield

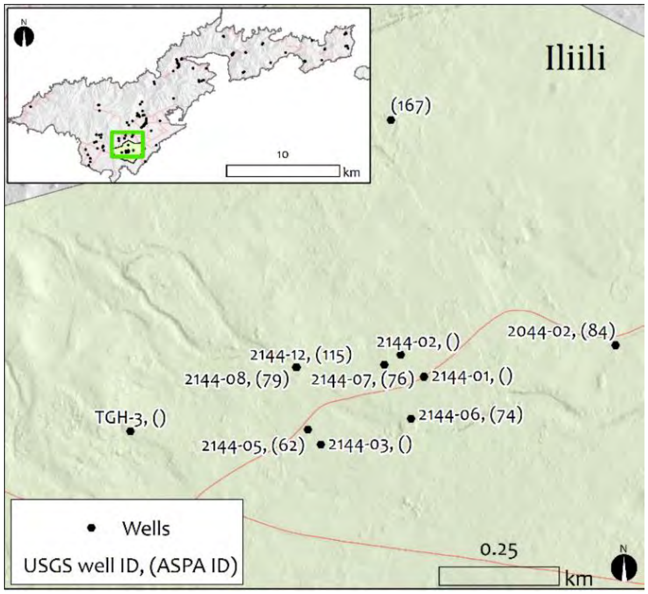


Figure 4.33: Location map of Iliili Region with locations of active and abandoned wells. *Green shading* denotes Thiessen polygon boundary based on clustering of wells into wellfields. This boundary is not intended to delineate aquifer extent. Labels indicate well ID numbers.

The Iliili Wellfield (Figs. 4.33, 4.34, and 4.35) is located in the southwestern region of the Tafuna-Leone Plain. Iliili is near the Pavaiai Wellfield and it is likely that the thin basal-lens aquifer is interconnected through the Iliili, Pavaiai, and Tafuna Wellfields since there is a generally high hydraulic conductivity throughout the whole area. However, the Iliili Wellfield may be distinct in its local permeability distribution as it is located closer to the ash cones on the southern portion of the Leone Rift. The geology is inferred to be relatively more pyroclastic rich (Stearns, 1944) and thus there is likely to be a significantly lower vertical hydraulic conductivity in this area than the more northeasterly wellfields. Levels of total coliform and *Escherichia coli* bacteria in Well 84 (Shuler, unpublished data, 2016) are generally lower than in the Tafuna and Malaeimi Wellfields, indicating that there may indeed be longer travel times or more aquifer filtration in the Iliili Region. Also the deep borehole TGH-3 was drilled in the western portion of the wellfield and the lithologic log and core samples give a detailed record of the aquifer structure at that point (Table 4.10).

Although there have been numerous wells drilled in this area, there are only four active wells in the wellfield that together produce about 1.2 Mgal/d. Pumping rates are relatively high and drawdowns are relatively low indicating the high overall hydraulic conductivity in this region. Well 84 has an exceptionally high Cl^- level which averages about two times the U.S. standard, indicating this well's and potentially the whole region's susceptibility to saltwater upconing. The annual average composite chloride concentration has increased from 30 mg/L in 1975 to about 175 mg/L in 1989, and now averages about 210 mg/L. The long term trend of increasing salinity in conjunction with measurements of a relatively thin fresh water lens in this area suggests that current rates of groundwater extraction have already begun to impact the sustainability of the resource in this area. Further groundwater development in the lower elevations of the Iliili Region are not recommended, though there may be some potential to tap thicker aquifers in the lower permeability area of the rift zone.

The Tafuna Plain Region is estimated to receive between 24.5 and 45.9 Mgal/d of recharge (range of all estimates), whereas the extraction at the wellfields active wells averages 1.5 Mgal/d (1012 GPM). The roughly estimated area weighted recharge use ratio for Iliili Wellfield is between 22 and 41% (average of 32%).

Table 4.10. Iliili region aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl- [mg/L]	Cl- trend [mg/L/yr.]
2044-02	**84**	**1.8**	**0.6**	**283**	**577**	**11000**	**3825**	**475**	**↑, 91**
2144-01	-	-	-	-	-	-	-	44	-
2144-02	-	-	-	-	-	-	-	76	-
2144-03	-	-	-	-	-	-	-	45	-
2144-05	**62**	**2.6**	**0.4**	**239**	**736**	**7000**	**1126**	**121**	**↑, 11**
2144-06	74	1.8	-	-	-	-	-	-	-
2144-07	**76**	**1.4**	**-0.8**	**265**	**478**	**3446**	**992**	**101**	**↑, 15**
2144-08	79	0.9	-	-	-	-	-	-	-
2144-12	115	1.8	-	-	-	-	-	-	-
-	**167**	**-**	**1.0**	**225**	**-**	**-**	**-**	**101**	**↑, 17**
TGH-3	TGH-3	1.9	-	-	-	-	-	-	

* Pump rates and Ave. Cl- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl- trend ↑ denotes increasing Cl- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

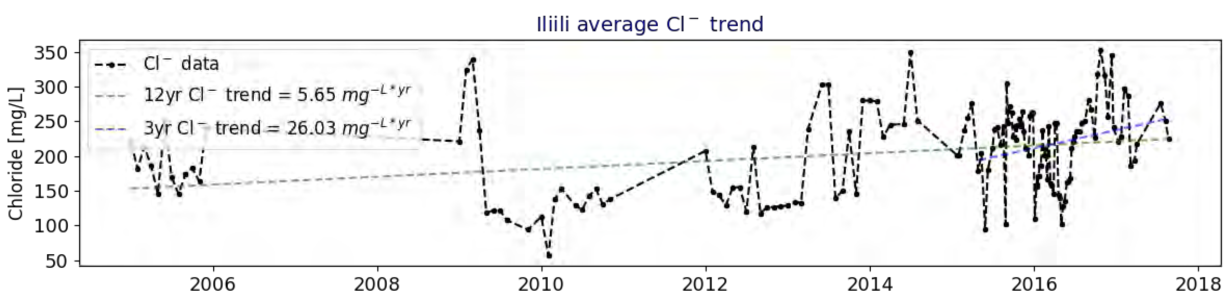


Figure 4.34: Cl- concentrations averaged across all active wells in the Iliili Wellfield. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: The Iliili area shows thinning of the freshwater lens and as such, the wells in this area produce groundwater with fairly high Cl- concentrations, with Well 84 producing the highest. This is to be expected, as Well 84 is the closest to the coast and is located in the thinnest part of the lens. Shifting production towards more upgradient wells, such as Well 167, and reducing withdrawals at Well 84 may help to alleviate the issue somewhat.

Future development: If future groundwater development is considered in this area, locating wells closer to the Leone Rift Zone, near the TGH-3 location, and as far from the coast or Well 84 as possible will decrease chances of encountering continued issues with salinization.

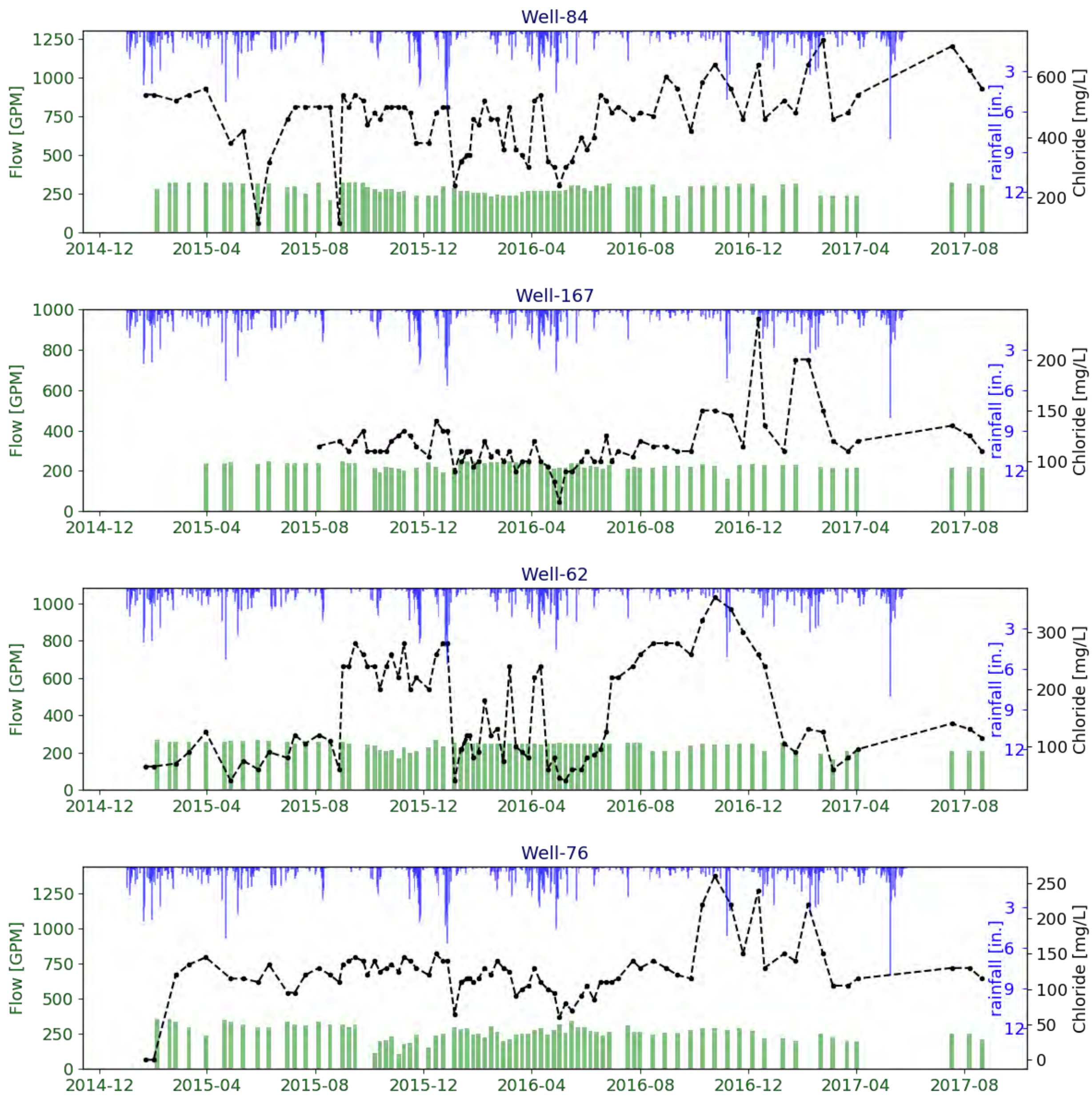


Figure 4.35: Plots of pump rates (*green bars*), Cl⁻ values (*black line*), and rainfall (*blue bars*) for each active well in the Iliili Wellfield for the period 2015-2017.

4.3.3 Pavaiai Wellfield

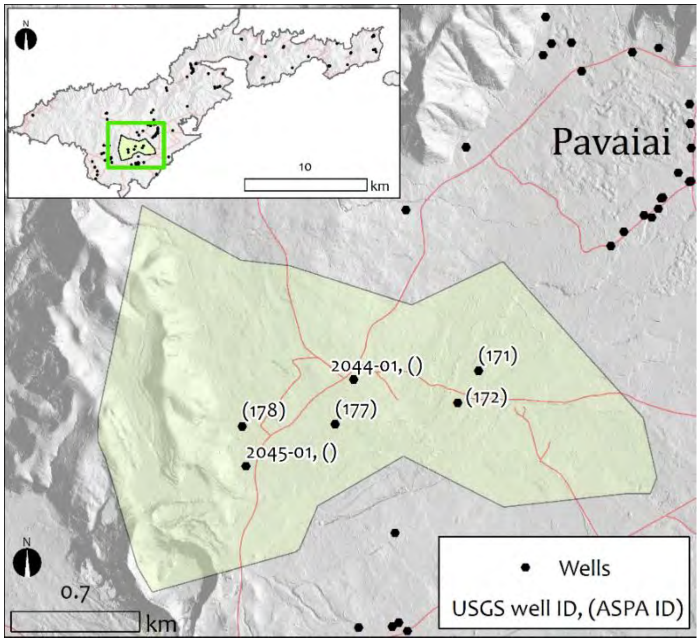


Figure 4.36: Location map of Pavaiai Wellfield with locations of active and abandoned wells *Green shading* denotes Thiessen polygon boundary based on clustering of wells into wellfields. This boundary is not intended to delineate aquifer extent. Labels indicate well ID numbers.

The Pavaiai Wellfield (Figs. 4.36, 4.37, and 4.38) could be considered to be an extension of the Tafuna or the Iliili Wellfields, which are all likely share the same aquifer. The Pavaiai field is distinguished here because it shares aquifer characteristics with the Tafuna Wellfield, high-hydraulic conductivities and large specific capacities, but produces groundwater that does not seem to show the same effects of surface water contamination that the Tafuna field is subject to. Similar to Iliili, some wells produce water with high Cl^- concentrations and have static water levels that are near to sea level. These observations suggest the basal lens is thin in this region as well (Table 4.11).

The Tafuna Plain Region is estimated to receive between 24.5 and 45.9 Mgal/d of recharge (range of all estimates), whereas the extraction at the wellfields active wells averages 1.4 Mgal/d (962 GPM). The roughly estimated area weighted recharge use ratio for Pavaiai Wellfield is between 20 and 38% (average of 29%).

Table 4.11: Pavaiai Wellfield aquifer parameters.

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
2044-01	-	-	-	-	-	-	-	-	-
2045-01	-	-	-	-	-	-	-	15	-
-	**171**	**-**	**1.0**	**245**	**44291**	**99753**	**4616**	**456**	↑, 55
-	**172**	**-**	**0.8**	**242**	**2947**	**21778**	**5372**	**481**	**↑, 63**
-	**177**	**1.3**	**1.0**	**380**	**691**	**6300**	**870**	**241**	**↑, 27**
-	**178**	**-**	**1.7**	**95**	**100**	**1200**	**77**	**28**	0

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

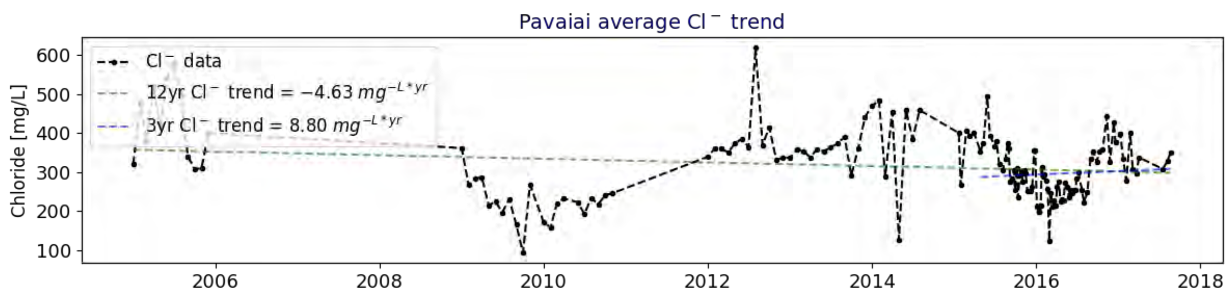


Figure 4.37: Cl^- concentrations averaged across all active wells in the Pavaiai Wellfield. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Wells in the Pavaii Wellfield pump at fairly high rates and produce water with Cl^- concentrations reflecting the effect of these rates in a hydraulically conductive aquifer with a thin basal lens. The generally high Cl^- concentrations in this area seem to decrease in response to rainfall events, thus pumping rates could be reduced in these wells during periods of low rainfall. Any additional reduction in pumping rates in this well field would likely help to alleviate the currently observed problems of high Cl^- levels and increasing Cl^- trends.

Future development: If future groundwater development is considered in this area, locating wells closer to the Leone Rift Zone, near the elevation of Well 178, may increase the chances of reducing continued issues with salinization. Well 178 is located in an area with a higher proportion of volcanic ash, the Leone Pyroclastics Geologic Unit, and as such would be expected to have lower ***K*** values, with a thicker freshwater lens.

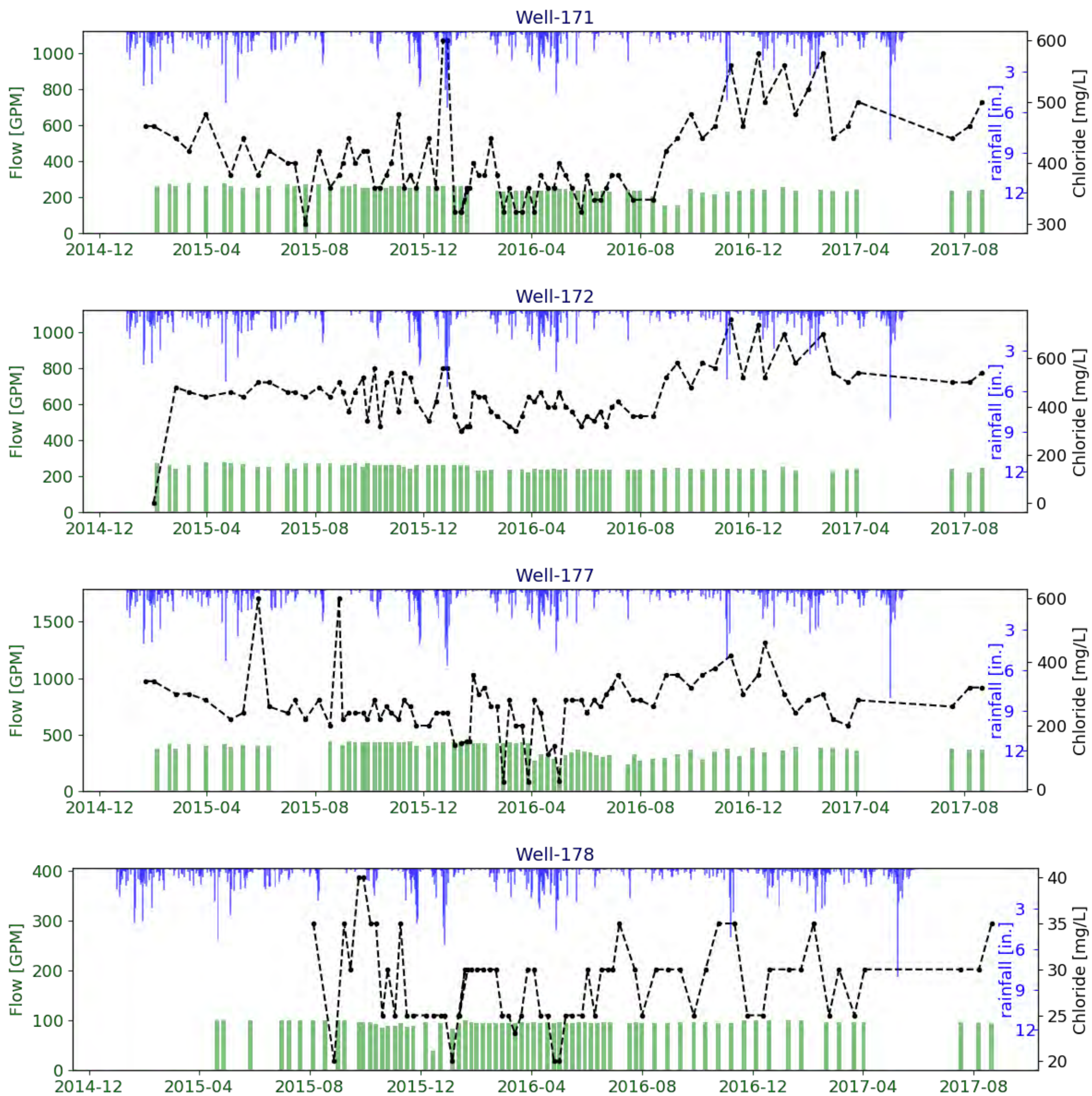


Figure 4.38: Plots of pump rates (*green bars*), Cl⁻ values (*black line*), and rainfall (*blue bars*) for each active well in the Pavaii Wellfield for the period 2015-2017.

4.3.4 Lower Malaeloa Wellfield

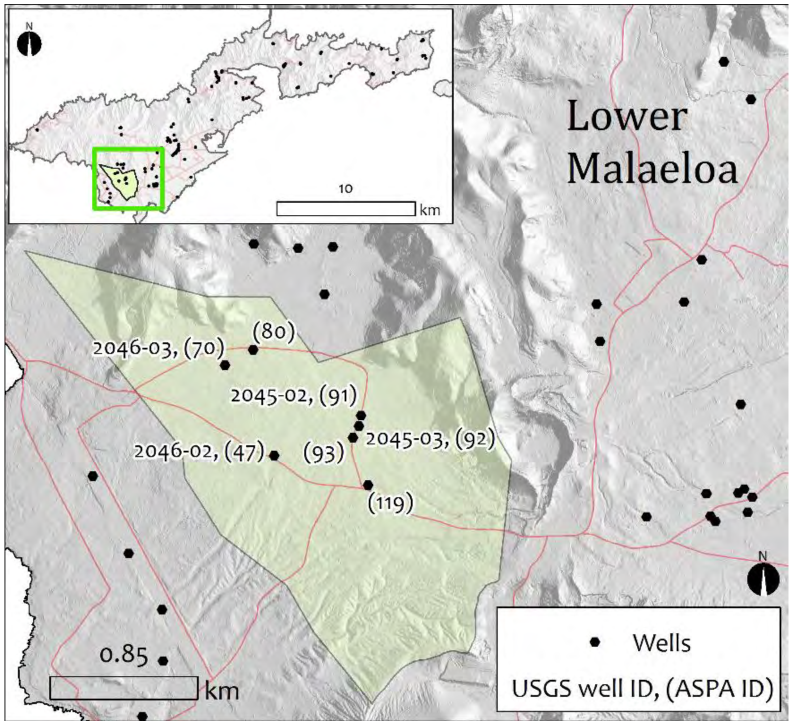


Figure 4.39: Location map of Lower Malaeloa region with locations of active and abandoned wells. *Green shading* denotes Thiessen polygon boundary based on clustering of wells into wellfields. This boundary is not intended to delineate aquifer extent. Labels indicate well ID numbers.

The Lower Malaeloa Wellfield (Figs. 4.39, 4.40, and 4.41) is one of the most productive on Tutuila. Historically, total extraction from the this wellfield increased from 0.1 Mgal/d in 1977 to 1.7 Mgal/d in 1989, and it currently produces a total of 3.0 Mgal/d from eight wells. In this report the Lower Malaeloa wells are distinguished from the upper Malaeloa wells based on proximity to the mountains composed of Taputapu Shield rocks. The more northerly wells are likely to tap into the Taputapu unit, whereas the southerly wells only encounter Holocene age Leone Volcanics. While the aquifers are likely to be hydraulically connected, they probably have different overall properties. The Lower Malaeloa Wellfield contains five active pumping wells that together produce 1.6 Mgal/d of generally low Cl^- water. The exception is the most southerly well (119), which has had an average Cl^- concentration of about 290 mg/L since 1989. In addition to direct recharge this area also gains additional recharge from MFR processes. Pre-development water levels in this portion of the Leone Plain were approximately 1.0 to 1.5 m and even relatively high extraction rates do not cause substantial aquifer drawdown. This observation is supported by relatively high values of ***T*** and ***K***, which are expected in the young Holocene Volcanics. Although NO_3^- levels in Malaeloa wells are currently only about 1/10th of the U.S. drinking water maximum contaminant limit, the Malaeloa Wellfield is located in an area of high on-site disposal system density and is downgradient from some of the island's most significant row crop agricultural operations. These potential contaminant sources are a consideration for future water development in this region. Since the majority of contaminant sources are located downgradient of the Upper Malaeloa Wellfield, this portion of Maleloa is a more conservative area for future development. Salinity values are generally low except at Well 119, which shows a higher Cl^- concentration as well as a steeper rate of Cl^- increase with time (84 mg/L/yr) (Table 4.12).

The Leone Plain Region is estimated to receive between 8.7 and 18.7 Mgal/d of recharge (range of all estimates), whereas the extraction at the wellfield's active wells averages 1.6 Mgal/d (1134 GPM). The roughly estimated area weighted recharge use ratio for Lower Malaeloa Wellfield is between 37 and 80% (average of 53%).

Table 4.12: Lower Malaeloa Wellfield aquifer parameters.

Well # [USGS ID]	**Well # [ASPA ID]**	**Drilling WL [m]**	**Pumping WL [m]**	**Pump rate [GPM]**	**Specific capacity [GPM/m]**	**T [m²/day]**	**K [m/d]**	**Avg. Cl^- [mg/L]**	**Cl^- trend [mg/L/yr.]**
2045-02	**91**	**1.8**	**1.2**	**245**	**2063**	**6900**	**1765**	**27**	**↑, 1**
2045-03	92	1.2	-	-	-	-	-	-	-
2046-02	47	1.2	0.0	80	66	-	-	15	-
2046-03	**70**	**2.6**	**0.8**	**372**	**1129**	**6500**	**1257**	**30**	**↑, 4**
-	80	-	2.4	-	-	-	-	20	-
-	**93**	**-**	**1.0**	**263**	**718**	**3800**	**406**	**27**	**↑, 2**
-	**119**	**-**	**0.9**	**254**	**826**	**6300**	**496**	**245**	**↑, 84**

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

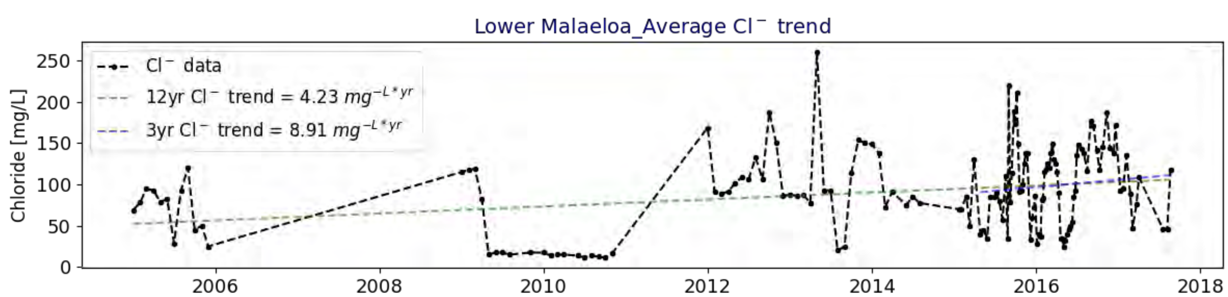


Figure 4.40: Cl^- concentrations averaged across all active wells in the Lower Malaeloa Region. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells: Most of the wells in this area show fairly low Cl^- concentrations with the exception of Well 119, which is located closest to the coast and thus in the thinnest part of the lens. Cl^- concentrations at Well 119 can be seen to fluctuate with rainfall. Shifting production towards more upgradient wells, and reducing withdrawals at Well 119 may help to alleviate the issue somewhat.

Future development: Due to already significant extraction rates, additional groundwater development is not recommended in the Lower Malaeloa Wellfield.

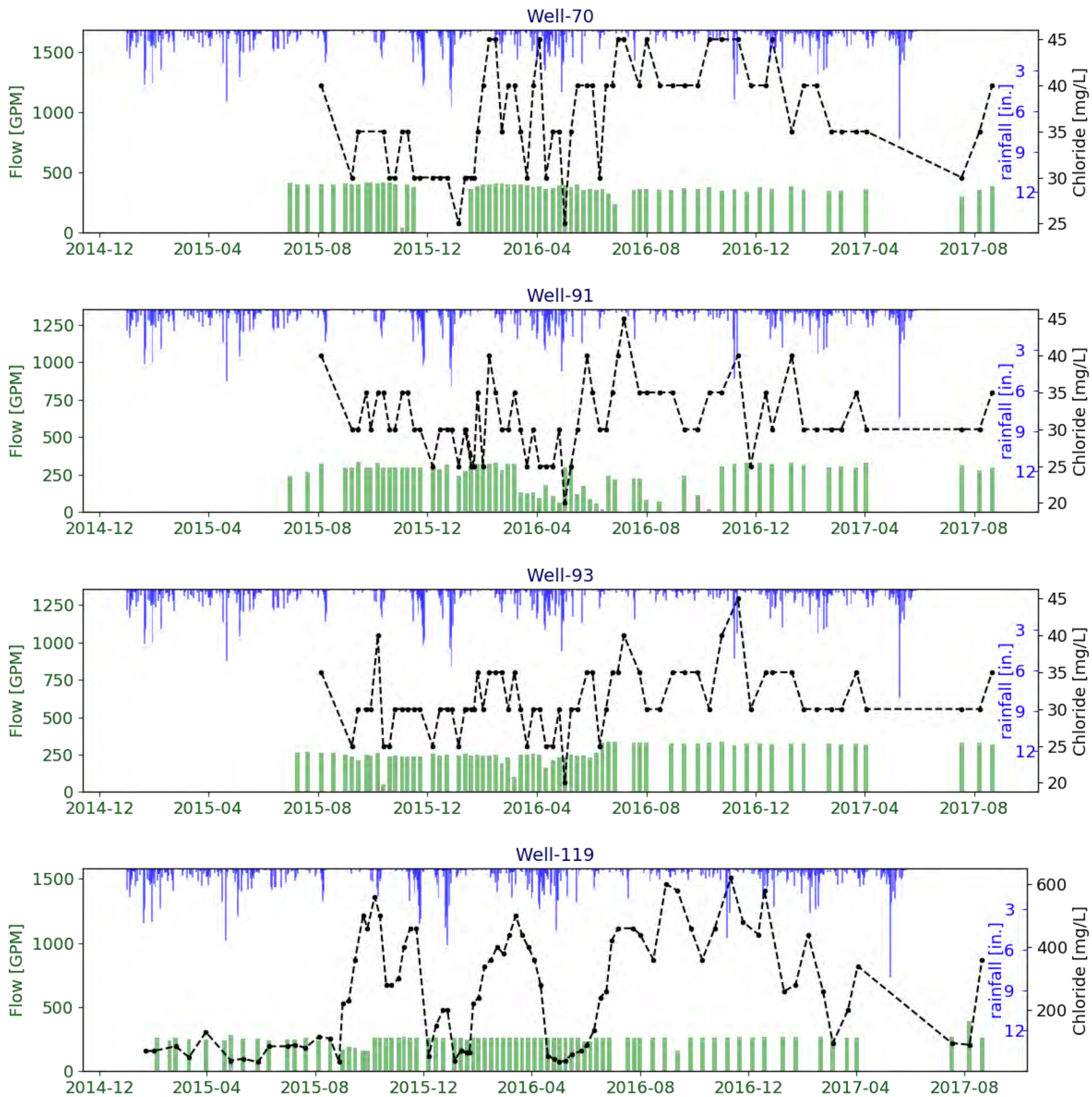


Figure 4.41: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Lower Malaeloa Wellfield for the period 2015-2017.

4.3.5 Leone Abandoned Wellfield

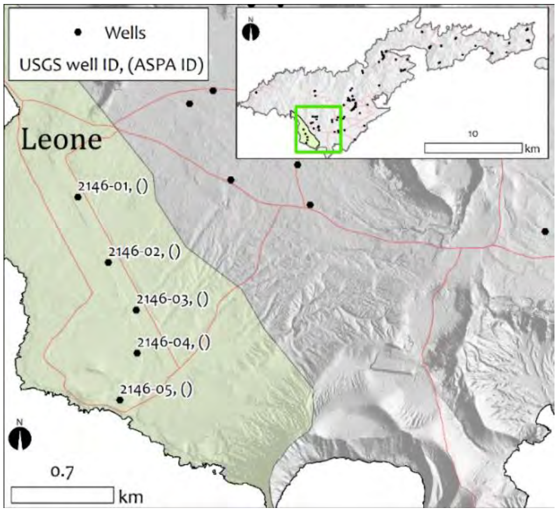


Figure 4.42: Location map of the coastally proximal Leone region with locations of now abandoned wells. *Green shading* denotes Thiessen polygon boundary based on clustering of wells into wellfields. This boundary is not intended to delineate aquifer extent. Labels indicate well ID numbers.

While the Leone area (Fig. 4.42) no longer has active pumping wells, it is described in this section as it is likely to be hydraulically connected to the heavily utilized Lower Malaeloa Wellfield. The old wells in this region were likely abandoned due to salinization, which is an expected effect of pumping from a thin nearshore freshwater lens. Pre-development water levels indicate that the lens height above sea level was never more than a meter even before pumping began. It is unknown whether reported Cl^- values are from pre-development or from production samples. Since this area has already been abandoned from previous groundwater development, future development in this region would likely prove to be un-sustainable. Additionally, this area is downgradient from a high OSDS and other non-point source pollution source density, and water quality may subject to anthropogenic impacts (Table 4.13).

Preliminary recommendations for sustainable aquifer management

Existing wells: Not applicable, all wells have been abandoned.

Future development: Additional groundwater development is not recommended in the Lower Leone area.

Table 4.13: Leone region aquifer parameters

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m^2/day]	K [m/d]	Avg. Cl^- [mg/L]	Cl^- trend [mg/L/yr.]
2146-01	-	0.2	-	-	-	-	-	94	-
2146-02	-	0.4	-	-	-	-	-	73	-
2146-03	-	-	-	-	-	-	-	260	-
2146-04	-	0.6	-	-	-	-	-	257	-
2146-05	-	0.0	-	-	-	-	-	-	-

* Pump rates and Ave. Cl^- values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl^- trend ↑ denotes increasing Cl^- trend. Values for inactive wells were taken from sources as described in Section 4.0.

4.3.6 Tafuna Wellfield

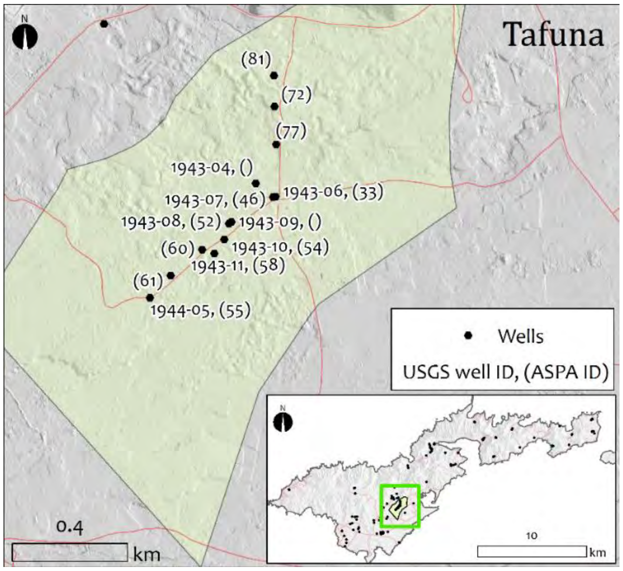


Figure 4.43: Location map of Tafuna Wellfield with locations of active and abandoned wells *Green shading* denotes Thiessen polygon boundary based on clustering of wells into wellfields. This boundary is not intended to delineate aquifer extent. Labels indicate well ID numbers.

While the Tafuna Wellfield (Figs. 4.43, 4.44, and 4.46) is currently one of the production workhorses of the ASPA municipal water system, this area may be destined for abandonment in the near future due to USEPA designation of seven of its highest producing wells as groundwater under the direct influence (GUDI) of surface water wells. This designation has necessitated the island's current Boil-Water-Advisory for nearly a decade. This issue is likely to be a consequence of very high hydraulic conductivity of the Tafuna Aquifer, which greatly exceeds the conductivities of any other region on the island (Bentley, 1975; Kennedy, 1987; Izuka et al. 2007). Numerous aquifer tests and water level measurements performed by multiple investigators support this conclusion. Since the region is generally constructed of thin bedded pahoehoe flows, the high permeability is likely to be manifest as secondary porosity in the form of fractures or lava tubes (Table 4.14).

Currently, the Tafuna Wellfield consists of eight closely-spaced active wells that together produce a total of 2.9 Mgal/d. Pre-development water levels averaged about 1.2 m above sea level, static water levels are reported to be about 1 m above sea level, and pumping water levels are around -1 m below sea level (note, this measurement includes well losses). While the unconfined basal aquifer is highly productive, relatively high chloride levels in many wells indicate that the freshwater lens is thin and at risk of overexploitation. Izuka (1999) observes that Cl^- concentrations in the Tafuna Wellfield vary with rainfall, slowly increasing during dry periods and rapidly decreasing during high-recharge events. Eyre and Walker (1993) note that exceptionally dry periods (droughts) such as those observed in 1979, 1983, and 1987 cause significant saltwater upconing and a subsequent rise in average Cl^- concentrations to over 350 mg/L. Bentley (1975) noted that wells in this region drilled to a depth of more than -6 m below sea level, experienced higher Cl^- concentration peaks during dry periods.

Two abandoned Wells, 2043-01 and 2043-02, that lie to the east of the tightly grouped active Tafuna wells show water levels that grade towards sea level and were documented to have produced fairly brackish water. The records of these abandoned wells illustrate the shape and the limited vertical extent of the of the Tafuna Region's freshwater lens.

The Tafuna Plain Region is estimated to receive between 24.5and 45.9 Mgal/d of recharge (range of all estimates), whereas the extraction at the Tafuna Wellfields active wells averages 2.23 Mgal/d (1552 GPM). The roughly estimated area weighted recharge use ratio for Tafuna Wellfield is between 69 and 130% (average of 99%).

Table 4.14: Tafuna Wellfield aquifer parameters. Records in **bold** are active wells as of 2016

Well # [USGS ID]	Well # [ASPA ID]	Drilling WL [m]	Pumping WL [m]	Pump rate [GPM]	Specific capacity [GPM/m]	T [m²/day]	K [m/d]	Avg. Cl⁻ [mg/L]	Cl⁻ trend [mg/L/yr.]
1943-02	17	1.0	-	-	-	-	-	450	-
1943-04	-	0.8	-	-	-	-	-	8	-
1943-06	**33**	**2.6**	**-1.1**	**211**	**-**	**-**	**-**	**230**	**↑, 68**
1943-07	46	2.4	-1.3	150	57	576	83	145	-
1943-08	52	0.6	0.2	95	208	4069	621	15	-
1943-09	-	1.1	-	-	-	-	-	45	-
1943-10	54	0.9	-4.5	200	37	446	18	15	-
1943-11	58	0.9	0.3	250	410	1087	38	820	-
1944-05	55	-	-	50	137	483	23	280	-
2043-01	-	0.3	-	-	-	-	-	280	-
-	**60**	**-**	**-1.4**	**325**	**-**	**-**	**-**	**298**	**↑, 107**
-	**61**	**-**	**0.5**	**226**	**-**	**-**	**-**	**306**	**↑, 124**
-	**72**	**1.8**	**-0.6**	**243**	**108**	**5880**	**478**	**85**	**↑, 36**
-	**77**	**-**	**-0.3**	**240**	**-**	**-**	**-**	**385**	**↑, 233**
-	**81**	**-**	**-2.5**	**307**	**-**	**-**	**-**	**6**	**↑, 20**
2043-02	-	0.5	-	-	-	-	-	1060	-
2143-01	-	0.6	-	-	-	-	-	1650	-

* Pump rates and Ave. Cl⁻ values are taken from averages of last 3 years ASPA data, ↓ denotes decreasing Cl⁻ trend ↑ denotes increasing Cl⁻ trend. Values for inactive wells were taken from sources as described in Section 4.0. Records in bold are active wells as of 2016.

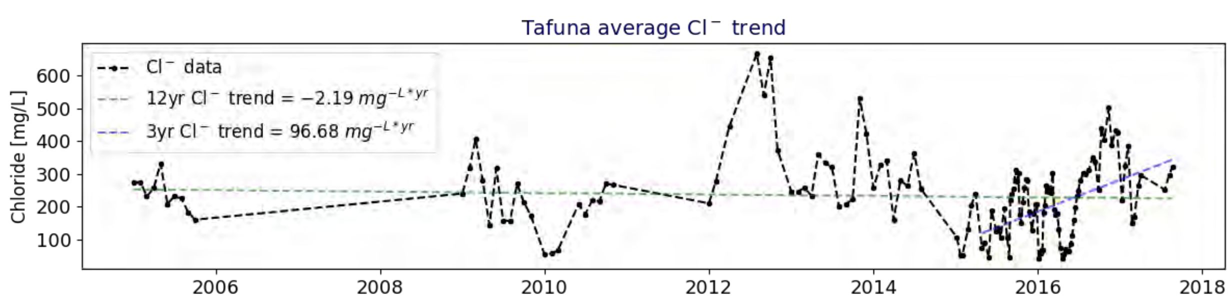


Figure 4.44: Cl⁻ concentrations averaged across all active wells in the Tafuna Wellfield. *Green dashed line* shows the linear regression trend line for all data, generally about 12 years, and *blue dashed line* shows the linear regression trend line for the most recent 3-year period, 2015-2017.

Preliminary recommendations for sustainable aquifer management

Existing wells:
Concentrations of Cl^- in this area decrease in response to heavy rainfalls and this is accompanied by (or basically caused by) an increase in water levels during these high-recharge events (Fig. 4.45). Cl^- concentrations show seasonal cycles in this wellfield, whereas concentrations are lower during the wet season than in the dry season. This rapid response is one symptom of the very high hydraulic conductivities in this area, another of which is detections of surface water contamination during high-rainfall events. Combined, these factors make production water from this wellfield less-desirable, because the salinity increases with low rainfall, and bacterial contamination increases with ample rainfall. Reduction of extraction rates can help with the salinization issue, but the contamination issue may be best solved by abandonment of wells in this area.

Future development: Additional groundwater development is not recommended in the Tafuna Wellfield area, specifically considering the ongoing issues presently experienced with groundwater affected directly by surface water

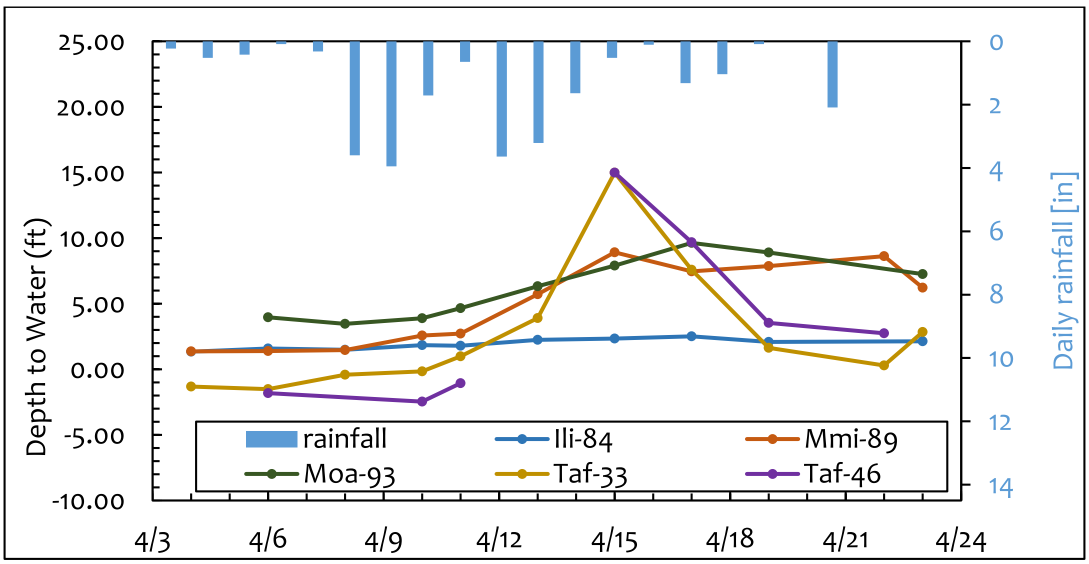


Figure 4.45: Results of water level monitoring for April 2016 at Tafuna-Leone Plain wells. Note: Rapid water level response due to high-rainfall events.

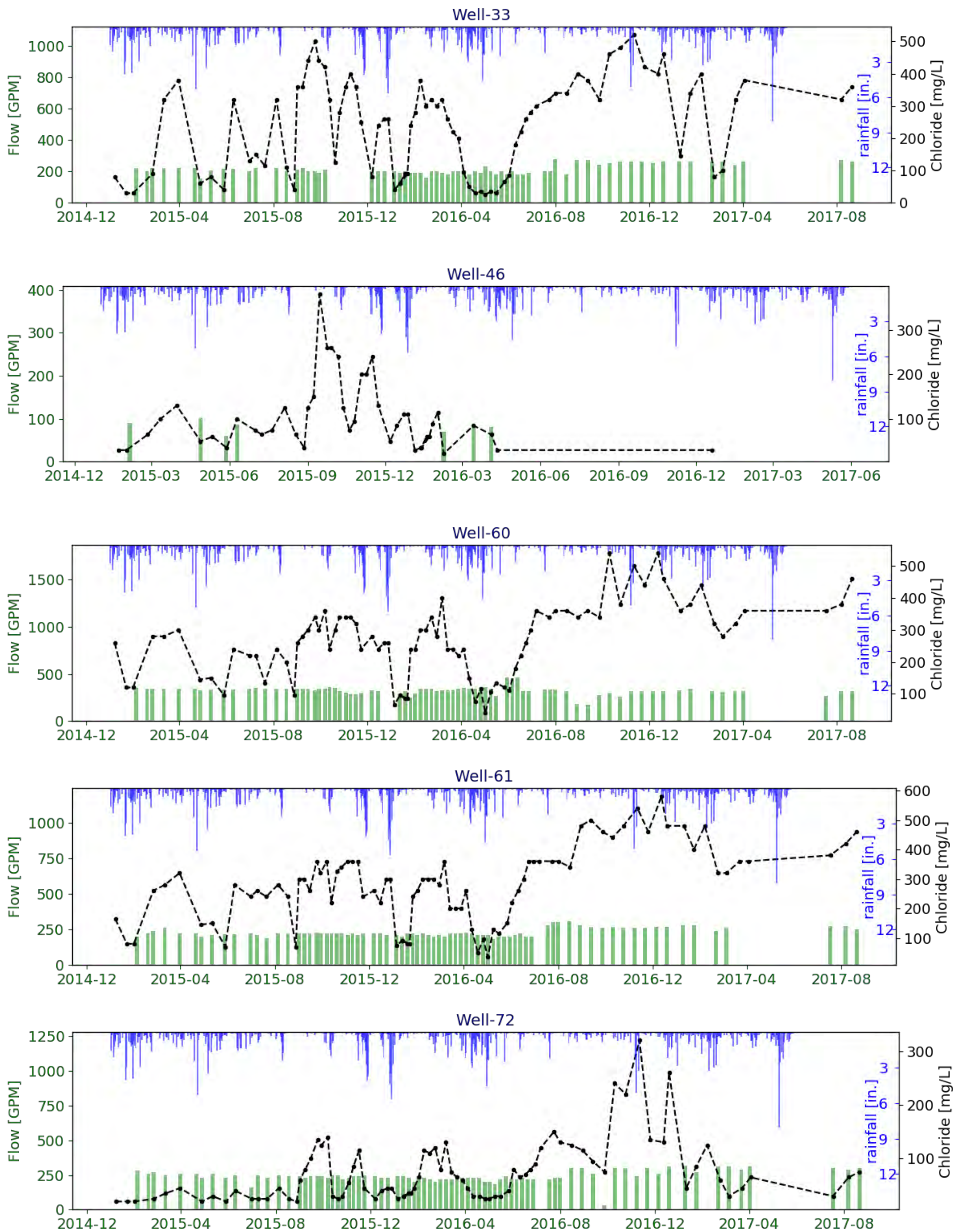


Figure 4.46: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Tafuna Wellfield for the period 2015-2017.

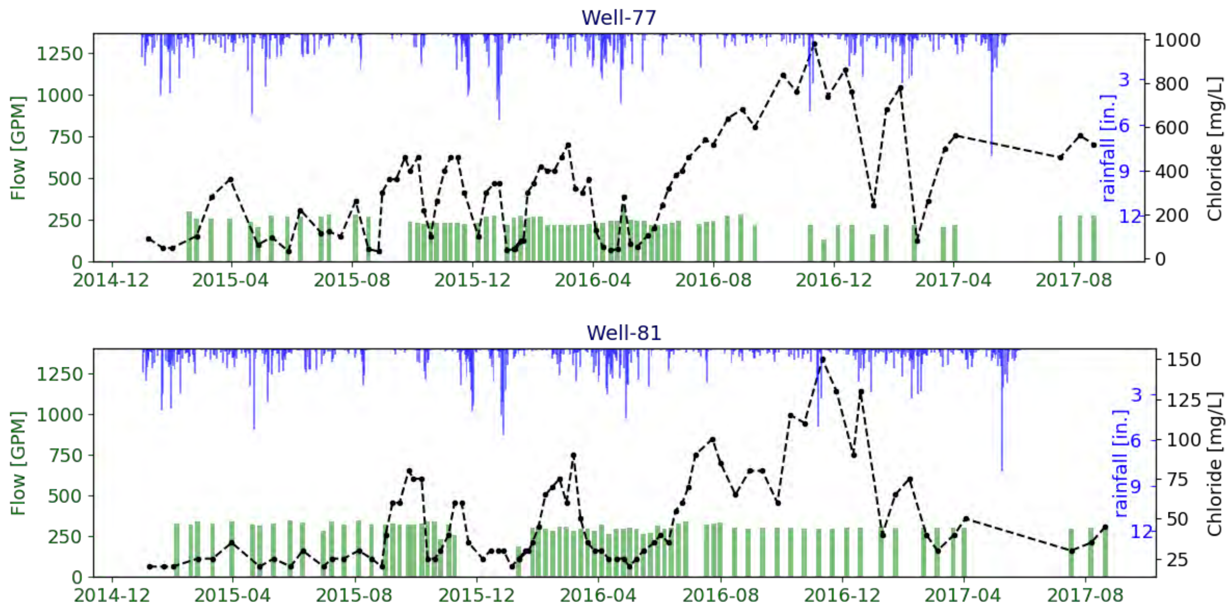


Figure 4.46 continued: Plots of pump rates (*green bars*), Cl^- values (*black line*), and rainfall (*blue bars*) for each active well in the Tafuna Wellfield for the period 2015-2017.

5.0 Groundwater Use and Development Recommendations

Since Tutuila is an island, the amount of sustainably developable groundwater is fundamentally limited by the rate of groundwater recharge, thereby highlighting the continued need for more accurate and up to-date recharge estimates. In addition to groundwater supply in the form of recharge, the ecological utility of groundwater discharge is important to consider in calculating groundwater availability. This water provides baseflow to streams and supplies coastal environments with nutrients. Some coastal ecosystems, such as that of Pala Lagoon, are adapted to receive brackish water and the organisms within may suffer if salinity is altered by heavy freshwater withdrawals. Also as noted before, underlying seawater must be kept distant from well intakes with a hydraulic freshwater buffer to keep production salinities low.

Past experience shows that wells tapping the basal-aquifer in the Pleistocene Volcanics should be expected to yield only low quantities of water (<30–50 gpm), though localized areas, particularly in the Taputapu Shield, may exceed these expectations. Pumping at higher rates creates the risk of large drawdowns that will either induce saltwater upconing and/or drain the water-producing zone. Basal aquifers are at risk of saltwater intrusion, if exploited, because they are hydraulically connected to the underlying seawater. This risk can be minimized by drilling production wells as far from the coast as possible, and by using angled boreholes or Maui Type Shafts (Gingerich and Oki, 2000) to finish wells in thicker parts of the freshwater lens. It is of paramount importance to carefully assess aquifer parameters during and/or after drilling with step-drawdown testing to set the appropriate pumping rates. Additional and useful data can also be gained via pumping (and assessed by modeling) and continued monitoring of long term static water levels and Cl^- concentrations. When chronic static water level declines or substantial increases in Cl^- concentrations are detected, pumping rates should be reduced to allow aquifer recovery. Targeting high-elevation (above sea level) perched, dike-impounded, or semi-perched water "pockets" is a riskier strategy than targeting basal water supplies, though elevated water often has a lower contamination potential. Successfully developing high-level reservoirs on Tutuila will probably necessitate use of geophysical exploration and drilling multiple wells to find high-yielding zones.

Assessment of the degree of connectivity between more-permeable compartments/pockets in a localized area as described in Section 2.0 would be useful for determining the risk of altering stream flows with groundwater pumping, and for developing more accurate numerical groundwater models. This may be accomplished by careful collection of water level and aquifer parameter data during exploratory drilling or while drilling production wells in the Pleistocene rocks.

5.1 Physical Controls on Cl^- Concentrations

Future groundwater development in the Pleistocene Shields, may benefit from a broad assessment of existing well characteristics. The salinity of wells in many of Tutuila's small nearshore aquifers will ultimately be a function of the well depth, pumping rate, hydraulic conductivity of the aquifer tapped, and the geometry of the well placement, specifically its proximity to the coast. As one might expect, many of the higher salinity wells on Tutuila are located near the coast (Fig. 5.1).

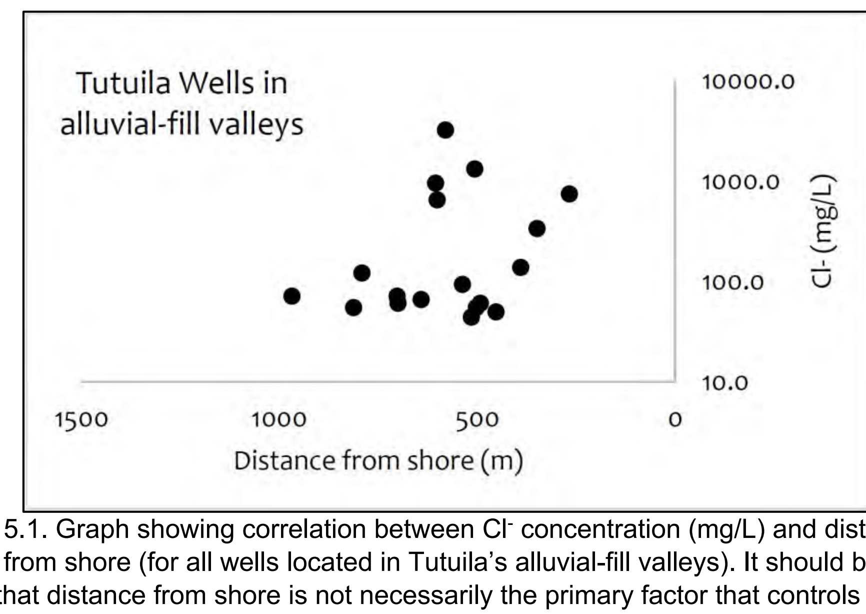


Figure 5.1. Graph showing correlation between Cl^- concentration (mg/L) and distance of well from shore (for all wells located in Tutuila's alluvial-fill valleys). It should be noted that distance from shore is not necessarily the primary factor that controls groundwater Cl^- concentrations. Cl^- measurements are from unpublished WRRC data (2014).

Well depth may also play a role in controlling groundwater Cl^- concentrations. In the Pleistocene shield units, only wells drilled deeper than approximately -20 m are currently producing water with elevated Cl^- levels (Fig. 5.2). However, it should still be noted that any well below sea level has the potential to be affected by seawater if over-pumped. Although groundwater production below -20 m below sea level is not generally recommended, exploratory drilling below this depth would certainly be useful to assess the location of the saltwater-freshwater interface. In light of the above observations, a well drilling strategy focused on targeting areas as far inland as possible where the main groundwater body is expected to be thicker, and by utilizing angled drilling methods to further gain access to more inland parts of the lens will decrease the likelihood of encountering future issues with salinization.

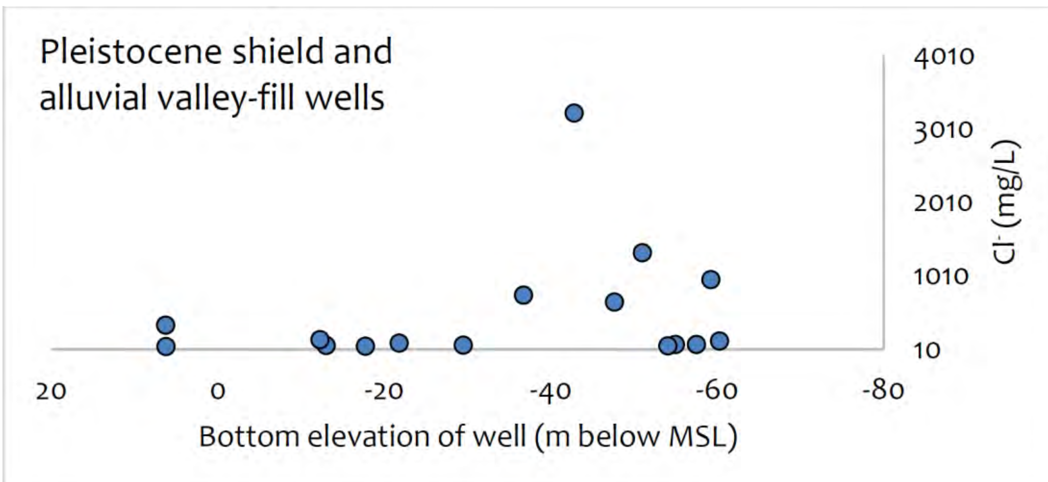


Figure 5.2. Graph showing correlation between Cl^- concentrations (mg/L) and well depth (in m below sea level) located in selected Pleistocene shield and alluvial valley-fill wells. Well depth is not necessarily the primary factor that controls groundwater Cl^- concentrations. Well depth is taken from various sources and is not confirmed. Cl^- measurements are from unpublished WRRC data (2014).

5.2 Well Drilling Data Collection Recommendations

Capturing lithological, hydrological, and geochemical data for informing conceptual and numerical models of the subsurface is a high-priority for exploratory and production well drilling. Although specific drilling and testing procedures will be contingent on available equipment and resources, it is recommended that the following tests be conducted when possible, in the following order of priority. Procedures at the top of the list are inexpensive, simple, and recommended for every well drilled, including production wells.

1. Regular (at least daily) documentation of water levels, and events that may have affected water levels. Ideally water levels are measured in the morning before being disturbed by drilling activities. A decrease in head with depth could indicate vertical downward flow, whereas a complete loss of water could indicate that a perching member has been punctured.
2. Accurate surveying of ground surface elevation, and thorough documentation of measuring point elevations (casing geometry, distance from old measuring point to new measuring point if the casing top is changed).
3. Documentation of lithological and drilling conditions. The following should be thoroughly documented in each drilling log: drilling speed, circulation pressure, and assessment of rock samples. Ideally, driller's logs are of sufficient quality to be later used to infer material type, formation structure, and to explain hydrological response. For collection of samples using air rotary methods, about 250 ml of recovered drill cuttings (i.e., chips) can be taken about every 2 m depth and should be analyzed by a geologist to assess lithology. Drillers should also be instructed to collect samples in a way that accurately represents the rock at or near the depth of the drill bit during the time of sampling.
4. Sampling formation water for Cl^-, or taking electrical conductivity/salinity readings. If possible, employ measures to reduce drilling fluid contamination of the formation water.
5. Aquifer tests: a step-drawdown test is the most important, followed by a constant-rate pump test, and then a recovery test. See Section 5.3 for specific test procedures.
6. Using a conductivity-temperature-depth (CTD) logger, profiles of open holes may be run once the hole has been purged of non-formation fluid and recovery has stabilized. This may show discharge into the well from multiple formations or may indicate the position of the saltwater-freshwater interface.
7. If there are other observation wells in the area, monitoring the effect that pumping in one well has on the water level in another well may indicate the degree of connection and hydraulic conductivity in the area between wells, and also may provide values for aquifer storage (a useful modeling parameter). Effects of groundwater withdrawals on the discharge of nearby streams could also be assessed.

5.3 Aquifer Test Recommendations

Upon completion of a well, the following tests are recommended to be performed in the following order.

5.3.1 Step-Drawdown Pumping Test

The test should be performed with a data logging pressure transducer deployed in the hole. Additionally, manual measurements with a water level tape should also be periodically taken throughout the test to calibrate and ensure accuracy of the digital instrument. The pressure transducer should be deployed at a depth that will not be surpassed by drawdown in the well. Locating the pressure transducer on the bottom of the hole will avoid missing high-drawdown data (as long as the transducer is rated to withstand the amount of pressure at that depth). The logger may be set at 15 to 30 sec intervals to capture the drawdown curve shape during transitions between steps. At least three, but ideally four to five steps of pumping rate should be set, starting with the lowest rate first. The duration of pumping at each step should be the same, about an hour is reasonable, and no recovery should be allowed between steps.

Analysis of step drawdown tests to obtain values of ***T*** and ***K*** can be performed with numerous methods. Two methods used in this report are using the Cooper-Jacob Method (Halford and Kuniansky, 2002), and the Zangar method (Zangar, 1953; Eyre and Walker, 1991). Accurate analysis with these tests relies on collection of data with a long enough duration and high enough pumping rate to produce appropriately shaped drawdown curves. Example curves are provided in Figs. 5.3 and 5.4.

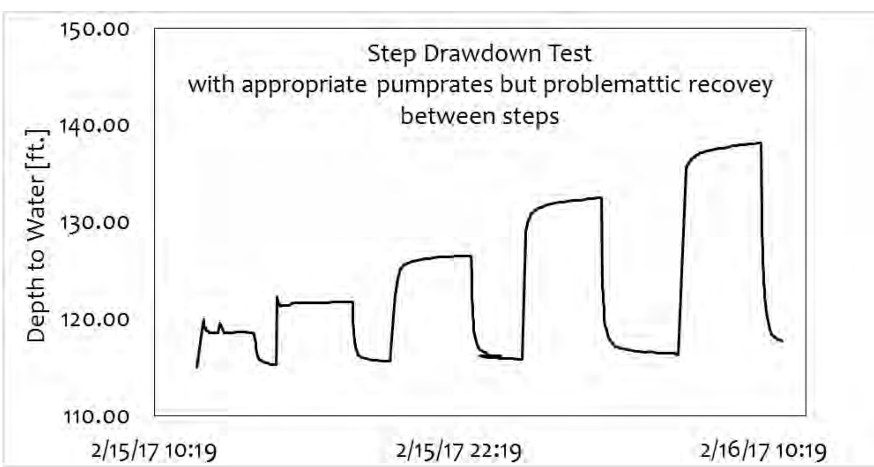


Figure 5.3. An example of a step drawdown test illustrating the appropriate range of steps. Note that the pumping rate in the beginning of the test is not stable and fluctuations can cause water level inconsistencies. Higher rate steps produce well shaped curves. These steps need to be pumped for a longer duration to allow the water level to stabilize. Allowing for recovery between steps (1) increases the amount of time required to achieve a stable pumping water level at subsequent steps, and (2) invalidates some analysis methods. It is recommended that no recovery between steps is allowed.

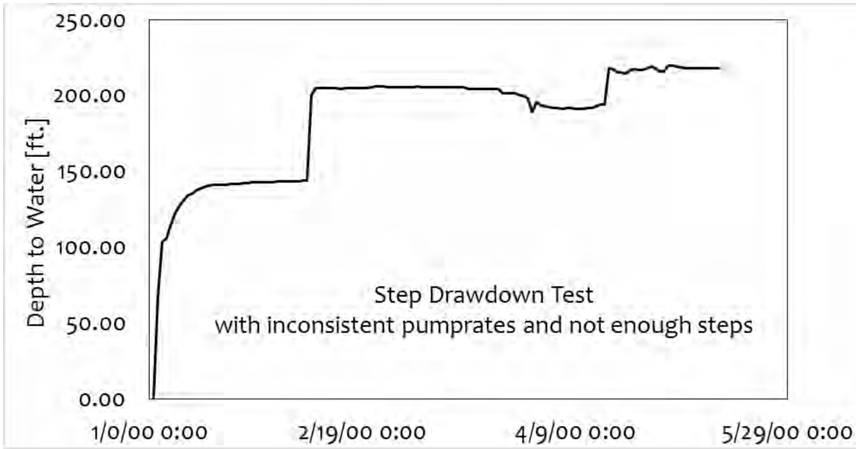


Figure 5.4. An example of a step drawdown test showing inconsistent pumping rates. Note that additional steps due to higher pumping rates would help to characterize the aquifer properties better.

5.3.2 Constant-Rate Pumping Test

Following a step-drawdown pumping test, the well should be allowed to fully recover to the pre-step-drawdown pumping test water level (this may take days). A constant-rate pumping test may then be performed with a data logging pressure transducer deployed in the hole, and again with periodic manual water level measurements. The datalogger should be set at short logging intervals in the beginning of the test and these intervals can be extended during the later portion of the test.

An example of this logarithmic logging interval would be:

a. Every 10 sec for the first 5 min

b. Every 1 min for the next 10 min

c. Every 5 min for the next 10 min

d. Every 10 min for the next 90 min

e. Every 30 min for the next 180 min

f. Every 1 hr. for the next 300 min

g. Every 4 hr. for the duration of the test

The constant-rate test for exploratory wells should be run for as long as possible, 168 hr. (5 log cycles) is ideal, though 96 hr. (4 log cycles) is a reasonable goal as well. A 168 hr. (7 day) test will allow a better characterization of distal boundary conditions that may intersect the cone of depression. The first log cycle (first 10 min) is often unusable because the drawdown curve has not achieved a straight line in a semi-log plot. It is important to find a way to dispose of the test water, away from the site, to ensure that it does not recharge the aquifer during the test. A concrete lined ditch is ideal, though a natural drainage channel is a sufficient disposal area for pumped water. The pump rate should be determined based on the results of the step-drawdown test. Pump rates that are too low, or test durations that are not long enough will not produce curves that are sufficient for analysis (Figs. 5.5 and 5.6). The later portion of the curve is the most valuable for curve fitting purposes.

5.3.3 Recovery Tests

At the end of the constant-rate pumping test the data logger may be reset and redeployed before shutting off the pump to capture the recovery portion of the curve. The datalogger should be reset at short-logging intervals for the beginning of the test and these intervals can be extended throughout the later portion of the test. Once the logger is in place and recording, the pump may be shut off for recovery to be recorded for at least the same duration of the pump test. The recovery test will allow for a second analysis of the pumping/recovery curve and is valuable because it is not affected by variations in the pump discharge that may be a factor in the pumping test.

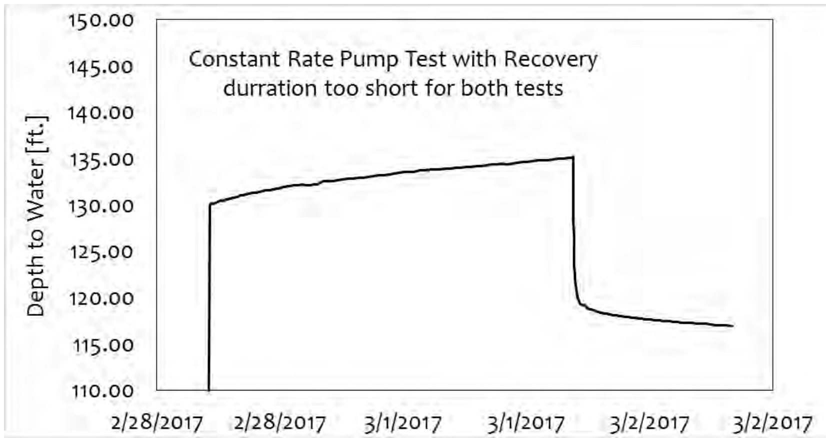


Figure 5.5. An example of a constant rate pump test. Drawdown data shows ideal post-test recovery curve. Note that the analysis would benefit from a longer test duration in both the constant rate and the recovery test data. The stable pumping rate produces a uniform smooth curve.

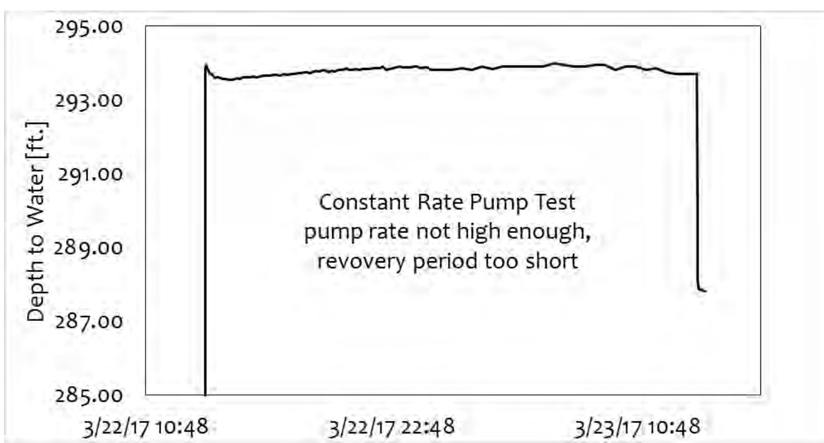


Figure 5.6. An example of a constant rate test with unclear results due to setting the pumping rate too low, and from variability in pumping rates. These factors contribute to the straight line instead of a drawdown curve, which is needed for analysis. Note that the initial pumping rate was probably set too high before the pump was successfully throttled to the intended pumping rate. Thus, some recovery from prior extraction is observed in the beginning of the test.

6.0 Hydrologic Data Gaps

The following pieces of information have been identified as key goals to meet for continuing progress in developing the water budget and numerical groundwater models that can be applied to the ultimate goal of developing accurate and comprehensive sustainable yield estimates.

1. **Updated, high-temporal, and spatial resolution recharge distribution**. Numerical groundwater models used to develop predictions of sustainable aquifer capacity are only as accurate as the input data with which they are compiled. Existing recharge estimates for Tutuila vary widely and sometimes do not consider factors, such as mountain front recharge, that are significant terms in the island's water budget. Presently WRRC is developing a water budget model in order to produce an up to date recharge coverage.

2. **Assessment of mountain front recharge (MFR) runoff to infiltration ratio**. While the process of MFR is qualitatively understood and has been applied to existing recharge calculations, the amount of MFR has still only been roughly estimated (Eyre and Walker (1991) estimated 50%, Izuka, et al., (2007) estimated 75%) of runoff entering the Tafuna-Leone Plain area. Installation of multiple stream gauging sites on the perennial sections and the intermittent sections of streams that drain to the Tafuna-Leone Plain would be useful for developing a better estimate of the amount of MFR the plain's aquifers receive.

3. **Conceptual model testing and validation**. While a number of different conceptual models and hypotheses have been developed to explain high-level water and general groundwater occurrence on Tutuila, sufficient data to confirm these models is still lacking. Additional exploratory drilling in areas with the potential for high-level water would be useful for developing a better understanding of these resources.

4. **Higher resolution Cl^- information from production wells**. Measurement of salinity, electrical conductivity, or Cl^- concentration is essential for understanding the behavior of the bottom of the freshwater lens and transition zone. Presently, measurements of Cl^- concentration are taken manually on a biweekly basis. However, the installation of conductivity sensors in wells has the potential to provide real-time and high resolution salinity data (which can be easily converted to Cl^- concentration).

5. **Aquifer testing for existing wells with no existing aquifer test records**. These tests could include pumping tests, step drawdown tests, or recovery tests, which can be performed with the installed production pumps, thereby negating the need to remove pumps at all.

6. **Improved assessment of aquifer boundaries**. Presently surface topography provides the only indication of aquifer boundaries on Tutuila. However, it is known from other island environments that watershed divides may not be an appropriate representation of groundwater divides, and there are likely to be unknown subsurface features that control the flow of groundwater. While WRRC has conducted a basic geochemical assessment of

production well waters, the assessment has not been helpful in delineating aquifer boundaries. A detailed study of water levels, pumping effects on observation wells, production well drawdowns, and tidal attenuation may be useful in determining aquifer boundaries for some areas.

7. **Development of sustainable yield criteria**. Sophocleous (1997) determined that *"maintaining the long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge,"* is an important component of sustainable yield, but other water uses should also be considered. In addition to salinity constraints and water level decline, ecological and social water uses should also be integrated to develop a successful sustainable yield criterion. Such aspects should be evaluated through a process that involves local stakeholder's input across a diverse array of fields, including engineering, natural resources management, biology, ecology, and anthropology.

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