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Groundwater Development Potential and Exploratory Drilling Recommendations for Tutuila, American Samoa

Phase I: Well Data and Provisional Conceptual Hydrogeologic Model

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ABSTRACT

Development of new groundwater sources with low-contamination potential is a high priority on Tutuila, the main island in the Territory of American Samoa. Updated conceptual hydrogeological models are needed to assess the viability of new groundwater sources and to make sound, scientifically based exploration decisions. This report presents a comprehensive assessment of existing hydrological information and recently acquired subsurface datasets for the purpose of recommending exploration drilling sites that target new groundwater sources on Tutuila.

Tutuila is the third largest, and third oldest (1.5–1.0 Ma), island in the Samoan hot-spot island chain, where two phases of volcanism (a shield building phase and a rejuvenated phase) affected Tutuila and the islands of Western Samoa. Tutuila consists of two primary regions: a highly-permeable rejuvenated-phase lava delta, the Tafuna-Leone Plain, which although favorable for groundwater development, is susceptible to anthropogenic contamination, and a mountainous assemblage of Pleistocene age shield volcanos that make up the bulk of the island and are generally less-favorable for groundwater development. While some water development has occurred in the Pleistocene shields, existing wells primarily tap basal water supplies 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.

In this report, pertinent hydrological datasets are compiled and summarized in order to assess surface geology, estimate aquifer parameters, compare recharge estimates, and characterize the regional differences in surface water characteristics. Driller's logs from two recently drilled deep boreholes and from shallow production wells, in addition to an analysis of surface outcrop characteristics is used to assess the lithologic construction of the island. A recently conducted magnetotelluric (MT) survey of subsurface electrical resistivity beneath the Tafuna-Leone Plain and the Taputapu Volcano is interpreted to inform a regional scale understanding of the distinct hydrological zones within the western portion of the island. Also, hydrogeological data from recently acquired and previously published well-test data sets are compiled and analyzed to assess the regional differences in groundwater development potential throughout the island.

Generally, these data sets support the existing conceptual hydrogeological model of the island, however recent information suggests that the Taputapu Shield region may be more favorable to water development than previously thought. Recharge estimates generally show predictable recharge patterns, whereas the western portion of the island receives substantially more recharge than the eastern portion. Examination of stream flow and significant high-level spring characteristics indicates areas with larger amounts of baseflow derived from high-level aquifers, thereby suggesting locations where significant high-level groundwater resources might be found.

ABSTRACT CONTINUED

Compilation of this data allows a comprehensive and up-to-date reassessment of the existing conceptual hydrogeological model of the island as originally developed by Harold Stearns in 1944, and later refined in 2007 by Scot Izuka et al. Based on the updated conceptual model, exploration targets focused on three types of groundwater occurrence on Tutuila are here recommended: (1) six target sites in basal or potentially semi-perched aquifers, (2) four target sites in high-level dike-impounded or perched aquifers, and (3) one target site in an extensive perched aquifer at Aoloau. Available hydrological and geological parameters for each target site were tabulated and each site is ranked by the estimated probability of encountering favorable water-producing conditions. This report concludes with recommendations of procedures for exploratory drilling and for the sustainable development of new water supplies on Tutuila. Supporting data and discussions are presented in Appendices A and B, and additional large datasets are compiled and presented in a data supplement to this report.

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1.0 INTRODUCTION

1.1 Purpose and Scope

On Tutuila, the main island in the Territory of American Samoa, the sustainability of existing drinking water resources is threatened by anthropogenic contamination and by the overuse of limited groundwater reservoirs. Tutuila's most productive aquifers, located in the Tafuna-Leone Plain region, are directly influenced by surface water (ASEPA, 2010). This has led to the longest-standing boil-water notice in U.S. history (ASEPA, 2016). Additionally, a number of smaller aquifers on the island are affected by saltwater intrusion. Development of new groundwater sources with lower contamination potential is a high priority on Tutuila. To accomplish this, new hydrogeological information and updated conceptual hydrogeological models are needed to make scientifically informed groundwater exploration decisions.

In this report, existing hydrological information is compiled with recently acquired subsurface datasets to inform three hypotheses of groundwater occurrence on Tutuila. These hypotheses are used to develop and prioritize recommendations for exploration drilling sites targeted at finding new groundwater sources. It should be noted that due to data limitations, the quality and conclusiveness of some information presented herein may be unknown. Nonetheless, because this work is specifically intended to inform exploration decisions, the authors have decided to err on the side of comprehensiveness, and to present all known information pertaining to the island's fairly unexplored subsurface conditions, regardless. The reader should be aware that the recommendations presented herein are hypotheses that are intended for further evaluation by collection of additional subsurface data from future exploratory drilling efforts, well-logging, and geophysical study.

1.2 Regional Setting

Tutuila, the largest and most populous island in American Samoa, is located around 14° 20' 0" S and 170° 40' 0" W (Fig. 1). The island has an area of 140 km^2 and a population of 56,000 residents (ASDOC, 2013). Tutuila is within the South Pacific Convergence Zone, thus there is abundant rainfall year round. Tutuila experiences some seasonality in precipitation, and has a wet season and a less-wet season. Monthly average precipitation in November–March is roughly double that of May–August. Rainfall varies significantly with location and elevation (Fig. 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).

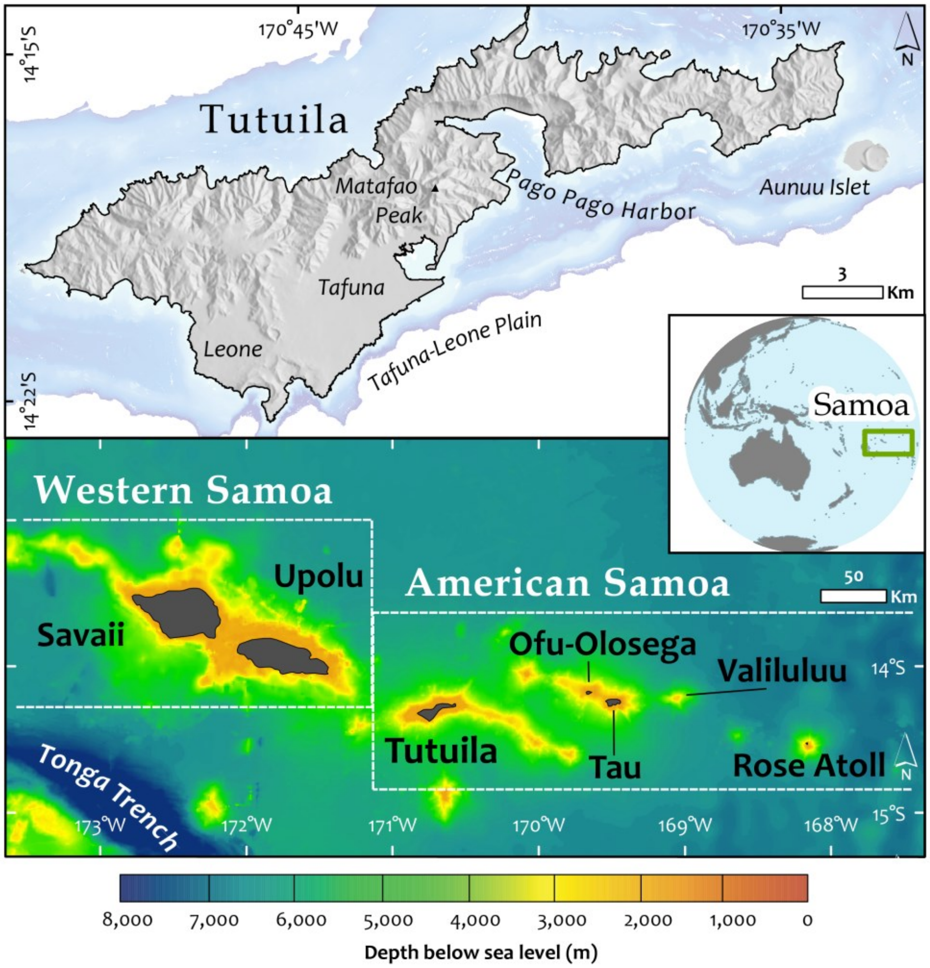
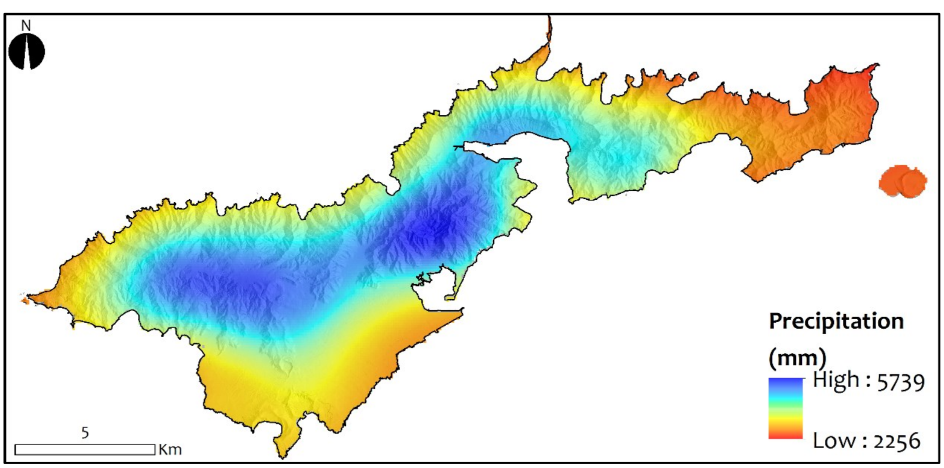


Figure 1. Bathymetric map of Samoan archipelago (bottom), and map of Tutuila Island (top). Divisions between Western and American Samoa are drawn to show political jurisdictions and do not constitute actual territorial boundaries. Regional location map shown in center-right inset.



Note: Data from Daly et al., 2006.

Figure 2. Average annual precipitation from climate data recorded from 1971 to 2000.

Tutuila can be divided into two primary geographic regions: (1) an east-west trending series of Pleistocene age shield volcanoes that has been eroded into a sharp 32 km long ridgeline, and (2) a geologically young (Holocene) series of lava and ash flows on the island's southwestern flank that primarily makes up the Tafuna-Leone Plain (Fig. 1). The plain is bisected by a north-south trending ridge of cinder cones, and the eastern (Tafuna) side of the plain is about twice the size (15 km^2) of the western (Leone) side (8 km^2). The older-volcanic shields generally rise from 300 to 400 m in elevation with the island's highest point at the summit of Mt. Matafao (653 m). Only a third of the island has a slope of less than 30%, and therefore, development density is high in the flatter areas such as the Tafuna-Leone Plain and the small alluvial-fill valleys that ring the island. The steeper parts of the landscape are heavily forested with tropical jungle.

1.3 Regional Geologic History

The Samoan Archipelago is located near the northern boundary of the Tonga Trench, at the crest of a plate flexure where the seafloor of the Pacific Plate bends southward (Natland, 2003). Volcanism in the archipelago is likely controlled by both tectonic and hotspot processes, and the islands' eruptive history can be categorized into two distinct phases respective of these processes. The first phase of Samoan volcanism is attributed to hot spot activity. This phase is thought to have constructed the shield volcanos that make up the 'core' of each main Samoan island, similar to the way that other hot-spot chains in the Pacific, such as Hawaii, were created. As the Pacific Plate moves westward over a stationary mantle plume, the islands propagate eastward with the youngest island most proximal to the hot spot. Currently, the hot spot is thought to be underneath the volcanically active Vailuluu Seamount, about 20 miles east of Tau Island (Fig. 1). The oldest rocks from the chain were dredged from the submarine flanks of the island of Savaii and are dated to 5.2 millions of years before present (Ma) (Koppers et al., 2008). On Upolu, older rocks range from 3.2 to 1.4 Ma, and Tutuila's older-volcanic mountains date from 1.5 to 1.0 Ma (Natland, 2003). The ages of the Manua islands (Ofu-Olosega and Tau) to the east of Tutuila are much younger, dating to 0.3 and 0.1 Ma (Mcdougal, 1985), and submarine eruptions from Valiluluu are ongoing (Johnson, 1977).

The second phase of Samoan volcanism was a rejuvenated phase (i.e., post-erosional phase) that probably occurred fairly contemporaneously throughout the late Pleistocene and Holocene on the islands of Savaii, Upolu, and Tutuila (Natland, 1980). The extent of this second phase of eruptions traverses the length of an approximately 300+ km long plate flexure zone across Savaii and Upolu, and to the eastern shore of Tutuila. On Tutuila, the rejuvenated phase created the Tafuna-Leone Plain on the southwestern flank, and Aunuu Islet off of the eastern coast. Natland proposes that this rejuvenated volcanism results from extensional fracturing caused by the structural effects of lithospheric bending as the Pacific Plate subducts into the Tonga trench. Interestingly, this phase of volcanism was more voluminous on Savaii and Upolu and almost completely covered the original shields, thus making them larger and creating domed edifices that are clearly less eroded than the highly dissected islands of Tutuila, Ofu, and Olosega. As a whole, the surficial appearance of the Samoan archipelago makes it appear that the more westerly islands (Savai and Upolu) are younger, although they are not. This apparent discrepancy sparked much scientific debate regarding the validity of the mantle-plume hot-spot model until accurate dates from Savaii's volcanic pile were measured (Koppers et al., 2008).

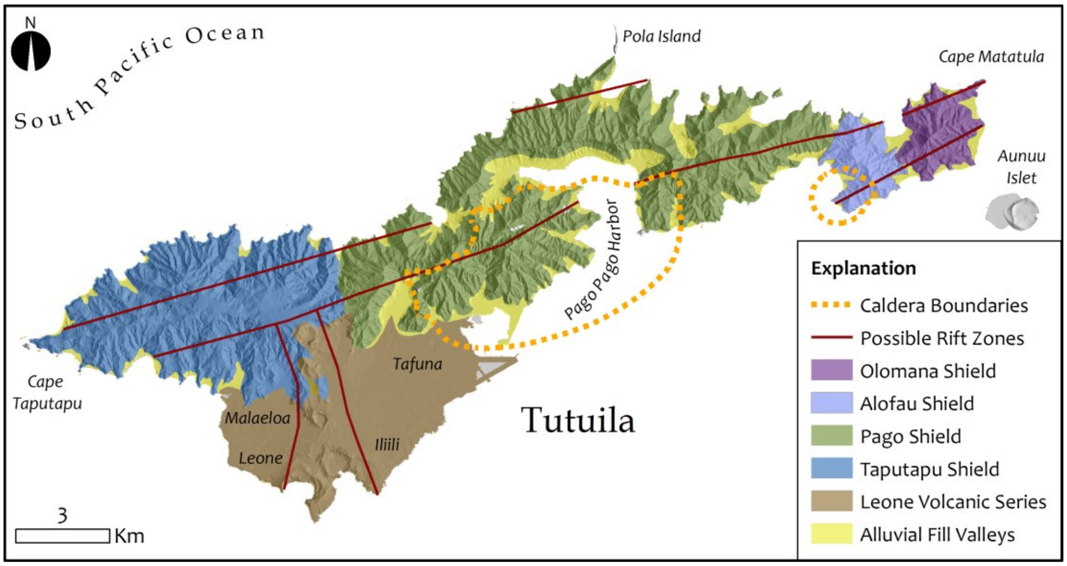
1.4 Geology of Tutuila

1.4.1 Pleistocene Volcanic Shields

In the Samoan archipelago, Tutuila is third in both size and age, having erupted about two million years ago from two or three parallel east-northeast trending rift zones on the ocean floor. During the island's hot-spot phase, four overlapping volcanic shields (Pago, Taputapu, Olomoana, and Alofau) (Fig. 3) were thought to have contemporaneously erupted over about a half-million years, starting around 1.5 Ma (Sterns, 1944; McDougall, 1985). These eruptions produced a complicated and heterogeneous assemblage of alkalic igneous rocks, in the form of thick lava flows, pyroclastic deposits, and crosscutting intrusive dikes and plugs. At its peak size, about 1.25 Ma, the island may have been nearly 45 km in length, 12 km in width, and about 1,500 m (5,000 ft) tall (Stearns, 1944). Also around that time, a large collapse in the center of the Pago shield created the 9 km wide Pago caldera, which was later deeply eroded by surface water and then inundated by rising sea level at the end of the Pleistocene Epoch to create the fjord-like feature of present day Pago Pago Harbor. The nearly vertical north wall of the harbor is interpreted by Stearns as direct evidence of the collapse. After the collapse, additional eruptive activity inside of the caldera created a distinctive lithologic unit consisting of low-permeability ponded flows, tuffs, breccias, and trachyte intrusions that are collectively referred to as the Pago Inner-Caldera Unit. This unit postdates the Pago Outer-Caldera Unit, which is primarily composed of gently sloping lava flows and some pyroclastics (Stearns, 1944). The neighboring Alofau Shield may also have experienced a similar caldera collapse, whereas the westerly Taputapu Shield shows no evidence of such an event.

Tutuila's shield building phase ended about 1 Ma with the eruption of massive lava flows that filled several valleys, and the intrusion of numerous Trachyte plugs and dikes that remain today as the island's highest and most prominent peaks (Stearns, 1944; NPS, 2008). The shape of the original shields could be inferred from the existing island profile as seen in the slopes of the long ridges that emanate from the island's central axis. These ridgelines dip at about 15°, which corresponds to the dip of many individual lava flows measured by Eyre and Walker (1991). What remains of Tutuila today, after much subsidence below sea level, is the deeply eroded and weathered summit of the original island.

Rock samples from each shield were collected by McDougall (1985) to determine potassium-argon ages of their flows. Though the dates suggest relatively contemporaneous eruptions, they do show that the Pago Shield (1.53–1.14 Ma) is probably slightly older than the Alofau and Olomoana Shields (1.11–1.48 Ma), and that the Taputapu Shield (1.01–1.25 Ma) is probably younger than the rest. Stearns (1944) also notes that Taputapu flows appear to overlie Pago flows in Aasu Valley, and that the geomorphology of the Taputapu Shield suggests it is younger than the Pago Shield, as it shows less erosional dissection.

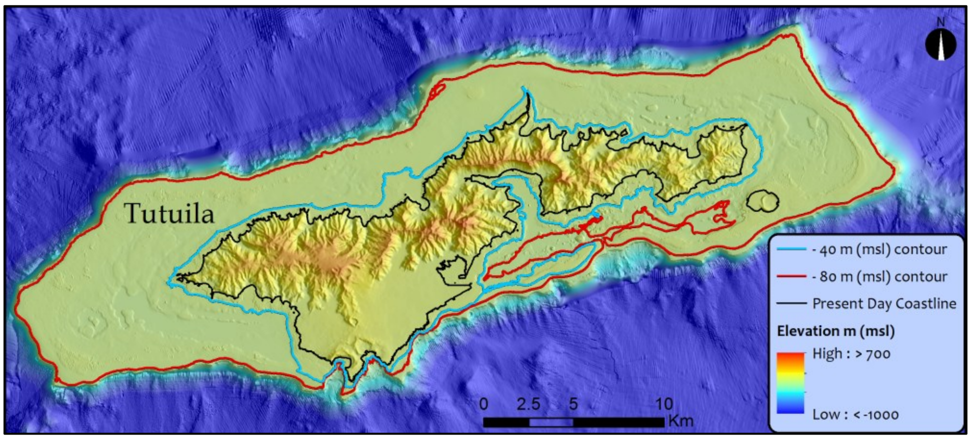


Modified from Stearns 1994 and Knight Enterprises Inc. 2014.

Figure 3. Simplified geology of Tutuila showing volcanic shields and inferred volcanic structures such as rift-zones and caldera boundaries.

1.4.2 Sedimentary Units and Changes in Sea Level

After the cessation of the shield-building phase, Tutuila experienced between 120 m to 800 m of isostatic submergence (Sterns, 1944). At some point during this interval, a Pleistocene-age barrier reef formed around much of the island. Behind the barrier reef, a lagoon environment allowed the growth of fringing reefs and the deposition of carbonates, marls, and terrestrial alluvium (Mayor, 1920). Next, there was a period where coral growth could not keep pace with the rate of the sea-level rise, and the lagoon and barrier reef were drowned. Today these carbonate deposits form a submarine plateau that lies unconformably on the eroded upper surface of the older volcanic shields. Bathymetric data show that the top of the plateau occupies a remarkably uniform depth from –50 to –90 meters below sea level (Fig. 4). In the Tafuna-Leone Plain region, a deep borehole drilled in 2015 shows two carbonate horizons. The lower horizon sits at –58 to –74 m below sea level and is thought to be a part of the carbonate bench. Dating with ^{14}C methods (Reinhard, unpublished data, June 2016) have shown that the middle of the horizon is 10,300 years old. Above this horizon, Leone Volcanic flows continue up to –15 m depth where a second carbonate layer is found. The layer is 9 m thick and was deposited during an interval between 7,000 and 4,400 years ago. This upper layer is probably one of many carbonate horizons or lenses that may have been interfingered with the Leone Volcanics. The existence of these horizons could result from a combination of the intermittent growth of the volcanic plain and global sea level fluctuations, which included a rise from –120 m at the end of the Pleistocene Epoch 12,000 years ago, and a +2 m high stand about 5,000 years ago (dates and elevations are approximate).



Sources: Lim et al. 2010 for bathymetry; Sterns 1944 for -80 and -40 m contours (red and blue lines).

Figure 4. Bathymetry surrounding Tutuila. The sharp drop from the coastline (3–7 km) is interpreted as the former sub-aerial extent of the older shield volcano(s) prior to submergence. The flat area between -80 m and -40 m depth (red and blue lines) is the top of a carbonate rich sedimentary unit that is thought to have been deposited in a lagoon environment behind an ancient drowned barrier reef.

To the north of the Tafuna-Leone Plain area and along the coastline of the rest of the island, are numerous deeply-incised valleys eroded into the older shields. The bottoms of many of these valleys are filled with terrestrial alluvium that collects as streams erode material from the mountains. The larger valleys also contain marine sediments and reef material, some standing up to 2 m above current sea level, which correlates with sea-level high stands within the last 5,000 years. These alluvial wedges provide some of the few flat spots around the island for building villages, and most of them probably contain at least a small basal-lens aquifer.

1.4.3 Holocene Leone Volcanics

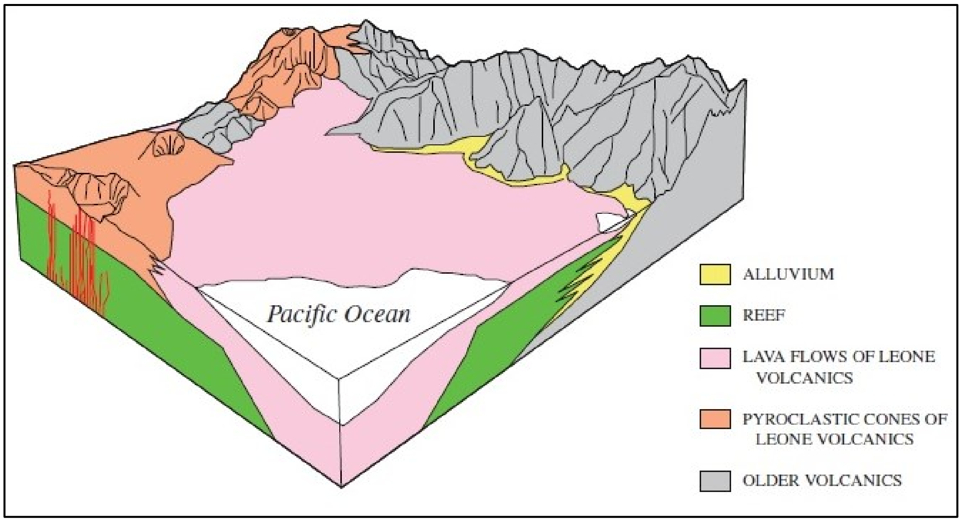
After the last glacial period, and up until indigenous-historical times, Tutuila's rejuvenated volcanic phase produced eruptions along the southern flank and up to the summit of the Taputapu Shield (Natland, 1980; Addison, 2006). Recent unpublished carbon dates from interbedded carbonate layers under the plain suggest that the rejuvenated phase eruptions began before 10,000 years ago and continued after a point 4,000 years ago

(Reinhard, unpublished data, June 2016). Additionally, archeological excavation of a widespread red-ash layer throughout the plain indicates that pyroclastic eruptions were still occurring around 650–750 years ago (Addison, 2014). These Holocene age lava flows, ash eruptions, and cinder cones, make up the Leone Volcanic Series.

The Leone Series primarily originated from a ≈7 km long north-south trending rift-zone that is clearly demarcated as a ridge topped with cinder and ash cones, running between the villages of Tafuna and Leone. The Tafuna-Leone Plain represents the bulk of the erupted material from Tutuila's rejuvenated phase, during which submarine eruptions blasted through the carbonate shelf, and ash deposits and lava deltas flowed down the flank of the older shields (Keating, 1992). The pyroclastic cones closer to the sea have more ash in their compositions, indicating they were formed from explosive eruptions (likely due to intruding seawater), whereas the cinder cones and pahoehoe flows located farther north are indicative of subaerial effusive eruptions. Aunuu Islet, a small tuff cone 1.3 km off of the southeastern coast of Tutuila, was also thought to have been created by submarine eruptions during this phase. It is interesting to note that the southern boundary of the Tafuna-Leone Plain is located at the edge of the carbonate shelf, which suggests that the rejuvenated volcanics must have flowed outwards until they reached the edge of the shelf where they cascaded down the submarine slope into the depths.

1.5 Existing Hydrogeologic Model

Izuka et al. (2007) delineated seven hydrologic units for Western Tutuila based on the island's geologic construction (Fig. 5). The Taputapu and Pago Shields were consolidated into one low-conductivity unit—the Pleistocene Older-Volcanics Unit—as lack of data precluded their differentiation into separate hydrological 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 presented in this report provide new evidence for proposed updates to this conceptual model.



Reprinted from Izuka et al. 2007 with permission.

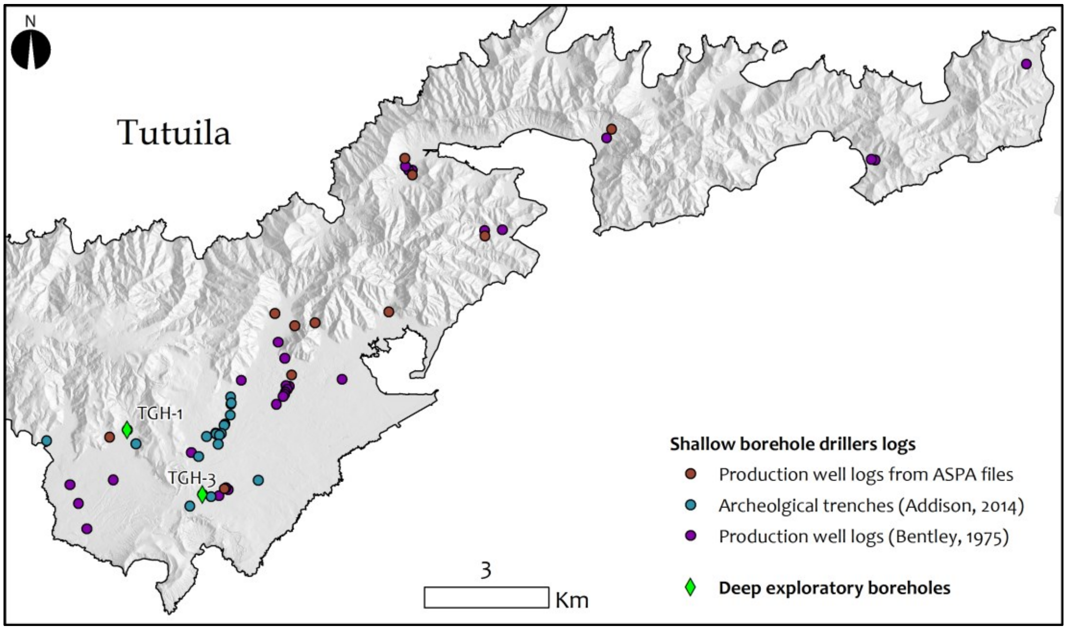
Figure 5. Conceptual hydrogeological model of the Tafuna-Leone Plain region showing distinctive hydrological units.

2.0 DATA

2.1 Compilation and Interpretation of Subsurface Logs

Borehole logs from well drilling or other below ground exploratory operations allow a direct assessment of subsurface structure, materials, and conditions. The logs show that Tutuila is constructed of a complex arrangement of lava flows, associated clinker zones, a limited amount of marine and terrestrial sedimentary units, and pyroclastic materials—including pockets of cinder and ash layers.

Throughout Tutuila there have been numerous shallow (<100 m) boreholes drilled during the last 30 years, primarily as production wells. Two deep exploratory boreholes were also drilled in 2015, one on the northern Leone Plain in the village of Upper Malaeloa (TGH-1), and the other on the southern Tafuna Plain in the village of Iliili (TGH-3). Driller's logs of varying quality were found for about one-third of the shallow holes, and excellent logs were made, and core samples were collected, for nearly the full depth of the deep boreholes. Trenches dug for archaeological purposes, though usually <2 m deep, also provide information about the shallow subsurface. Locations of each log or trench are shown in Figure 6. Despite some significant variation in the quality and terminology used between different logs, they are nonetheless somewhat useful for comparing the subsurface characteristics of different areas and for assessing the subsurface elevations of recognizable geologic features.



Sources: ASPA files and Bentley 1975 for production well logs; Addison 2014 for archeological trenches.
Note: Symbols represent log sources.

Figure 6. Location of boreholes and trenches.

2.1.1 Deep Exploratory Boreholes (TGH-1 and TGH-3)

The information collected from the two deep boreholes in the Tafuna-Leone area provides an informative visualization of subsurface conditions and lithology at each point. The core samples recovered from these holes provide a record of the geologic past via visual inspection, ^{14}C dating methods, and major/minor element chemistry. For example, although upon visual inspection they both appear similar, the Leone Volcanics can be distinguished from the Taputapu Volcanics in their bulk mineral chemistry (Geologica Geothermal Group, Inc, 2016). As would be expected, the lithologic column in these holes consists primarily of dense lava sections that are interbedded with rubble and/or pyroclastic materials. Also a few isolated horizons of clay/alluvium or carbonate materials corresponding to discrete events can be observed. Three distinct hydrogeologic units and a handful of notable events can be interpreted based on known geologic history and inspection of the cores and logs. The sequence of these events and a hydrogeological interpretation of significant units are presented in Tables 1 and 2, with imbedded photos from Geologica Geothermal Group, Inc (2016).

Table 1. Simplified log from TGH-1 core interpretation.

Depth (bottom of unit, m)	Height (above MSL, m)[a]	Geologic Unit and Hydrologic Notes	Unit Thickness (m)	Core Samples[b]
24.2	18.9	Sediments, alluvium, pyroclastics, and basalts? No core recovered. Unsaturated zone. Reports of poorly sorted material suggest moderate permeability.	24.2	
34.1	9.0	Sediments, alluvium, and pyroclastics. Unsaturated zone, limited permeability (core recovered).	9.9	
61.6	-18.5	Leone volcanics, fractured vesicular basalt. High permeability. Water table encountered at 39.6 m depth (3.5 m above MSL), unconfined aquifer below.	27.4	
76.2	-33.1	Leone volcanics, vesicular basalt, mixed with clinker, scoriacious zones, and massive units. Heterogeneous permeability, though overall high.	14.6	
89.0	-45.9	Sediments, alluvium, massive boulders, clay. Likely a debris flow. Probably low permeability.	12.8	
114.9	-71.8	Loss of circulation, no data. Assumption that circulation loss indicates highly permeable formation is reasonable.	25.9	
279.5	-236.4	Taputapu volcanics alternating zones of massive and vesicular basalt, lapili tuff, clinker, and scoria. Various thin paleohorizons and debris flows encountered. Heterogeneous permeability distribution, with zones of potentially high permeability. Notable rubble zone at 231 to 236 below MSL.	164.6	
>663	-620 (bottom of hole)	Taputapu volcanics. Basalt and volcanoclastics, predominantly massive texture, most pore spaces filled with secondary mineralization. Generally lower permeability than upper Taputapu.	>383	

[a]Ground elevation at TGH-1 estimated at 43.1 m above Mean Sea Level (MSL).
[b]Photos from Geologica Geothermal Group, Inc. (2016).

Table 2. Simplified log from TGH-3 core interpretation.

Depth (bottom of unit, m)	Height (above MSL, m)[a]	Geologic Unit and Hydrologic Notes	Unit Thickness (m)	Core Samples[b]
74.4	1.9	Leone basalts, unsaturated zone. Fractures and vesicularity suggest high permeability.	74.4	
82.3	-6.0	Leone basalts and ash layer at bottom. Upper water table encountered at 74.4 m, unconfined saturated zone. Basalts look permeable, ash may have low permeability.	7.9	
91.4	-15.1	Carbonate. Coral sand, intact reef, and fine grained marl. Probably more permeable than lower carbonates.	9.1	
134.1	-57.8	Leone basalts between carbonates. Mostly vesicular. Fractures and vesicularity suggest high permeability.	42.7	
150.3	-74.0	Second carbonate unit. Mostly carbonate marl, some coral fragments. High clays suggest low permeability. Potentially a confining unit?	16.2	
157.3	-81.0	Leone basalts and tuff. Iron oxide and secondary mineralization visible in fractures. Low vesicularity, thus potentially low permeability.	7.0	
167.8	-91.5	Debris flow, mud, clay, and clasts. Potentially a confining layer?	10.5	
>645	-568 (bottom of hole)	Taputapu volcanics. Many alternating units of basalt and lithic lapili tuff. Some scoriatious units. Heterogeneous permeability distribution. Large rubble zone at 199 to 232 below MSL.	>480	

[a]Ground elevation at TGH-3 estimated at 76.3 m above MSL.
[b]Photos from Geologica Geothermal Group, Inc. (2016).

Statistics regarding the lithology of the Leone and Taputapu Units were compiled in Table 3. These statistics include the proportion of total summed thickness of basalt sections to pyroclastic sections, the proportion of total thickness of massive basalts (with or without fractures) to vesicular or soft/rubbly rock, and the ratio of assumed more-permeable to less-permeable sections overall. These analyses show that in both boreholes, the Taputapu and Leone Volcanic Units are composed of similar materials and have lithological sections ranging from massive basalt, vesicular basalt, fractured basalt, pyroclastic materials, unconsolidated regions; to sedimentary horizons, many of which seem to alternate rather quickly (average section thickness in both holes was between 2.0 and 2.4 m) in a non-regular sequence. Each layer was classified here based on its lithology as well as an assumption of its permeability, with vesicular basalt, rubble and unconsolidated zones having higher assumed permeability and massive lavas, ash and clay having lower assumed permeability. This analysis indicates the Taputapu series generally has a higher proportion of less-permeable material, whereas the Leone series is constructed of a greater proportion of rock types that were assumed to be more permeable. Notably large rubble zones are seen in the Taputapu Series in both holes, at –231 to –236 m and –199 to –232 m below sea level at TGH-1 and TGH-3, respectively. It remains unclear if these zones are connected between holes. Temperature logging was also performed during and after drilling, the results suggest the presence of a lower temperature aquifer within TGH-3's rubble zone. These results, along with a more detailed discussion of deep borehole data, lithology, and detailed tabulated data, are discussed in Appendix A.1.

Table 3. Physical characteristics of deep borehole logs based on visual examination of core.

Borehole (Unit)	Total Thickness of Unit (m)	Proportion of Basalt Layers: Pyroclastic Layers (%)*	Proportion of Massive Basalt: Vesicular/Clinker/Rubble Rock (%)	Proportion of Less-Permeable: More-Permeable Flow Units (%)
TGH-1 (Leone Series)	89.0	85:15	47:53	48:52
TGH-1 (Taputapu Series)	548.3	92:8	58:42	87:13
TGH-3 (Leone Series)	153.0	96:4	37:63	33:67
TGH-3 (Taputapu Series)	477.3	85:15	50:50	79:21

*Only the first 215 m of each hole was analyzed due to difficulty in distinguishing pyroclastics in lower layers.

2.1.2 Shallow Borehole Logs

Lithologic sections from shallow production-well borehole logs and archeological trenches were also classified into a simplified database. The lithological descriptions between logs were highly variable, as logs were recorded by different drillers through different decades. For simplicity, each lithologic section was classified into one of two categories: (1) tuff, ash, clay or massive non-vesicular basalt sections that were assumed to have 'lower-permeability,' and (2) cinder, sand, aʻa clinker, decomposed basalt, or pahoehoe sections that were assumed to have 'higher-permeability.' Unfortunately, the available driller's logs often lacked clear lithological descriptions, and frequently only documented changes in drilling speed as "hard" or "soft" sections. In volcanic island settings these terms have been interpreted to signify the difference between impermeable massive lava sections and more-permeable rubble or clinker zones, respectively (Eyre and Walker, 1991). However, this assumption may be an oversimplification, as drilling speed can also increase if a lower-permeability clay or weathered volcanic rock horizon is encountered. Nonetheless, for this report, the logs were classified to the best possible resolution, and ratios of the total thickness of assumed 'more-permeable' sections to assumed 'less-permeable' sections were averaged for boreholes in each region (Table 4). Strong differences in permeability between regions (as is seen in the analysis of the deep-borehole core) are not seen with this analysis. However, the logs do show a similar degree of geologic heterogeneity as the deep-borehole core, and many logs show massive lavas (or hard drilling zones) interlayered with cinders, weathered basalt, rubble, or other soft materials. A more extensive discussion regarding the analysis methods and other uses of the shallow subsurface logs is presented in Appendix A.2.

The most useful aspect of these logs may be simply to show the relative degree of subsurface heterogeneity, which is informative for refining our conceptual model of the island's geologic construction. This utility is evident upon examination of the lithological sequence found in seven very closely spaced shallow borehole logs from the Tafuna Plain (recorded in Bentley, 1975). These boreholes lie along an 850-m-long southwest to northeast profile (Fig. 7). Despite being quite close to each other, the flow sections they encounter are poorly correlated between holes (Fig. 8). This lack of correlation shows the complex structure of the Tafuna Plain flows, which are composed of alternating sequences of massive lavas, and rubble or fractured zones that are not aerially extensive. Figure 9 shows a conceptualized schematic interpretation of how these alternating permeable and impermeable sections might create borehole observations that fit the log data shown. This conceptual picture supports the conclusion that Tutuila's subsurface is hydrogeologically complex.

Table 4. Interpretation of shallow borehole logs, grouped by region. Lithologic units in each log are classified as either permeable or impermeable and the proportion of each type (% of total thickness) is averaged over the logs within each region.

Region	n*	Average Proportion of Permeable Units (%)	Average Proportion of Impermeable Units (%)
Iliili	5	52 ± 24	48 ± 24
Leone and Malaeloa	5	51 ± 26	49 ± 27
Tafuna and Malaeimi	16	47 ± 22	53 ± 22
Pago Shield and Alluvial-fill valleys	15	49 ± 28	51 ± 27

Note: ± = 1σ from mean value.
*n = number of logs available in each region.

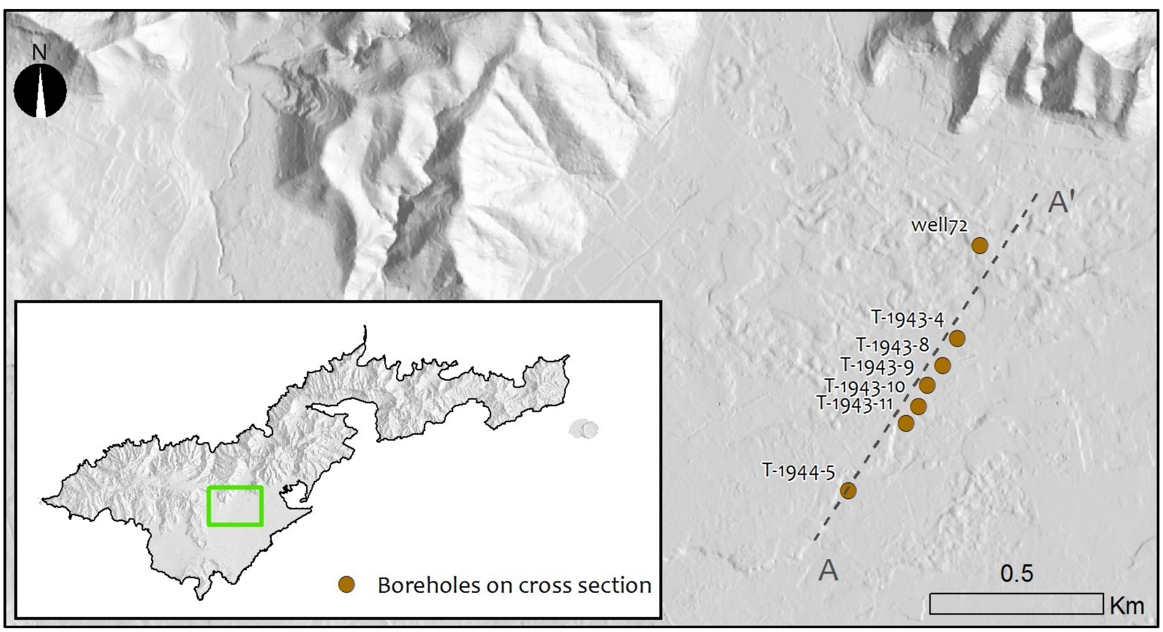
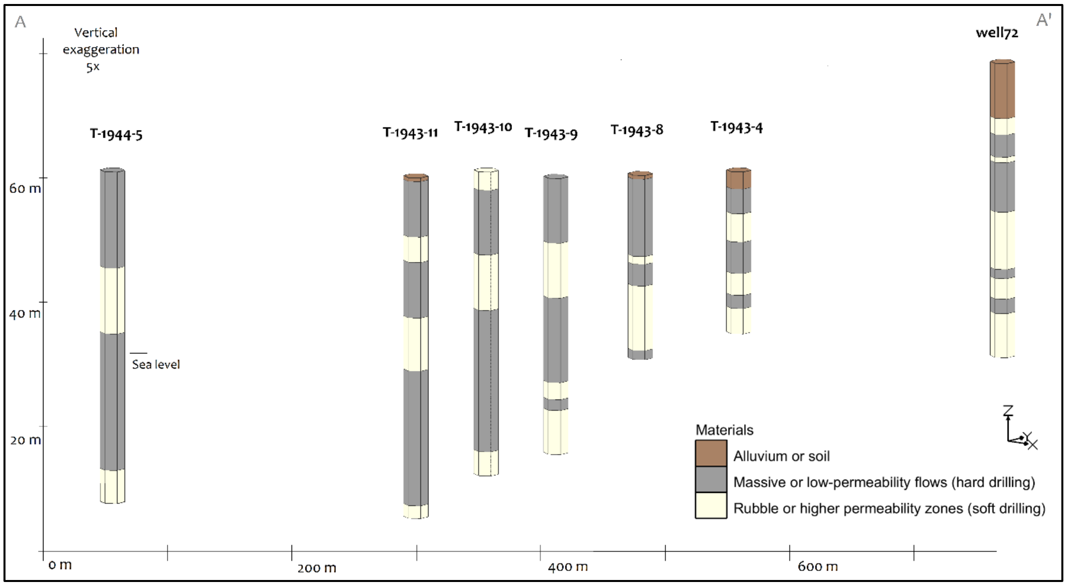
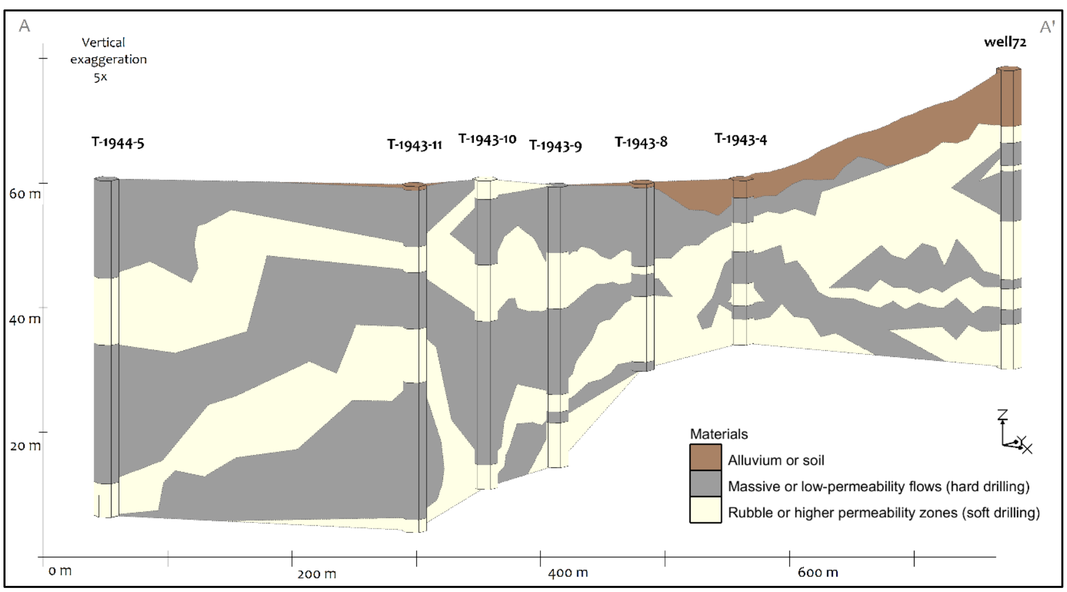


Figure 7. Location of Tafuna well field profile.



Source: Bentley 1975 for log information.
Note: Reference datum is arbitrary.

Figure 8. Interpretation of driller's logs (from Fig. 7) into lithologic units with simplified hydrological properties.



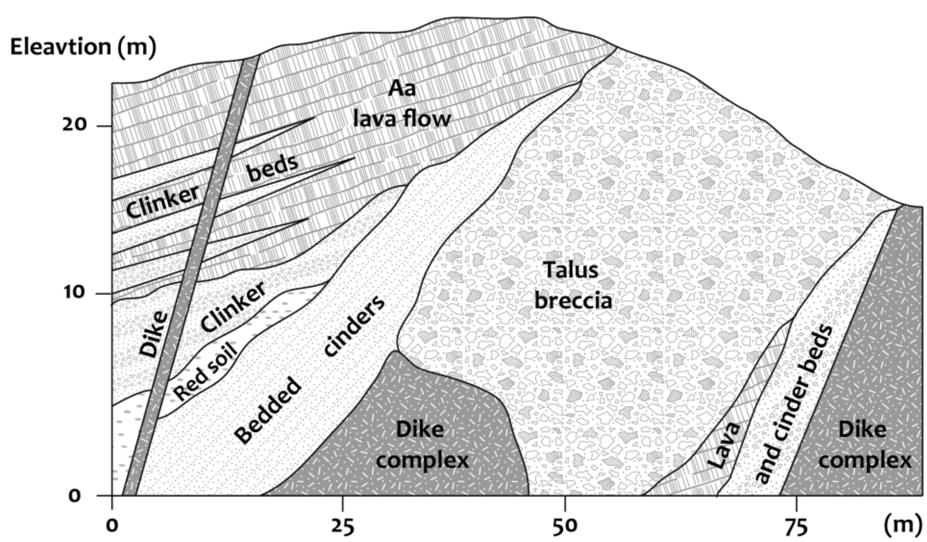
Based on Walker 1991.

Figure 9. Conceptualized cross section of the Tafuna-Leone lava delta. The model is based on conceptual occurrence of lava delta formation when overlaid on seven borehole logs shown in Figure 8.

2.2 Examination of Lava Outcrops in Pleistocene Volcanic Rocks

Over 50 quantitative measurements of outcrop characteristics in the Pleistocene Volcanic rocks were made by Eyre and Walker (1991). Measurements of (1) thickness of each lava flow section, (2) the separate thickness of the flow interior and rubble layers of aʻa flows, (3) the vesicularity of the flow interior, and (4) the overall dip of the lavas were taken at road cuts, coastal cliffs, and promontories throughout the island A map of these measurements, and a table of the resulting values are given in Appendix A.3. When summarized, the data show only 2.4% of the total flow thickness of the Pleistocene rocks were classified as pahoehoe—the majority consisted of aʻa flows. Within the aʻa flows, massive aʻa cores were able to be distinguished from rubble or clinker layers, and rubble was seen to make up about half (46%) of the total aʻa flow thickness. The proportion of rubble to massive sections in outcrops is proportionally similar to the amounts of permeable vs. impermeable zones that were observed in the driller's logs from both the Pleistocene rocks as well as the Tafuna-Leone Unit.

Although the large fraction of aʻa rubble in the Pleistocene aquifers would seem to suggest a high overall permeability, aquifer tests in this unit show the opposite (see Section 2.4). This discrepancy may be caused by the presence of low-permeability features that reduce the connectivity and aerial extensiveness of the rubble zones, effectively reducing the overall permeability. Since the subaerial extent of Tutuila is highly dissected by erosion, and dikes intrude much of the land remaining above sea level. The island has also experienced other disruptive events, such as small eruptions, faulting, landslides, and other mass wasting events. These events produce small and large pockets of talus breccia, debris flow material, cinders, or intrusive bodies. These features alter the aquifer's permeability and are heterogeneously dispersed throughout the body of the island (Fig. 10).



Modified from Stearns 1944 with permission.

Figure10. Diagram of the geologic components of the Pleistocene volcanics in an outcrop at Masefau Bay.

2.3 Interpretation of New Geophysics and Well Logging

A magnetotelluric (MT) survey of subsurface electrical resistivity beneath the Tafuna-Leone Plain and the Taputapu Volcano was conducted by Geologica Geothermal Group, Inc. (2014) for the purpose of exploration for a geothermal resource. In addition to the original motivation, the results are useful for interpreting the hydrogeology of the subsurface. The profiles indicate less-resistive zones that are inferred to be saturated with seawater, and also highly-resistive areas that are inferred to indicate the unsaturated zone. Moderately resistive areas could be interpreted as either permeable basalt saturated with freshwater or as regions of dense but unsaturated rock. The hydrology in these moderately resistive areas is difficult to discern on the profiles. An approach to resolve this issue with additional surveys might include a time-lapse sequence of MT imaging, which would evaluate transient changes based on water saturation and density conditions.

These profiles of subsurface resistivity (Figs. 11 and 12) vary in the specifics for different areas but share the common characteristic of an approximately 500 m thick high-conductivity layer, with resistivities of less than 10 Ω·m. This layer extends from the coast (sea level) to two to three miles inland where it fades into more resistive material (-600 m below sea level). This high conductivity layer is overlain, underlain, and bounded towards the central part of the island, by more resistive material having resistivities of 20 to 400 Ω·m. The high-conductivity layer seems to occur in the Tafuna-Leone lavas, the underlying carbonate reef platform, and into the edifice of the Taputapu Mountain. This layer is very likely the result of conductive seawater that underlies the freshwater lens. The more resistive materials that bound the conductive layer on three sides (top, bottom, and inland margin) have resistivities that correspond to either unsaturated or saturated basalt with freshwater. The overlying highly resistive layers (>10 Ω·m) most likely represent unsaturated basalt, and the moderately resistive layers in this region (≈20 to 120 Ω·m) may represent the same material saturated with freshwater. The inland resistive material at depth may well represent the islands rift zone where numerous volcanic dikes either (1) prevents the intrusion of seawater and possibly allows freshwater to penetrate hundreds of meters below sea level, or (2) creates a material of such low porosity that no significant amount of water (fresh or salt) penetrates it, thus yielding the resistivity of basalt with low moisture content.

The high resistivities shown underneath the conductive layer seaward of the island's interior are surprising; saltwater saturation would be expected. Either the material is of such low porosity that no significant amount of water penetrates it, yielding the resistivity of basalt with a low moisture content; or the development of the resistivity profiles, which are based on a data inversion process, were not performed in a manner that accurately reflects conditions in the region in question. Note that temperature and resistivity-conductivity depths mentioned here are only approximate due to potential inaccuracies in measurements and in estimation of depths from the Geologica profiles.

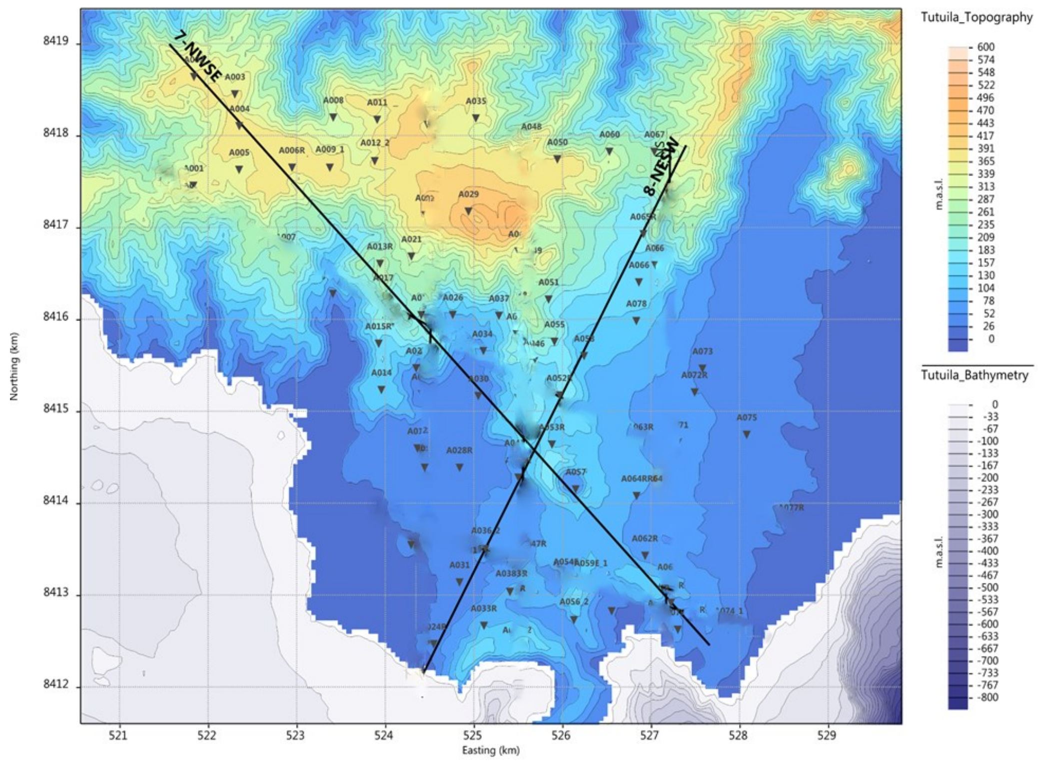


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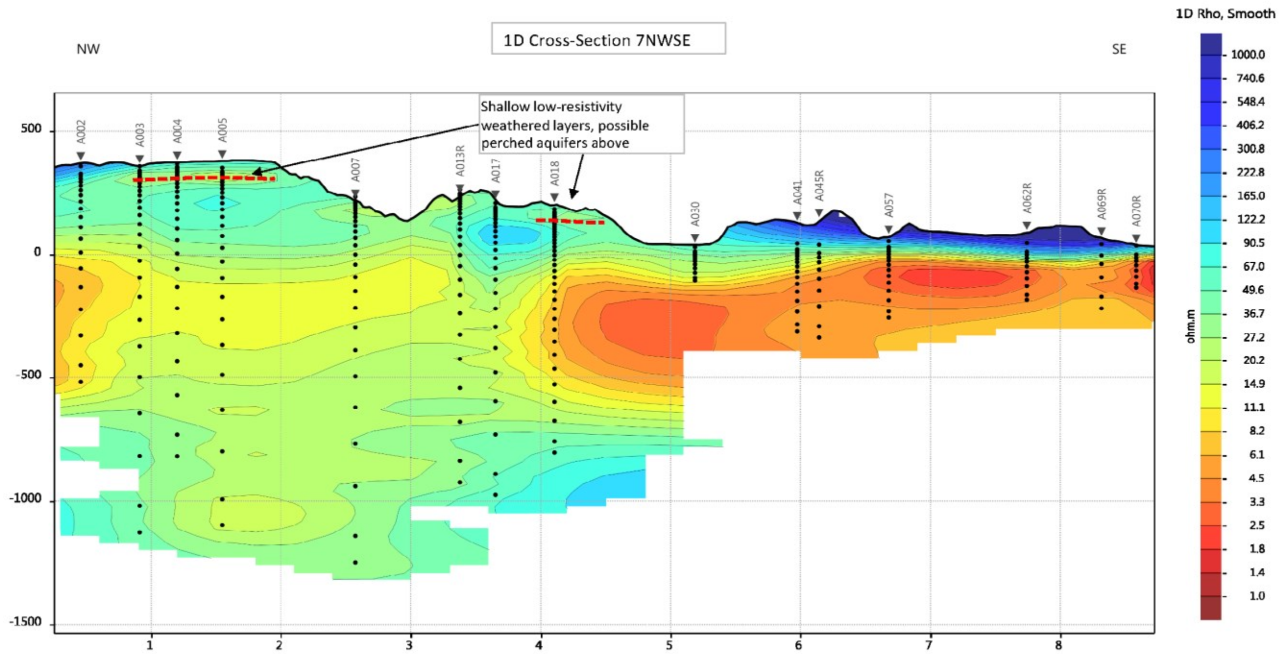
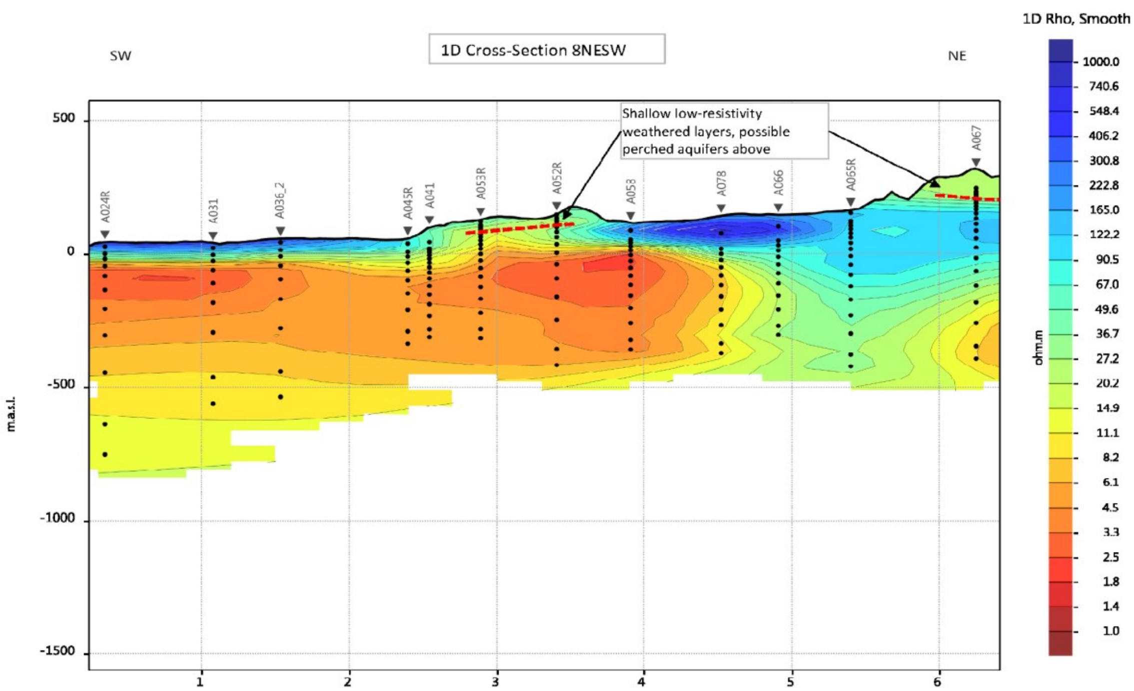
Figure 11. Map of the Tafuna-Leone Plain area showing locations of MT station measurements and cross sections (illustrated in Figure 12).

2.4 Hydrogeological Data from Recently Acquired and Previously Published Data Sets

2.4.1 Water Levels

Basic water level information can be used to assess the direction of groundwater flow, to infer aquifer properties, and to estimate magnitudes of hydraulic connectivity in different areas. Near sea-level water levels in the Tafuna-Leone Plain generally support observations of high-hydraulic conductivity, whereas wells in valley-fill alluvial aquifers and Pleistocene rocks have more variable water levels suggesting these areas have more heterogeneous conductivity distributions. Some water levels in the Pleistocene rocks might indicate that groundwater could be perched, semi-perched, or otherwise elevated above the basal level. Historical U.S. Geological Survey (USGS) reports authored by Izuka (1996, 1997, 1999a) contain water levels from American Samoa Power Authority (ASPA) records for the years 1984–1997. Eyre and Walker (1991) summarized water level data from USGS records for the period of 1975 to 1991. Other historical reported water levels contained in various sources are also summarized in Table 5. Note various uncertainties in water level data are detailed in Appendix B, Section 1. Also presented in Appendix B are results from a 2014 island wide water level survey performed by the University of Hawaii Water Resources Research Center.





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Note: Warmer colors indicate less resistive materials, interpreted to show conductivity from seawater saturation in the subsurface.

Figure 12. Cross sections of western Tutuila showing subsurface resistivity from Geologica Geothermal Group MT survey.

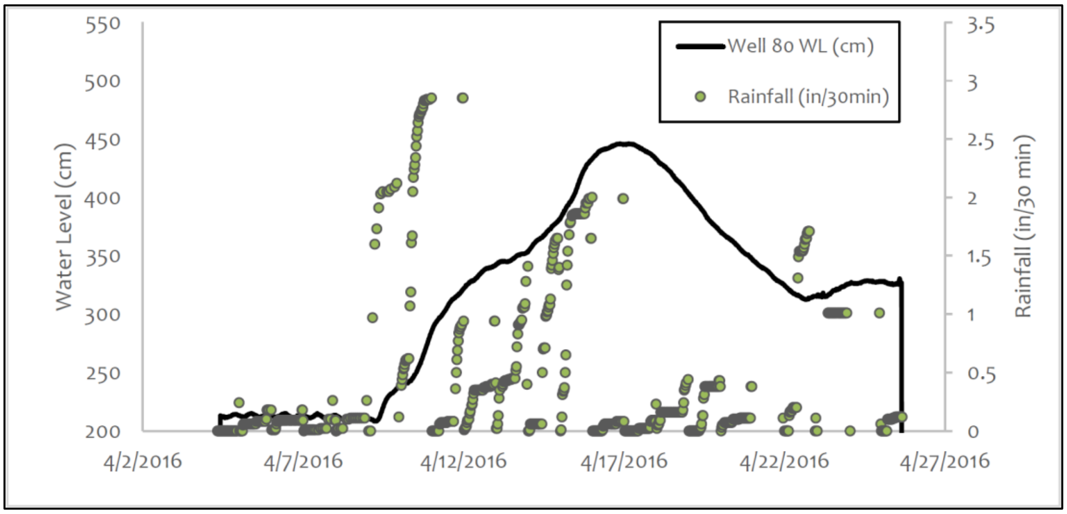
Table 5. Published historical water level data.

Well Field	Formation	Water Level (m)	Reference
Tafuna	Tafuna lava	0.3 to 0.6	Izuka (1996, 1997, 1999a)
Tafuna	Tafuna lava	≈1	Kennedy et al. (1987)
Tafuna	Tafuna lava	≈1-2	Eyre (1994)
Tafuna	Tafuna lava	1	Eyre and Walker (1991)
Iliili	Tafuna lava or pyroclastics	1 to 1.8	Izuka (1996, 1997, 1999a)
Iliili	Tafuna lava or pyroclastics	1 to 2	Eyre and Walker (1991)
Malaeimi	Alluvial or Pago Shield	12 to 27	Izuka (1996, 1997, 1999a)
Malaeimi	Alluvial or Pago Shield	2 to 35	Eyre and Walker (1991)
Malaeloa	Leone lava	≈1.5	Kennedy et al. (1987)
Malaeloa	Leone Lava and Taputapu	0.3 to 3	Izuka (1996, 1997, 1999a)
Malaeloa	Leone Lava and Taputapu	1 to 2	Eyre and Walker (1991)
Leone	Leone lava	0.3	Eyre and Walker (1991)
Pago shaft	Pago Shield	7.3	Davis (1963)
Pago shaft	Pago Shield	9	Eyre and Walker (1991)
Pago Village	Alluvial or Pago Shield	6 to 15	Izuka (1996, 1997, 1999a)
Pago Village	Alluvial or Pago Shield	1 to 20.5	Eyre and Walker (1991)
Fagatogo	Alluvial or Pago Shield	6.5	Eyre and Walker (1991)
Aua	Pago Shield	4.5 to 6	Izuka (1996, 1997, 1999a)
Aua	Pago Shield	6	Eyre and Walker (1991)
Laulii	Pago Shield	5 to 8.5	Izuka (1996, 1997, 1999a)
Laulii	Pago Shield	5.5 to 7.3	Eyre and Walker (1991)
Fagaalu	Alluvial or Pago Shield	4.5 to 10.5	Eyre and Walker (1991)
Fagaalu	Alluvial or Pago Shield	9 to 18	Izuka (1996, 1997, 1999a)
Fitiuli	Parabasal alluvial	20.4	Eyre (1994)
Amouli	Alluvial	1 to 1.5	Izuka (1996, 1997, 1999a)
Tula	Alluvial	0.03 to 3	Eyre and Walker (1991)
Sailele	Alluvial	3	Eyre and Walker (1991)

Note: Water levels are in meters above sea level.

2.4.2 Variability of Water Levels with Recharge, Drought, or Pumping

Water levels in the Tafuna-Leone Plain aquifers are quite variable in response to rainfall or extended dry periods, and baseflow and spring flow throughout the island has been reported to be significantly reduced by extended dry periods (Davis, 1963; Bentley, 1975). In the Pleistocene rocks, water-level drawdowns of up to 15 m are observed in response to pumping (Eyre and Walker, 1993). Although the plain's water levels do not seem to respond strongly to variations in pumpage (Shuler, unpublished data, July 2014), Kennedy et al. (1987) notes that water levels in Tafuna-Leone wells were found to increase and subsequently decrease rapidly, in response to high rainfall events. Water level declines and increased salinity have also been observed in Tafuna-Leone wells during droughts. An extreme example of rapid change in water levels from recharge events can be seen from a recent water level observation made in a non-pumping well in Lower Malaeloa Village during a period of heavy rain events (Fig. 13). Over the course of ten days during and following these events, the water level in Malaeloa Well 80 increased by over 2 m. Periods of heavy rainfall leading to large water level increases have also been correlated with increases in turbidity and *Escherichia coli* detections in some Tafuna-Leone wells, which is the primary issue that has mandated the island's long standing boil-water notice.

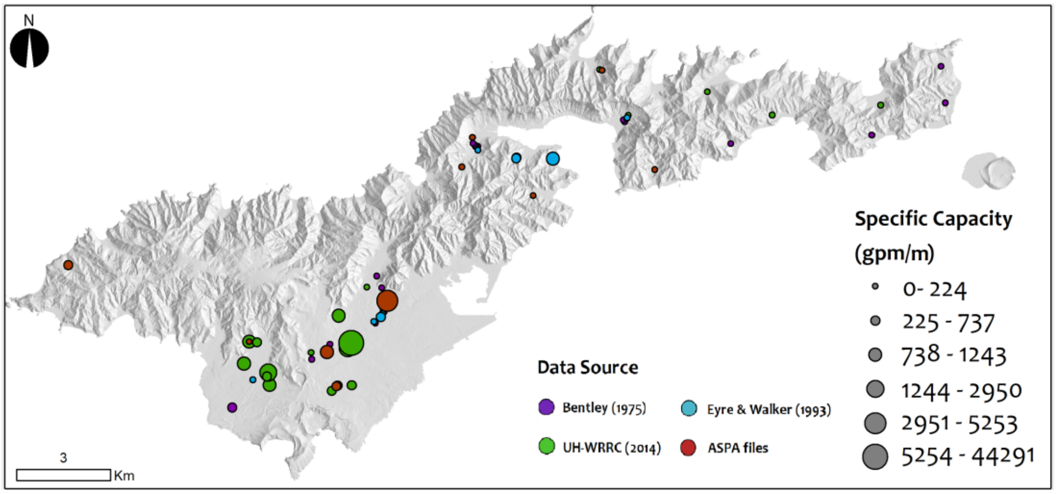


Note: Rainfall information from UH-WRRC weather station located in Malaeimi Village.

Figure 13. Time series measurement of water levels (WL) taken over an extended period of heavy rain events in Lower Malaeloa monitoring Well 80.

2.4.3 Specific Capacity

In pumping wells where the static and pumping water levels are available, the ratio of pump-rate to drawdown can be assessed. This measurement, known as specific capacity, is reported here in gallons per minute (gpm) per meter of drawdown. Higher specific capacities indicate better producing wells. This parameter can indicate the productivity of a well, but it is of limited use in describing aquifer characteristics as drawdown from both aquifer loss and the well loss (head loss resulting from attributes of well construction) are both included in the drawdown used to calculate specific capacity. Depending on the drilling and well construction methods, well loss can be, and often is, greater than aquifer loss. Measurements of specific capacity from past studies, ASPA records, and recently conducted University of Hawaii Water Resources Research Center (UH-WRRC) tests are shown in Figure 14, and shows expected regional variability. Specific capacity measurements on Tutuila indicate that in general, wells in the Tafuna-Leone Plain region yield more water per unit of drawdown then wells in other parts of the island.



Sources: ASPA files, Bentley 1975, Eyre and Walker 1993, and UH-WRRC 2014.
Note: Colored circles = data source, size of circle = specific capacity value (gpm/m).

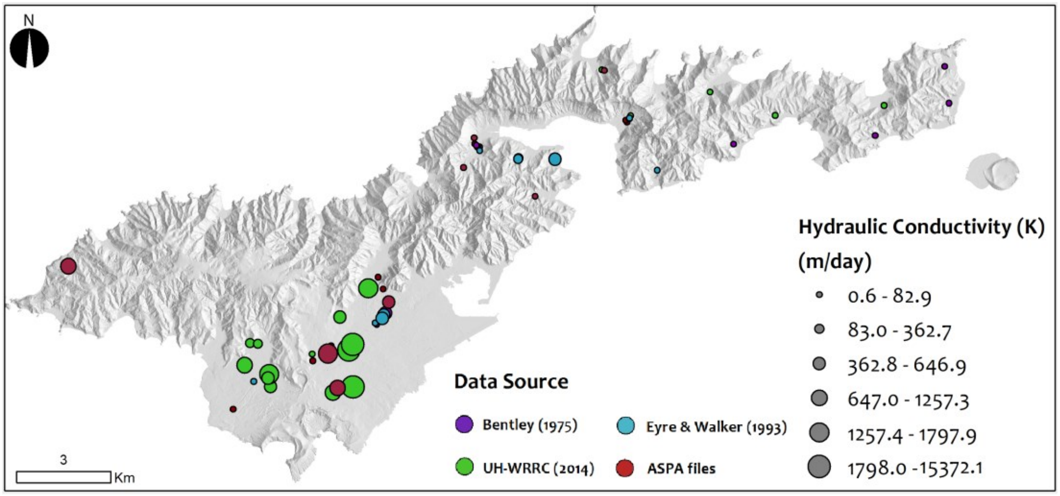
Figure 14. Distribution and magnitude of specific capacity values derived from historical records and from recently conducted UH-WRRC tests.

2.4.4. Aquifer Transmissivity and Hydraulic Conductivity

Transmissivity (***T***) and hydraulic conductivity (***K***) describe how fast water is able to move through saturated aquifer material over a given hydraulic gradient. These data are commonly gathered through constant-rate pumping, step-drawdown, and recovery tests when a new well is developed. The two parameters are related, ***K*** describes the rate of flow through a unit cross sectional area of aquifer, whereas ***T*** describes the rate of flow in regards to the entire thickness of the aquifer (b). This essentially means that T equals K times the aquifer thickness (b) (Freeze and Cherry, 1979).

To develop the most comprehensive estimates of aquifer parameters on Tutuila, all available pump test, step-drawdown, and recovery test data were compiled from USGS records (Bentley, 1975; Eyre and Walker, 1991), archived ASPA records, and the recently performed UH-WRRC aquifer tests. Values of ***T*** and ***K*** from Bentley (1975) and Eyre and Walker (1991) are estimates derived from pump tests performed by USGS or from data recorded during well development testing, and their analytical methods are detailed in the aforementioned reports. Analytical methods for deriving ***T*** and ***K*** values from ASPA records and UH-WRRC tests are detailed in Appendix B, Section 2. Island wide values of ***K*** are presented in Figure 15.

Compiled aquifer parameter values of ***K***, ***T***, and specific capacity from all data sources are summarized in Table 6. The data is summarized with three different measures of central tendency, these being the arithmetic mean [$\boldsymbol{\mu} = \boldsymbol{E}(\boldsymbol{x})$], the harmonic mean [$1/\boldsymbol{\mu} = \boldsymbol{E}(1/\boldsymbol{x})$], and the geometric mean {$\ln(\boldsymbol{\mu}) = \boldsymbol{E}[\ln(\boldsymbol{x})]$}, where ***E*** is the sum of individual values divided by the number of values. Considering the heterogeneous character of the Pleistocene aquifers, it is reasonable to assume that when characterizing ***T*** and ***K*** for entire hydrologic units, the best estimate of these parameters is probably represented by the harmonic or geometric means, rather than the arithmetic mean, of individual values from well tests (Eyre and Walker, 1991). See Appendix B for a more detailed description of analytical methods used to obtain and evaluate these values.



Sources: ASPA files, Bentley 1975, Eyre and Walker 1993, and UH-WRRC 2014.
Note: Colored circles = data source, size of circle = value of K (m/d).

Figure 15. Distribution and magnitude of *K* values derived from ASPA historical records and from recently conducted UH-WRRC recovery tests.

2.4.5 Numerically Modeled Values of Hydraulic Conductivity

Another method for estimating ***K*** values is to numerically model them where water level data is available. This approach yields a regionally integrated estimate of ***K***, as opposed to point based data. Groundwater models use subsurface flow equations (essentially Darcy's Law) and parameterize them with recharge rates, geographic geometry, well characteristics, and well flowrates. Generally, the most poorly constrained parameter (often ***K***) is numerically solved for using a calibration process. Two groundwater models of Tutuila have thus far been developed via two fundamentally different methods. Izuka et al. (2007) measured elevations of the water table and then set modeled ***K*** to create simulated water table elevations that matched observed data. In contrast, the model developed by Walters (2013) assumed that a measured estimate of ***K***, based on an aquifer test and geologic conditions, was valid throughout all of the Pleistocene rocks, and then used the numerical model to solve for the water table elevation based on that ***K***. The Izuka et al. (2007) model focused on the Tafuna-Leone Plain region only and used static water levels in six monitoring wells to determine modeled values of hydraulic conductivity (***K***), given in Table 7, via model calibration. The Pleistocene rocks were modeled as a fully saturated homogeneous anisotropic system. The Walters (2013) model on the other hand, utilized many of the parameters from the Izuka et al. (2007) model, but the Pleistocene rocks were assumed to contain both disconnected high-level groundwater (which was ignored in the model) and basal groundwater. This alternate conceptual model for the older-volcanic region was represented in the model by a change in K_h:K_v and an increase in the K_h of the older volcanic unit by a factor of about 50 from the Izuka et al. (2007) model. The increased K_h value is a better match with the measured K values from the pump tests in the Pago Shield (1–7 m/d), although it is significantly lower than pump-test values measured from the Taputapu Shield (270–410 m/d). A more in depth discussion of these different conceptual hydrogeological models and how they inform numerical models is given in Appendix B, Section 3.

Table 6. Summary of aquifer and well production characteristics from existing wells on Tutuila from 1973 to 1974.

SPECIFIC CAPACITY (gpm/m)				
Hydrogeologic Unit	n*	Arithmetic Mean	Geometric Mean	Harmonic Mean
Tafuna lavas	20	2,882	228	12
Leone lavas and ash	7	783	449	194
Pyroclastics of Leone Series	5	368	94	2
Taputapu Shield	4	628	524	426
Pago Outer-Caldera Shield	14	13	10	4
Pago Inner-Caldera Shield	5	26	15	9
Olomoana or Alofau Shields	2	19	19	19
Alluvial-fill valleys	10	309	32	4
TRANSMISSIVITY (m^2/d)				
Hydrogeologic Unit	n*	Arithmetic Mean	Geometric Mean	Harmonic Mean
Tafuna lavas	19	11,894	3,512	1,112
Leone lavas and ash	5	4,782	3,379	1,584
Pyroclastics of Leone Series	3	3,882	3,070	2,369
Taputapu Shield	5	7,791	5,984	5,002
Pago Outer-Caldera Shield	12	176	124	73
Pago Inner-Caldera Shield	4	210	129	85
Olomoana or Alofau Shields	2	181	110	66
Alluvial-fill valleys	9	1	278	70
HYDRAULIC CONDUCTIVITY (m/d)				
Hydrogeologic Unit	n*	Arithmetic Mean	Geometric Mean	Harmonic Mean
Tafuna lavas	13	7,652	708	98
Leone lavas and ash	5	1,270	635	130
Pyroclastics of Leone Series	3	837	355	86
Taputapu Shield	3	410	323	270
Pago Outer-Caldera Shield	10	6	4	3
Pago Inner-Caldera Shield	3	7	3	1
Olomoana or Alofau Shields	1	9	9	9
Alluvial-fill valleys	4	261	121	22

Source: Bentley 1975, Eyre and Walker 1991, UH-WRRC aquifer tests, and ASPA file cabinets.
*n = number of wells.

Table 7. Numerically modeled values of hydraulic conductivity.

IZUKA MODEL[a]		
Geologic Unit	K_h:K_v	K_h (m/d)
Alluvium	100:1	260
Leone lava and ash	100:1	1,300
Pyroclastics	100:1	10
Rift-zone	10:1	0.03
Tafuna lava	10:1	945
Old-volcanics	100:1	0.14
ASPA MODEL[b]		
Geologic Unit[c]	K_h:K_v	K_h (m/d)
Old-volcanics	44:1	6.7

[a]Izuka et al. 2007.
[b]ASPA 2013.
[c]Other geologic unit values are same as Izuka model.

2.5 Recharge Estimates

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 satur

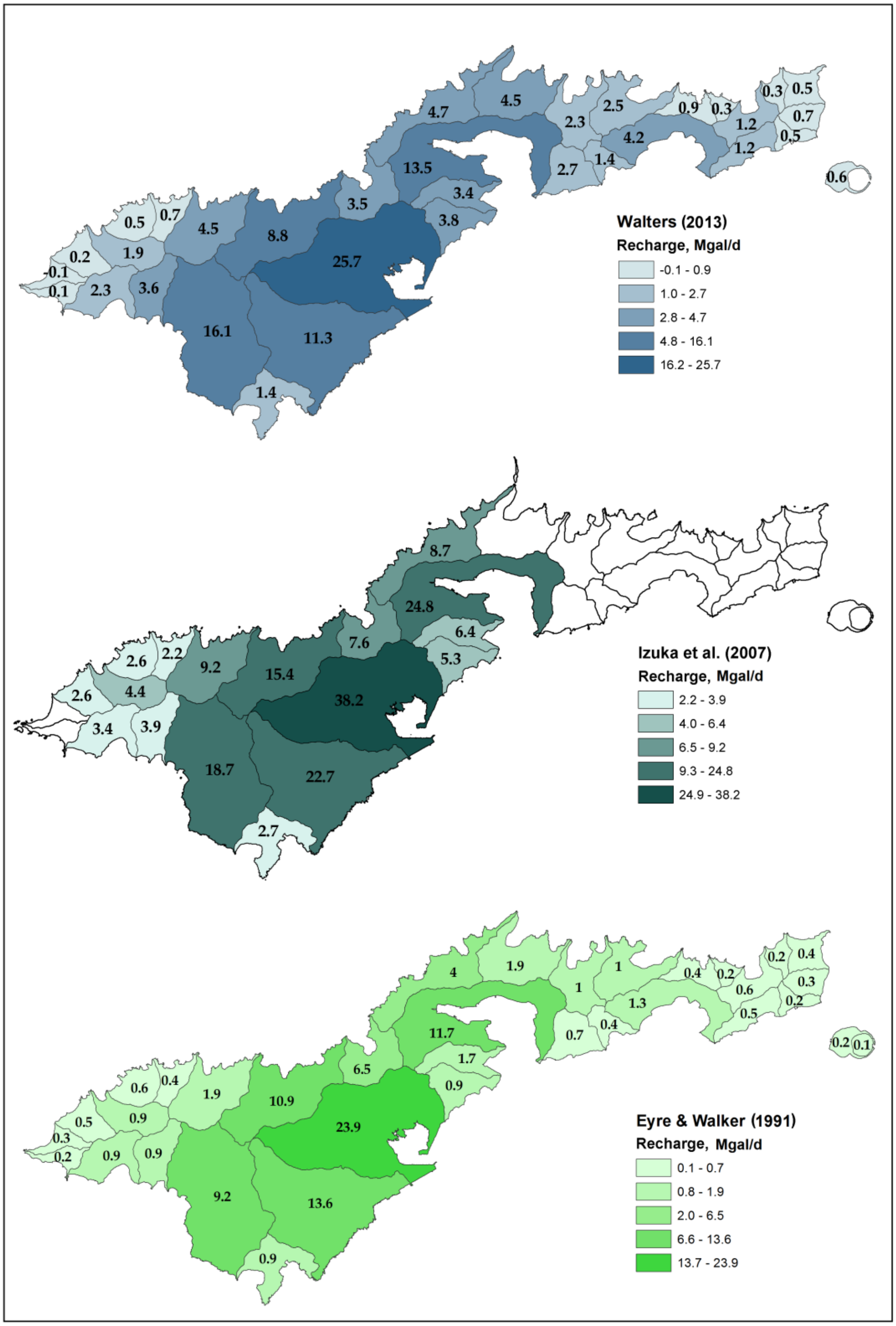
ated zone is termed recharge. In general, the spatial distribution of recharge on Tutuila follows a similar pattern to that of the rainfall, whereas higher elevations contribute more water to the subsurface than lower elevations. Available recharge estimates indicate that the eastern part of the island receives significantly lower amounts of recharge than the western portion.

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 Mountain Front Recharge (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 (Perault, 2010). This process is most significant in the Tafuna-Leone Plain where low-permeability rocks are positioned directly above and adjacent to high-permeability rock, although it has also been observed to a limited extent in alluvial-fill valleys.

Groundwater recharge is generally estimated with a water-balance/budget model. Past estimates have primarily considered basic hydrologic variables including precipitation, evapotranspiration, and runoff to inform recharge calculations. The three recharge estimates that have thus far been developed for Tutuila are detailed in Eyre and Walker (1991), Izuka et al. (2007), and Walters (2013), and are shown in a basin standardized format in Figure 16. Note that the recharge coverage calculated by Izuka et al. (2007) was focused only on the Tafuna-Leone Plain region, therefore, Eastern Tutuila was excluded from the result. A more detailed explanation of recharge calculations, and the existing long-term climatological datasets that they may be based upon is given in Appendix B, Section 4. Individual methods of calculation used for each recharge estimate vary, and are fully described in each estimate's respective paper. Note that as of this writing, a new hydrological monitoring network is currently collecting updated data which is intended to be used in up-to-date water budget modeling designed to constrain groundwater recharge at a high temporal and spatial resolution.

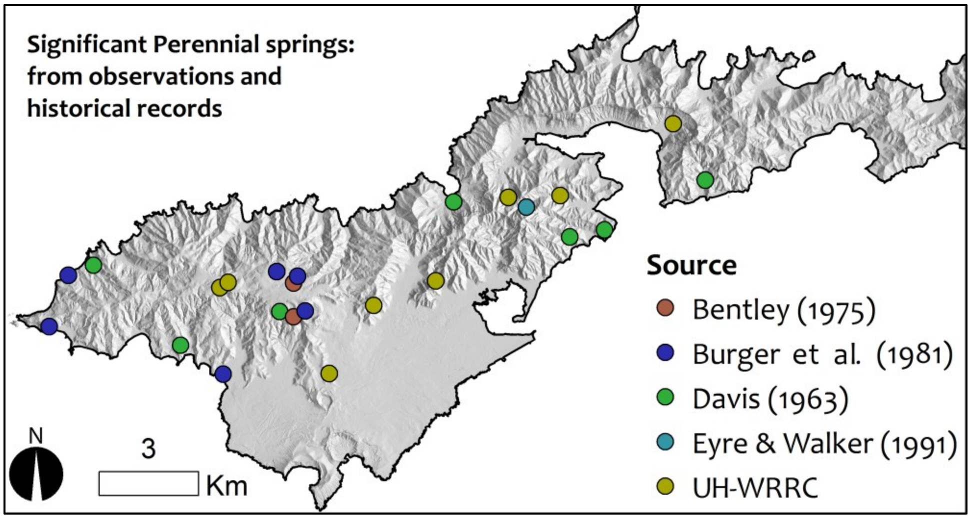
2.6 Significant High-Level Springs

There are a number of locations on Tutuila where springs with exceptional flow rates occur. These locations are often known and documented because of their historical use in village (or U.S. Navy) water systems. Prior to groundwater development in the 1970s, surface water supplies were the primary sources of drinking water on the island. Exceptional springs that have been located during UH-WRRC field expeditions or are documented in various literature sources are shown in Figure 17. A spring with a high flowrate suggests that the spring's subsurface source reservoir contains significant storage or that the recharge area for the reservoir is extensive. Such areas may indicate larger or more concentrated pockets of high-level water, potentially impounded by dikes, faults, or aerially extensive perching layers. It should be understood that water development in these areas will most likely result in reduction of spring and associated streamflow. Such actions have consequences for aquatic ecosystems as well as for residents who rely on village water systems that are dependent on springs. These consequences should be fully assessed prior to development of groundwater near significant springs.



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 16. Comparison of basin-standardized recharge estimates.



Sources: Bentley 1975, Burger and Maciolek 1981, Davis 1963, Eyre and Walker 1991, and UH-WRRC.
Note: Colored circles = data source, UH-WRRC = springs that were found by authors.

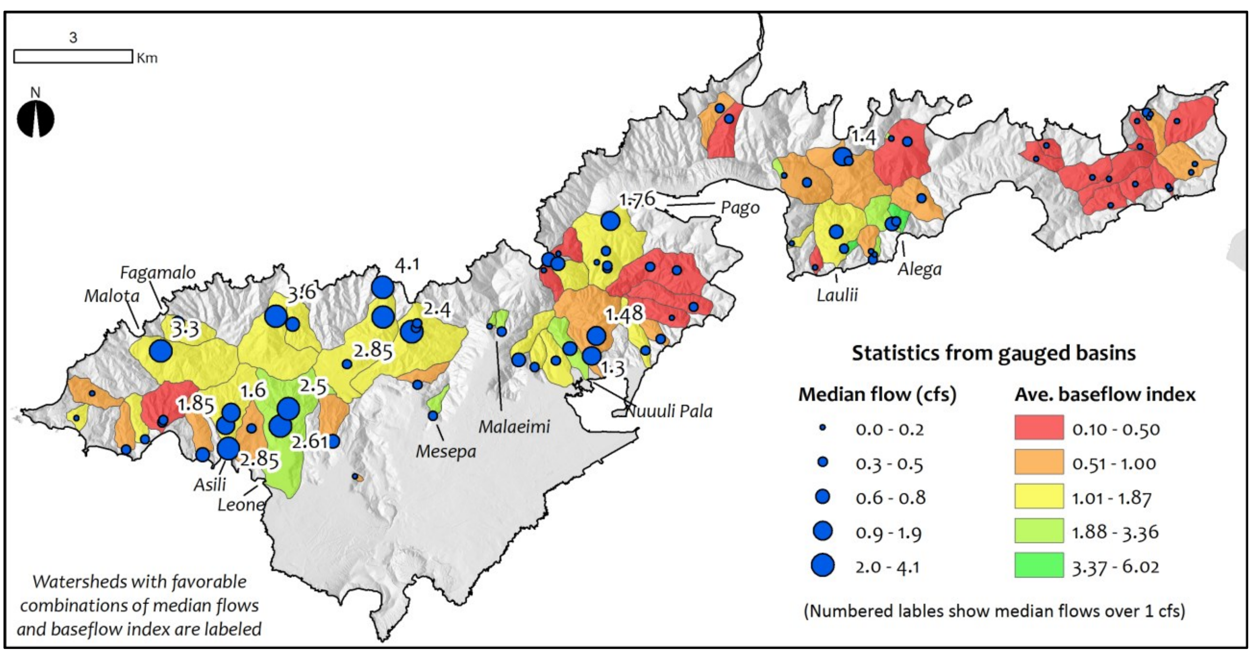
Figure 17. Locations of documented and/or observed freshwater springs that are likely to have significant flow rates.

2.7 Streamflow Analysis

Extensive stream gauging on Tutuila was performed by the USGS from the 1950s to 2008. The data from this effort remain as a significant asset to the understanding of American Samoa's hydrology. A summary of Tutuila's streamflow data and an analysis of low-flow characteristics is given by Wong (1996). Wong compiled analyses for 83 streams and tributaries in 63 basins or sub-basins. These included statistics regarding low flows at various recurrence intervals, mean and median flows, drainage basin characteristics, and variation in baseflow. Of particular interest to this work is the Baseflow Index (BFI), which is described in detail below.

Streamflow can be broken into two simplified components—baseflow and runoff—based on the process that generate them. The runoff component of streamflow can be considered to be the portion of flow that reaches the stream directly via surface or lateral flow, and primarily occurs during heavy rains. Baseflow, on the other hand, is discharged fairly consistently to the stream by an aquifer, which has been previously recharged by rainfall. In American Samoa, rainfall is generally heavy, the land is steep, and streams are short. These conditions create short-lived runoff events. However, the majority of the time, baseflow supplies the water that sustains streamflow in Tutuila's drainages. In Hawaii, stream baseflow has been shown to be equivalent to a flow value that falls within a range of the $\boldsymbol{Q}_{60}$ and the $\boldsymbol{Q}_{80}$ exceedance values (Bassiouni and Oki, 2013). These values are defined as the stream specific discharge ($\boldsymbol{Q}$) that is met or exceeded 60% of the time ($\boldsymbol{Q}_{60}$) or 80% of the time ($\boldsymbol{Q}_{80}$). Although the median flow of a stream ($\boldsymbol{Q}_{50}$), is likely to be slightly higher than the stream's true baseflow value, it is nonetheless a reasonable approximation for assessing the relative differences in baseflow between streams and is thus used here to represent baseflow. The variation in baseflow between different basins can indicate aquifer parameters, primarily the ability of the rocks in a basin to store and then slowly release water. Aquifers with higher water holding capacities will generally retain more precipitation as recharge, and streams in these basins will discharge a higher proportion of their total flow as baseflow as opposed to runoff.

The BFI was calculated by Wong (1996) for each gauged stream on Tutuila. This measurement is essentially the ratio of stream baseflow to runoff, standardized by the stream's basin size. The BFI is a useful relative indicator of the magnitude of groundwater discharge to each stream. The locations of stream gauges and the BFI of each gauged basin are shown in Figure 18. The BFI for streams in the Taputapu area are clearly higher than those in the eastern portion of the island, probably because of the addition of discharge from the many springs that issue from the cinder cap at Aoloau Mountain (Wong, 1996). Overall, there are a number of basins whose median flows and BFIs suggest that more substantial aquifers are able to contribute a larger proportion of water to the stream flow. The names of these notable basins are labeled on Figure 18 and include watersheds in the Taputapu Shield region, above the Tafuna-Leone Plain, in Nuuuli, and also around Rainmaker Mountain (Pioa Plug). Eastern Tutuila has less overall baseflow, and generally, shows lower stream BFIs indicating a lower potential for productive and sustainable high-level aquifers.



Based on data from Wong 1996.

Figure 18. Summary of low-flow streamflow characteristics for Tutuila.

3.0 HYDROGRAPHIC SETTING OF TUTUILA

Developed groundwater resources on Tutuila currently utilize four basic aquifer types: (1) groundwater of probably basal occurrence in Pleistocene-age volcanos, (2) basal-lens groundwater in the younger more permeable Tafuna-Leone Plain, (3) perched groundwater in rejuvenated pyroclastics capping older-volcanic rocks, and (4) basal-lens aquifers in small hydraulically isolated valley-fill units. Although a few water development tunnels and a number of high-level springs were formerly used on Tutuila for water resources, existing wells do not currently tap any high-level aquifers.

3.1 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 in a basic sense, constructed of gently dipping aʻa lava flows organized as an alternating sequence of more-permeable rubble zones and less-permeable massive sections (see section 2.1). 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 (Fig. 10).

All of Tutuila's groundwater originates as rain water, and as it percolates downwards through the surface, some of it is diverted laterally to streams or springs upon encountering less permeable bedrock below the soil. The remainder of the subsurface water (that which is not evapotranspired) infiltrates into the bedrock and becomes recharge, where it follows a tortuous path, encountering the rubble zones and less-permeable features of the shields. Some of the recharge may contribute to perched water bodies that accumulate upon massive layers, and some may be retained by vertical dikes, therefore contributing to dike-impounded reservoirs. Some recharge may also percolate downwards (probably slowly) through fractures in massive layers, and some likely moves laterally atop less-permeable features until it either encounters more-permeable material and continues downwards, or discharges to the surface as a high-level spring or stream baseflow. Eventually the remaining recharge percolates to an elevation where it begins to accumulate on top of the underlying seawater saturated rock and thus supplies the basal-freshwater lens.

This conceptual model of subsurface water movement on Tutuila predicts that multiple types of groundwater bodies, perched water, dike-impounded water, and basal water may accumulate and flow within Tutuila's Pleistocene rocks. The extent of each groundwater body is expected to be dynamic with variation in recharge and groundwater withdrawal. The basal-water elevation likely varies spatially and temporally, and may even merge with perched water bodies if the unsaturated material between is filled in response to high-recharge or cessation of pumping. Meinzer (1923) describes this condition as semi-perched, whereas these upper water bodies are connected through a continuous zone of saturation to the main (basal) water body, yet are hydraulically separated by a semi-leaky aquiclude where water flow is primarily downwards and slow through the low-permeability layer. In theory, the distinction between semi-perched and basal groundwater is that semi-perched water is supported by underlying rock, as opposed to underlying seawater.

Thus in Tutuila's shields, the upper portion of the basal-lens could be conceptualized as a semi-perched system with higher-conductivity water bearing zones interspersed within an arrangement of lower-conductivity barriers. This same geological arrangement could (for simplicity) also be conceptually modeled as a fully-saturated low-conductivity system where water movement is slow on average and controlled primarily by the low-conductivity features. The distinction between these two models essentially lies in the degree of connectivity between water-bearing high-permeability compartments. Upon groundwater withdrawals, a semi-perched condition would be expected to result in the upper portion of the lens losing hydraulic connection with the basal water body. Also if stream baseflow is fed from semi-perched aquifers, withdrawals from the basal-portion of the lens would not affect nearby streams. Needless to say, wells drilled into lower portions of the aquifer would not provide information regarding the quantity of developable water in the upper portion of the aquifer. In practice, distinguishing between these two scenarios is difficult, but could be assessed by taking water levels in an array of nested piezometers while pumping tests are performed in various portions of an aquifer. Although it is simpler, and probably functionally sufficient to consider the basal-lens within the Pleistocene rocks as a fully saturated system, the authors still caution that full connection throughout the basal aquifer(s) should not necessarily be assumed.

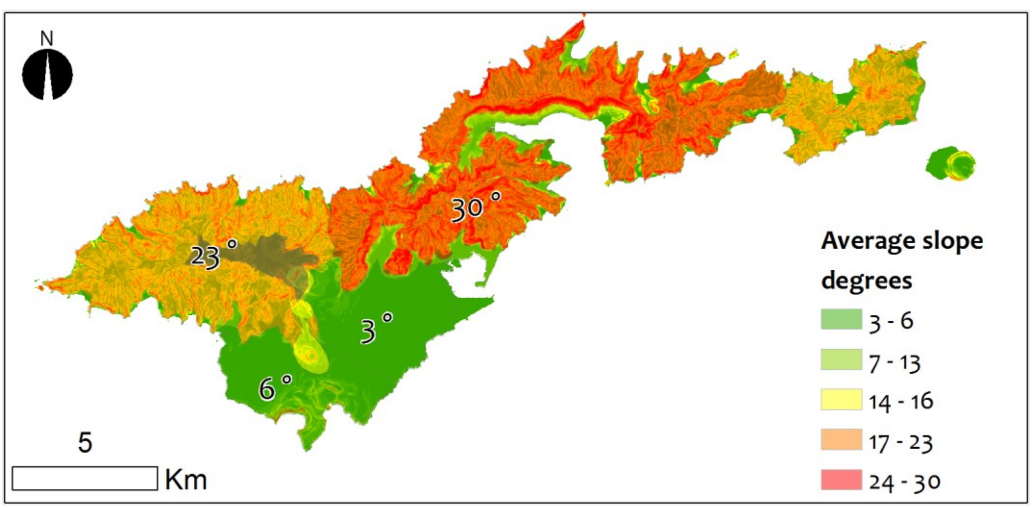
In light of the above discussion, the development potential of a new well at any location will be primarily dependent on the extent of the aquifer being tapped, and the local heterogeneity and complexity of porosity and permeability around the well. Groundwater withdrawals have the potential to affect local stream flows, depending on the connectivity between the aquifer and the stream. Where there is concern that groundwater pumping would reduce the baseflow of a stream, this connectivity can be assessed by comparing regional water levels and stream elevations, assessing stream baseflow characteristics, and by carefully monitoring water levels and geochemistry during well drilling. Also it should be noted that the thickness of a basal water body that exhibits a high vertical-to-horizontal flow ratio is not controlled by the water table height (i.e., the Ghyben-Herzberg relation does not apply in these conditions). Thus the depth to the saltwater transition zone should not be assumed from head measurements in the older-volcanic aquifers.

3.1.1 Differences Between Pleistocene Volcanic Shields

Although in other studies Tutuila's older shields have often been classified as a single unit with uniform properties, a number of recent observations suggest that there may be reason to subdivide this region into different hydrogeologic units. The Pago Shield itself has 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, 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). Interestingly, 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.

Measured aquifer parameters and geologic information suggests that the Taputapu Shield may have better water development potential than the island's other shields. This hypothesis is supported by the following:

1. Recent aquifer tests show specific capacities and K values that are significantly higher than those measured in the other shields (Table 6).
2. The Taputapu Shield may have experienced less erosion and mass wasting, which are processes that serve to reduce connectivity between permeable zones. This is supported by the observations that it is younger (Tarling, 1965; McDougall, 1985), and has a lower average slope (22°) then the Pago Shield (28°) (Fig.19).



Note: Geological units from Stearns 1944 and slope calculations from NOAA 10 m Digital Elevation Model.

Figure 19. Average slope (°) of simplified geologic units. Taputapu shield slope excludes the subdued topography region covered by Holocene Aoloaou cinders (shown in grey).

3. McDougal (1985) hypothesizes that the Taputapu and the Olomoana Shields are satellite shields of the main Pago Volcano, and therefore should have more high-permeability flank lavas, and less low-permeability caldera related features (intrusives, ponded lavas, hydrothermal alteration, etc.). This is supported by gravity anomalies as measured by Machesky (1965). These show a clear maxima (290 mGal) above the Pago Shield (Fig. 20), suggesting the Pago Shield contains more impermeable intrusive bodies, such as dike complexes or solidified magma chambers.
4. Inferred dike intensities as measured by Walker and Eyre (1995) and the locations of measured dikes by Stearns (1944) (Fig. 20) also suggests a greater density of impermeable intrusive bodies in the Pago Shield.
5. In comparison to the more easterly Olomoana and Alofau Shields, the average amount of groundwater recharge is significantly higher over the Taputapu region (Fig. 16).

Despite this evidence, the Taputapu Shield is nonetheless a large heterogeneous region, and more extensive aquifer testing should be performed to validate this hypothesis for specific areas.

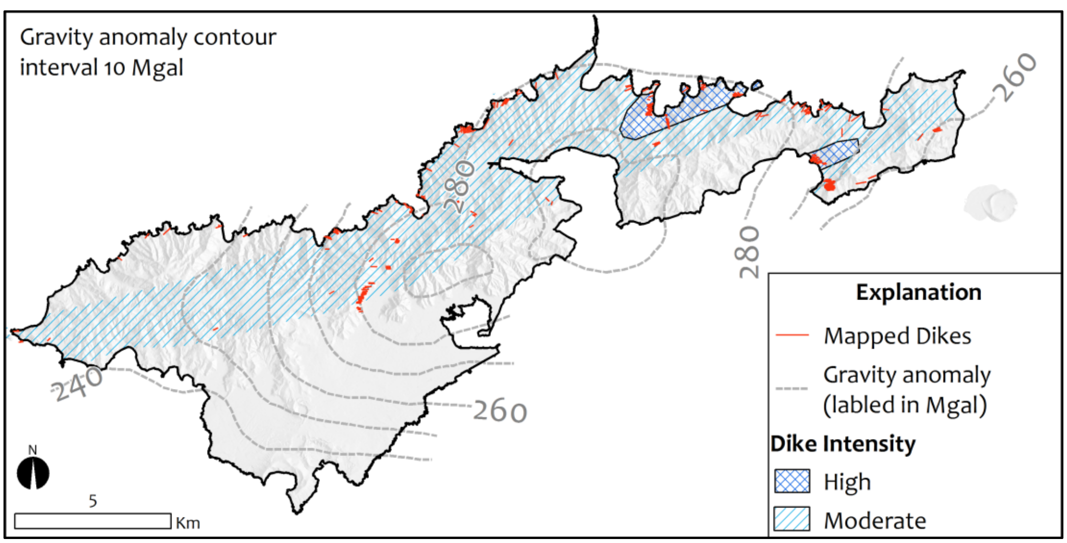


Figure 20. Geophysical and surface-mapping data showing inferred density of intrusive structures throughout Tutuila. Heavy cross-hatching indicates dike-complex areas and light hatching shows zones of moderate dike intensity from Walker and Eyre (1995). Bouguer gravity anomaly as measured by Machesky (1965) shows denser material nearer to the Pago Caldera. Also shown are locations of mapped dikes in outcrops by Stearns (1944).

Another potential zone for groundwater exploration within the Taputapu rocks lies beneath the Tafuna-Leone Plain. Both deep borehole logs indicate extensive rubble layers located at -231 to -236 m below sea level in TGH-1, and -199 to -232 m below sea level in TGH-3. During temperature logging in TGH-3, a cold-temperature anomaly was observed near this interval, which likely indicates fluid flow through this area (see Appendix A.1). It is unclear if the fluid in this zone is fresh or salty, as the anomaly could be caused by either freshwater flow in a confined system or by tidal seawater mixing if the rubble zone extends to the ocean. Deep exploration drilling or modification of existing deep boreholes in the Tafuna-Leone Plain would help to resolve this question.

3.1.2 High-Level Aquifers in Pleistocene Rocks

High-level groundwater refers to reservoirs of water that are supported by structural features, as opposed to the density contrast between freshwater and seawater, as in a basal-lens system. This type of water is desirable as it is generally less prone to contamination from surface activities, and is immune to the saltwater intrusion that threatens basal-lens aquifers. The existence of Tutuila's high-level groundwater is clearly indicated by the occurrence of perennial streams and springs throughout the upper elevations on Tutuila. However, the nature of these reservoirs is not well understood. Davis (1963), Eyre and Walker (1991), and Izuka et al. (2007) have noted that streamflow from the Pleistocene age volcanic rocks is generally fed by numerous and dispersed springs with low-flow rates. Davis describes high-level seepage zones that release small volumes of water, often along a lineation of some sort, and often with flow rates so low that they easily escape detection when seeping out under soil or thick vegetation. These conditions suggest that reservoirs containing high-level water in the Pleistocene volcanic rocks are dispersed, and often contain only small quantities of water. However, the existence of a few notable springs with higher flow rates does suggest that some of these reservoirs may be larger than others.

Locations of perennial high-level springs and measurements of baseflow provide clues for assessing the significance of an area's high-level water supplies (Fig. 18). The BFI is a basin-area-standardized metric for indicating a stream's potential to maintain flows that are supported by groundwater sources. A higher BFI indicates the basin has more significant groundwater storage (Wong, 1996), which serves to feed the stream in dry periods. Additionally, documentation of the existence of significant springs that have been used to supply water may also be an indicator of the region's high-level water potential.

On other tropical volcanic islands, such as the Hawaiian Islands, a number of different features are thought to be capable of impounding groundwater. Examples of these features that are pertinent to Tutuila can be simplified into three types: (1) dikes, (2) low-conductivity stratigraphic horizons (massive lava flows or clay/ash layers in the subsurface, and (3) combinations of the above and/or other complex formations (e.g., faults or paleo-valleys) that lie within low-conductivity units.

3.1.2.1 Dikes

In the Hawaiian Islands, high-level water supplies have been extensively developed with the use of horizontal water development tunnels. The Hawaiian conceptual hydrogeological model describes widespread dike zones, often on the margin of volcanic rifts, where large (>1 m wide), dense, sheet-like dikes impound water contained in higher porosity country rock (Gingerich and Oki, 2000) (Fig. 21A). On Tutuila, the distribution of dikes was mapped by Walker and Eyre (1995) (Fig. 20). They describe two predominant types of dikes on the island—thin clustered dikes contained in dike complexes (where >40% of exposed rock is dike material); and solitary dikes, which are fewer in number, wider, and likely feeders of surface eruptions. Tutuila's dike complexes are thought to have low-permeability and low water-storage capacity since they contain little permeable country rock between the dikes. It is recognized that dike-impounded groundwater is instead more likely to be found in areas of moderate dike intensity (<5% of total rock), which are termed marginal dike zones (Takasaki and Mink, 1985). The solitary dikes found in Tutuila's marginal zones (indicated as the edges of the hatched area in Fig. 20) are more likely to occur farther from the island's rifts and may be large and extensive enough to successfully impound groundwater. Some of these dikes are up to 3 m wide, and have been observed at elevations of 300 m (Stearns, 1944).

3.1.2.2 Low conductivity layers

Horizontally oriented layers or tongues of low-conductivity material such as ash, clay, massive lava flows, or paleosoils can act as perching members, effectively allowing lenses of groundwater to accumulate on top of them (Fig. 21B). If such layers are of significant size (e.g., an extensive weathered contact surface or massive valley filling lava flow) and located near sea level, the low-conductivity layer can potentially confine groundwater below while accumulating semi-perched groundwater above. Stearns and Macdonald (1942, 1946) describe numerous examples of perched groundwater impounded by lavas, soils, and ash beds on the islands of Maui and Hawaii. The complex geological history of Tutuila's Pleistocene rocks suggests that buried perching formations in the form of more-permeable zones overlying less permeable sections are probably not uncommon. Geophysical evidence from Tutuila suggests that the Leone Rift Zone may hold small amounts of perched water. However, the majority of the perched aquifers in Tutuila's older-volcanic rocks are probably too small to hold developable quantities of water, except for the pyroclastic unit at Aoloau Mountain, which is a regionally extensive cap of high-permeability material overlying older-volcanic rocks.

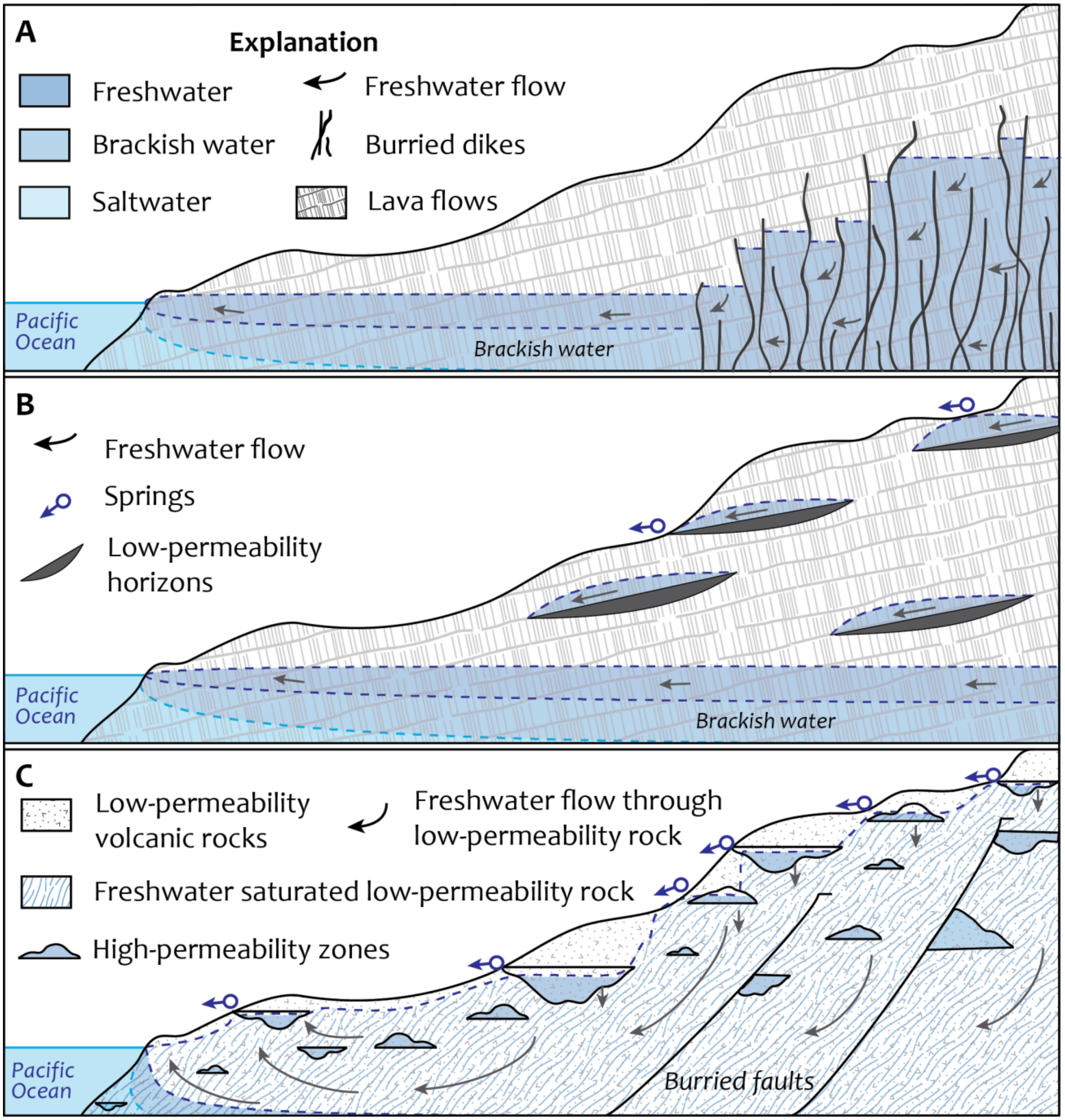


Figure 21. Idealized conceptual models of high-groundwater controlled by different types of water-impounding geologic structures. (A) Dike-impounded groundwater based on the Hawaiian conceptual model as described in Gingerich and Oki (2000), (B) Small perched aquifers within lava flows as described in Miller et al. (1997), (C) Complex geologic system including buried cinder cones, faults or paleovalleys as described in Lachassagne et al. (2014).

3.1.2.3 Complex formations

The aforementioned geologic features and structures likely occur together in Tutuila's Pleistocene subsurface and they are likely to act in concert to create barriers to groundwater movement. The structure of most volcanic islands is inherently more complicated than can be represented by simplified conceptual models. High-level water probably is often impounded by, and conveyed through, multiple combinations of structures and zones of differential permeability. Figure 21C shows a conceptual schematic of a "complex volcanic island model." A similar model has been proposed for a basaltic island in the Comoros Islands (Lachassagne et al., 2014). For the purposes of high-level groundwater exploration, it may be useful to conceptualize high-level groundwater on Tutuila as a complex system constructed of a diverse arrangement of high and low-permeability zones that, together, create a heterogeneous permeability fabric. Most of the permeable compartments are probably small and dispersed with uncertain connectivity. However, some may be large or connected enough to contain developable quantities of water.

3.2 Groundwater Occurrence in Holocene Leone Volcanics

The young aquifers of the Tafuna-Leone Plain region are primarily composed of pahoehoe and aʻa 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 on average, generally very hydraulically conductive and hold a thin basal lens. A prevalence of fractures, clinker zones, and lava tubes gives the region a high secondary porosity, making it favorable for groundwater development (Bentley, 1975). However, these features also make the Tafuna-Leone plain susceptible to groundwater contamination. Currently, 24 wells in the plain region together 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, 1999b). The unsaturated zone above the water table is often not more than 35 m deep, allowing only minimal travel time for contaminant attenuation. Within the plain there are three sub-regions which, can be distinguished into different hydrogoelogic 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 the two deep exploratory boreholes.

3.2.1 Tafuna Plain

The structure of the Tafuna side o f the plain has been described by Eyre and Walker (1991) as a lava delta, where lavas primarily travel downgradient via long tongues and subsurface tubes. In such terrains, subsurface transport of lava causes the exterior of the flow to dome and buckle, and these forces create structures such as tumuli, lava rises, and lava tubes, some collapsed some not, that create heterogeneity and preferential pathways for the movement of water. Subsequent lava flows, potentially with different final hydrogeologic properties, may then flow over, around or through these irregularities, producing a heterogeneous distribution of less-permeable and more- permeable zones. It should be noted that the aquifer does behave as an unconfined aquifer, and thus it is likely that the more-permeable sections are still somewhat interconnected by fractures through the denser sections. The structural complexity of the Tafuna Lava Delta is enhanced by the fact that the Leone series rests on the uneven topography of ancient buried ridges, valleys, pinnacles, and sedimentary basins of the Taputapu's ancient erosional surface.

3.2.2 Leone Plain

The Leone side of the plain is similar to the Tafuna side, though it contains more ash and pyroclastic material that was blown westward during eruptions by the southeasterly prevailing winds (Izuka et al., 2007). Extensive ash layers are observed in exposures on the Leone coast and in borehole logs. These layers likely serve to reduce the vertical permeability of the unit, potentially causing portions of the basal-lens to be locally confined or partially confined, though no definitive measurements have yet been made to support this hypothesis. Nonetheless, aquifer test data does suggest that overall hydraulic conductivities are generally lower on the Leone side than on the Tafuna side.

3.2.3 Leone Series Pyroclastics

The north-south trending ridge of ash and cinder cones that runs down the center of the Tafuna-Leone Plain is inferred to be the rift zone from which the rejuvenated phase Leone Series eruptions emanated. This rift appears to be underlain by a relic ridge of Taputapu rocks mantled by Holocene age pyroclastic deposits and interbedded lava flows. The subsurface structure of the area has not been well explored, and there is only one well (Well 178) that is currently developed within this hydrogeologic unit. This heterogeneous unit contains materials that range from highly-permeable unconsolidated cinder to nearly impermeable indurated tuff, thereby giving it a wide range of hydraulic properties (Izuka et al., 2007). Based on information in Izuka et al. (2007) and a recovery test of Well 178, the overall permeability of the unit is probably near to or less than the Leone side of the plain. Since ash cones are primarily distributed in the southern portion of the ridge, and cinder cones are primarily found in the more northerly section, it may be reasonable to assume that the northern section has better water bearing properties. Also in the central section of this ridge there is a shallow valley, which may be a remnant of paleo-ridgelines from the

Taputapu Shield. This valley displays a subdued topography, suggesting it is filled with either alluvium, recent lavas, or pyroclastic material. Although there are no borehole logs in this region, recently conducted MT geophysics might indicate either perched water or a fully saturated system in this area.

3.3 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 (see map in Section 6.3). 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. Although this aquifer could be considered a high-level groundwater resource, its extensiveness makes it unique on Tutuila. Three wells, two out of production (Wells 127 and 129) and one that is still producing (Well 128) have been drilled into the cinder unit. Well 128 currently produces about 35 to 40 gpm (190 m^3/d). 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 have been well documented and probably served as a source of village water prior to groundwater development. Geophysical cross-sections (Fig. 12) 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.

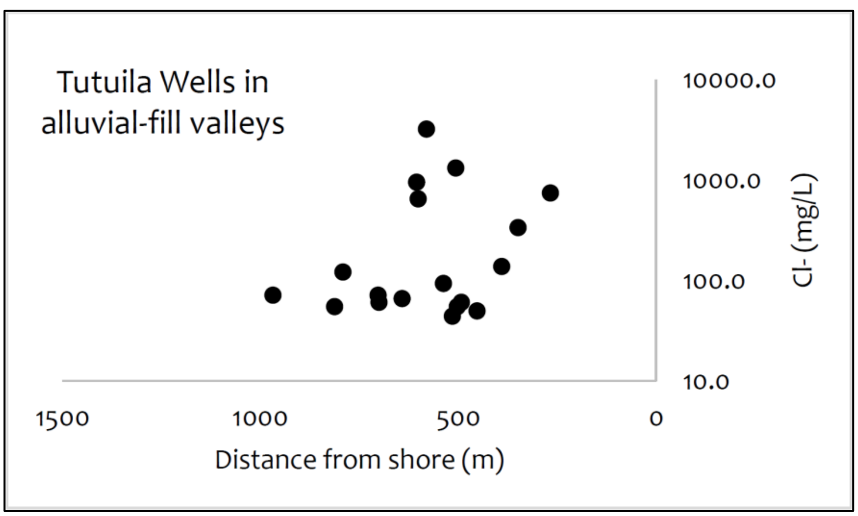
The thickness of the cinder is likely to be variable and depends on the underlying topography of the Taputapu Shield and the distance to source vents. A driller's log from Aasu Well 127, in the eastern portion of the unit, indicates the thickness of cinder deposits to be greater than 50 m (Eyre and Walker, 1991). The unit probably thins towards the west with increasing distance from visible vents. 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. Exploration of any part of this unit will help to constrain the quality and the quantity of the available resource.

3.4 Valley-Fill Aquifers

Numerous small alluvial-fill valleys ring the island and are often partially filled with eroded volcanic alluvium, mass-wasting debris, and marine sediments from ancient and contemporary reefs and shorelines. These valleys usually contain one or more perennial or intermittent streams. The streams help to recharge small basal-lens aquifers contained within the alluvium or underlying Pleistocene rocks. Around the island there are about 40 inhabited alluvial valley-fill plains that range in area from over 0.5 km^2 to under 0.005 km^2.

A dozen of the more populated valleys contain one to four municipal wells, drilled to provide water to the village. The aquifers that these satellite systems tap are generally less hydraulically conductive than the Tafuna-Leone Plain aquifers, and their water quality varies greatly between systems. Many of the wells drilled in these areas probably pass through the valley-fill and, depending on the open interval of the well, may also obtain water from the underlying Pleistocene volcanic rocks. Existing driller's logs may make it possible to interpret the thickness of the valley fill and hypothesize which geologic unit(s) the wells are developing. However, in many of the existing logs the location of the paleovalley bottom is ambiguous and the logs for many existing wells are missing. The available logs and aquifer tests do show that the materials and hydrologic properties are generally different between valleys.

A number of the valley-fill water systems tap aquifers with levels of chloride (Cl^-) that exceed U.S. Environmental Protection Agency (EPA) recommended limit of 250 mg/L Cl^-. The salinity of a well in these 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 to the coast (Fig. 22). Additionally, the pattern of urban development in these villages often places residences, piggeries, and agriculture directly above the alluvial aquifers. These potential sources of contamination may be able to affect the unprotected groundwater below. Nonetheless, the alluvial fill/Pleistocene Volcanic aquifers provide an important source of water to isolated areas and despite low predicted yields from most of the formations, the demand in many of these small villages is currently fairly low.



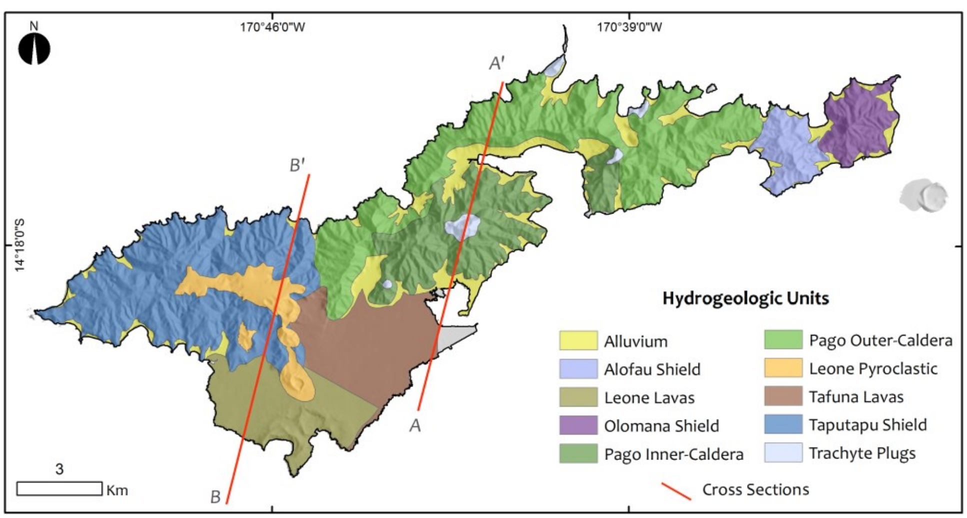
Note: Distance from shore is not necessarily the primary factor that controls groundwater Cl^- concentrations. Cl^- measurements are from unpublished UH-WRRC data.

Figure 22. Graph showing correlation between Cl^- concentration (mg/L) and distance of well from shore (for all wells located in Tutuila's alluvial-fill valleys).

4.0 HYDROGEOLOGIC SUMMARY AND EXPLORATORY RECOMMENDATIONS

4.1 Hydrogeologic Summary and Updated Conceptual Model

With currently available information, the island's geologic construction can be simplified into an updated hydrogeological conceptual model having just under a dozen primary hydrogeological units, with the approximate boundaries shown in Figure 23. Uncertainty remains regarding the subsurface hydrology of these units, although available evidence suggests that within each unit, groundwater may occur as one or more of the following types (1) basal and/or semi-perched groundwater, (2) compartmentalized high-level water contained in a complex arrangement of higher and lower-permeability (perched or dike-impounded) zones, and (3) an extensive perched water body, which is only seen in Holocene pyroclastics at Aoloau Mountain. The conceptual schematic cross-sections presented in Figures 24, and 25 show estimated differences in the distribution of higher-permeability compartments between hydrogeologic units, and also show inferred zones of freshwater or saltwater saturation, including basal water zones, potentially semi-perched areas and dike-impounded reservoirs. Small pockets of perched water are shown as partially saturated high-permeability compartments above the regional water table. Water levels and flow lines are inferred and drawn simplistically for schematic purposes, though they are certain to be more complex in reality. The Holocene age Leone Series rocks are illustrated with homogeneous aquifer properties based on the assumption of generally high-hydraulic connectivity throughout the region. It should also be noted that the saltwater-freshwater interface is shown only for schematic purposes since the assumption of large vertical head gradients (vertical flow) precludes determination of its actual position from freshwater head measurements.



Note: Unit boundaries are based on Stearns 1944 mapping and new geomorphological evidence.

Figure 23. Hydrogeological units within the conceptual model of Tutuila and locations of cross sections A – A' and B – B' (see Figs. 24 and 25).

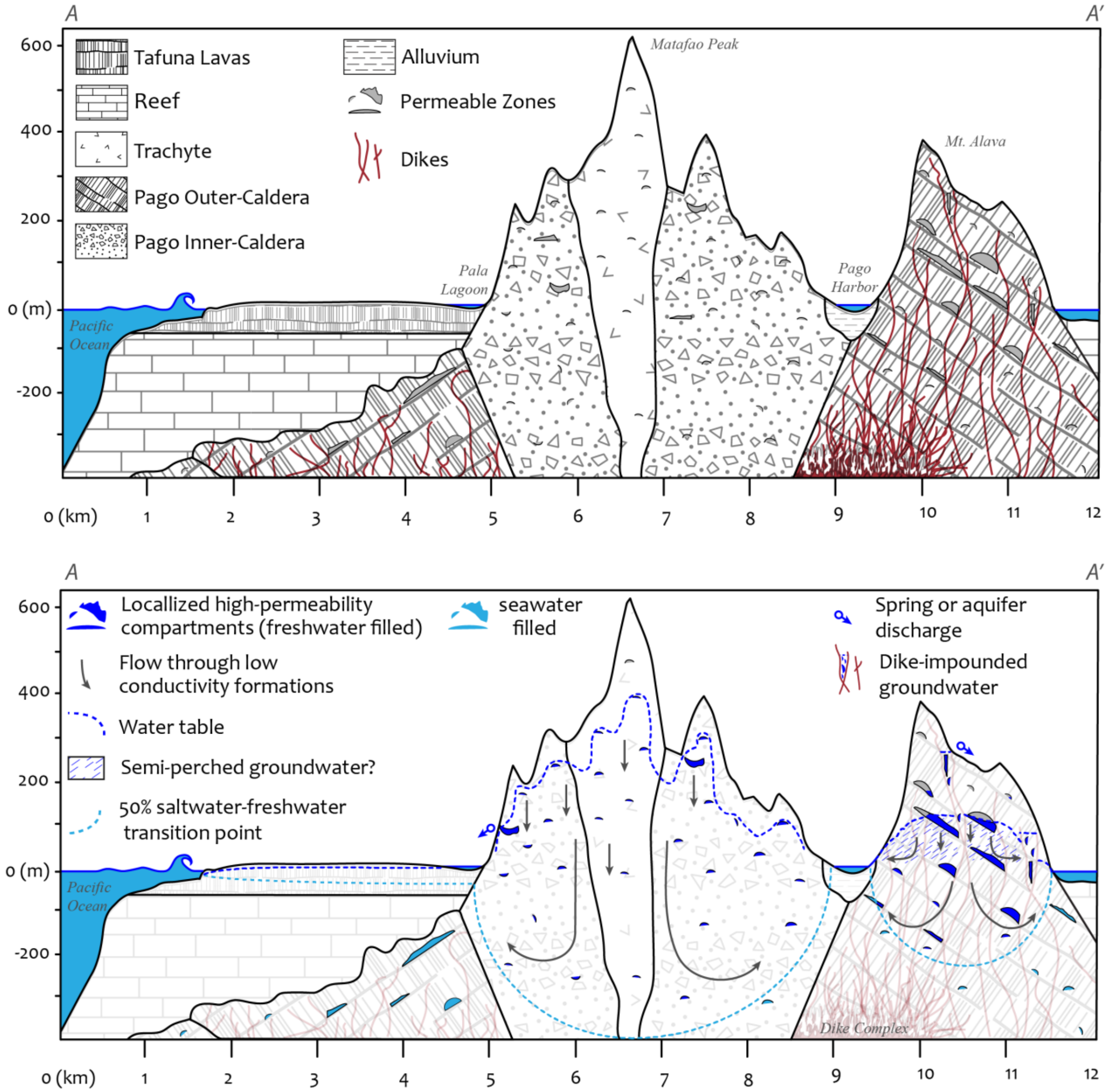


Figure 24. Geologic and resulting hydrogeologic conceptual models of cross section A – A'. (top): Geologic cross section through the Pago Caldera, Matafou Peak, and Tafuna Plain. Subsurface geology is based on the equivalent cross section from Stearns (1944), and locations and elevations of subsurface contacts are inferred. Locations of high-permeability pockets are inferred, and are representative of a conceptual heterogeneous permeability fabric of unknown extent and construction. (bottom): Conceptual hydrogeological model. Spring locations, water table elevations and transition zone midpoints are inferred, and the zone of semi-perched water is hypothesized. Note: Dike impounded water levels rise above the basal/semi-perched water table and have a 5× vertical exaggeration.

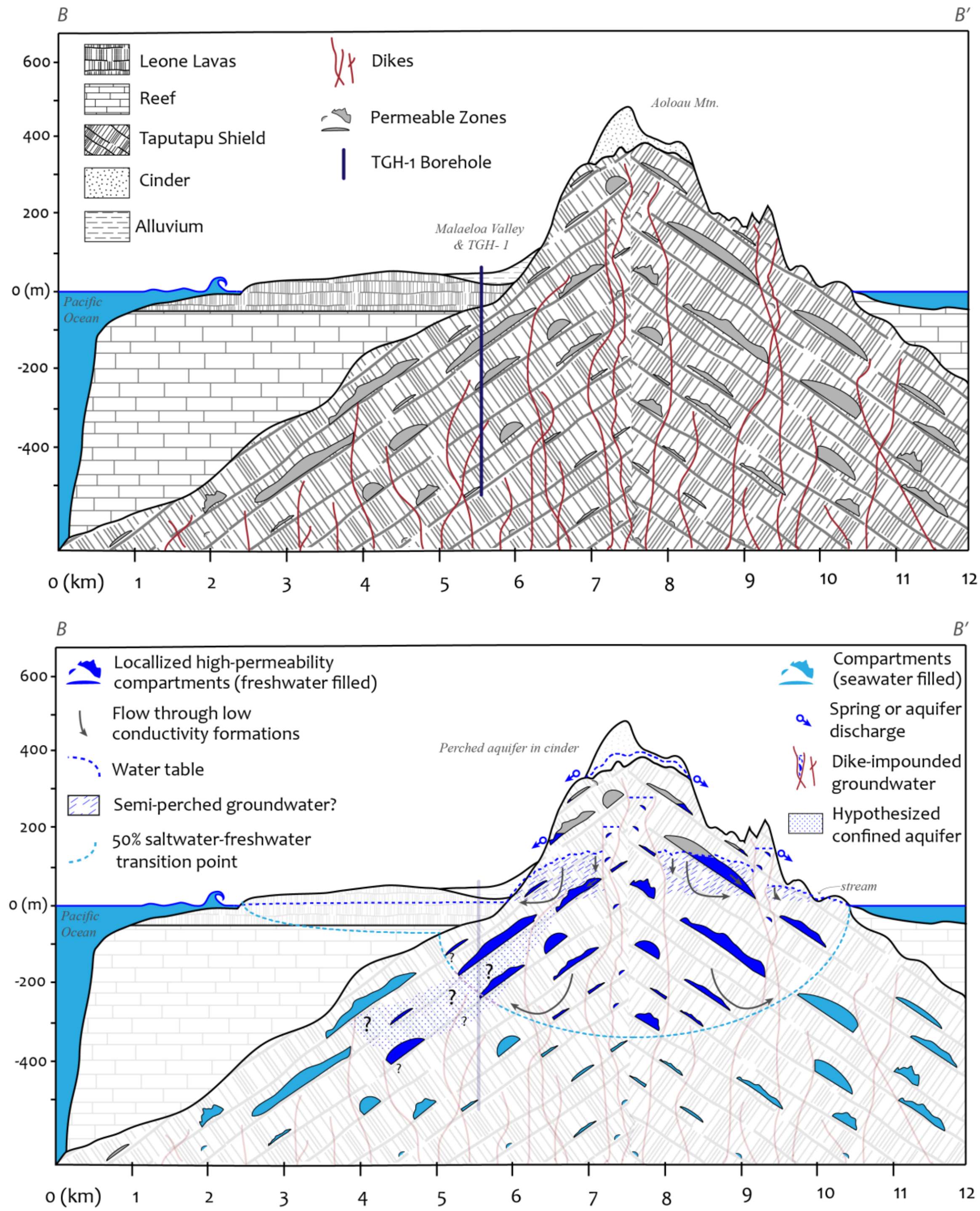


Figure 25. Geologic and resulting hydrogeologic conceptual models of cross section B – B'.
(top): Geologic cross section through Taputapu shield, Aoloau Mountain, and Leone Plain. Locations and elevations of subsurface contacts are based on data from deep borehole TGH-1 and inferred elsewhere. Locations of high-permeability pockets are inferred, and are representative of a conceptual heterogeneous permeability fabric of unknown extent and construction.
(bottom): Conceptual hydrogeological model. Spring locations, water table elevations and transition zone midpoints are inferred, and the zone of semi-perched water is hypothesized. Note: Dike impounded water levels rise above the basal/semi-perched water table and have a 5× vertical exaggeration. Existence of confined aquifer in Taputapu rocks below Tafuna-Leone Plain is hypothesized based on limited evidence.

4.2 Groundwater Exploration Recommendations

Based on the conceptual model of groundwater occurrence presented in this report and on experience with existing well performance on Tutuila, the authors recommend three strategies for developing new groundwater supplies: (1) targeting thicker or more elevated portions of basal/semi-perched water reservoirs contained in the Taputapu Shield or low-dike intensity regions of the Pago Shield with angled drilling; (2) targeting larger pockets of high-level groundwater, in locations indicated by large downgradient springs or streams having high baseflow indices with inclined or traditional wells; and (3) exploring the perched or high-level groundwater reservoir at Aoloau, both within the cinder unit and below it as well.

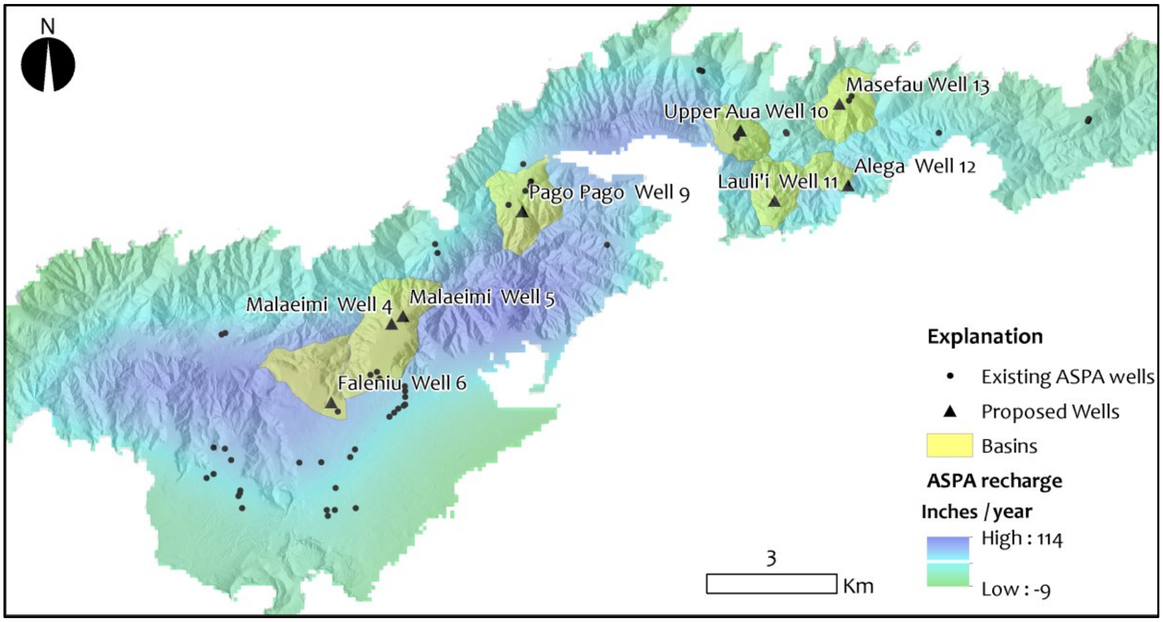
Past experience shows that wells that tap the basal-aquifer in the Pleistocene Volcanics should be expected to yield only low quantities of water (<30–50 gpm), though localized areas, particularly in the Taputapu Shield, may exceed these expectations. Pumping at higher rates creates the risk of large 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. Also it is paramount 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 monitoring long term static water levels and Cl- concentrations will help to assure sustainable withdrawals. If chronic static water level declines or if 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 drilling multiple wells to find high-yielding zones.

Since Tutuila is an island, the amount of sustainably developable groundwater is limited by the rate of groundwater recharge. Groundwater withdrawals must always remain as a fraction of the recharge, the magnitude of this fraction being dependent on local hydrogeologic conditions and the efficiency of well design. Also it is important to consider the ecological utility of natural groundwater discharge. 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. Additionally, a significant portion of freshwater recharge needs to escape development in order to provide a hydraulic buffer to keep seawater from encroaching on pumping wells.

Assessment of the degree of connectivity between more-permeable compartments/pockets in a localized area as described above in Section 3.1 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. Recommended strategies for data collection that may contribute to a better understanding of the degree of connectivity in the area of a borehole are elaborated upon in Section 7.0.

5.0 REVIEW AND PRIORITIZATION OF EXISTING ASPA DRILLING SITES: IN CONTEXT OF EXPLORATORY VALUE

Locations for the planned drilling of new ASPA production wells (Fig. 26) were assessed using the available data from existing or historical production well characteristics. Two of these wells (Wells 11 and 12) are in basins without existing wells, and the wells in Malaeimi Valley are to be drilled in locations that are relatively far (1.3 km) from areas where aquifer data has been gathered. The other planned locations are within about 300 m from existing data points. Aquifer characteristics of nearby wells and an assessment of the amount of recharge within the general area are given in Table 8. Data for existing wells is sourced from ASPA files, UH-WRRC aquifer tests and from other studies (Bentley, 1975; Eyre and Walker, 1991). A relative recharge/pumpage assessment for each basin was estimated from the recharge map documented in Walters (2013), and is given as the ratio of the calculated recharge within the basin over the amount of water currently extracted by existing wells in the basin. The predicted development potential of each of the eight sites are also ranked on three assessment criteria: (1) likelihood to yield sufficient quantities of water as assessed by specific capacity and local water levels in existing wells, as well as hydrogeologic properties of the region; (2) current stress on the local aquifer as assessed by Cl^- levels, and chronic drawdowns in nearby wells; and (3) exploratory value regarding the number of nearby wells with existing aquifer information. Additional discussion is provided in Section 7.1 regarding Wells 11 and 12.



Note: Recharge estimates are from ASPA (2013).

Figure 26. Location of proposed ASPA production well drilling sites, existing production wells, and recharge basins that new wells will utilize.

Table 8. Summary of well data for previously existing ASPA drilling sites.

Well Name	Nearby Wells	Average Distance to Nearby Wells (m)	Average Cl^- of Nearby Wells (mg/L)	Average Static Water Level in Nearby Wells (m)	Average Drawdown in Nearby Wells (m)	Average Specific Capacity in Nearby Wells (gpm/m)	Estimated Recharge Currently Used (%)	Exploratory Value	Hydrogeologic Unit	Rank
Faleniu Well 6	85	268	55	1.3	0.2	1,244	9	Medium	Tafuna lavas	1
Alega Well 12	none	–	–	–	–	–	0	High	Pago Shield	2
Laulii Well 11	None (2 historical)	192	25	6.4	8.5	8	0	High	Pago Shield	3
Malaeimi Well 5	89, 67 (1, 2, 3 offline)	1,489	50	2.9	6.0	39	12	Low	Taputapu or alluvial fill	4
Malaeimi Well 4	89, 67 (1, 2, 3 offline)	1,232	50	2.9	6.0	39	12	Low	Taputapu or alluvial fill	5
Masefau Well 13	242, 241	277	58	4.8	3.3	10	6	Medium	Pago Shield	6
Pago Pago Well 9	183, 165, 107, 105, 163	648	255	5.7	20.2	12	48	Low	Pago Shield	7
Upper Aua Well 10	99, 97	142	916	-0.8	15.3	10	40	Low	Pago Shield	8

6.0 DESCRIPTION OF NEW RECOMMENDED GROUNDWATER EXPLORATION SITES

6.1 Groundwater Occurrence: Basal/Semi-Perched in Pleistocene Shields

Basal/semi-perched groundwater refers to water within or connected to the lens shaped freshwater body that floats on saltwater within saturated rock. The height of the freshwater table is primarily controlled by the hydraulic conductivity (K) of the geologic formation and the area's recharge rate. If other parameters are constant, higher values of K will result in a lower water table, and thus a thinner lens, and higher recharge rates will contribute to a thicker lens, and vice versa. This lens likely makes up the majority of the developable groundwater on the island. Some existing wells in the Pleistocene rocks register elevated water levels, some of which, when pumped, are subject to high drawdown. These high drawdowns could either be caused by overall low-hydraulic conductivities (if a purely basal system was tapped) or by limitations in the aquifer extent (perhaps if the water was semi-perched in occurrence).

In the Pago, Taputapu, and Alofau Shields, a well drilling strategy focused on targeting areas that are likely to encounter continuous water bodies near sea level is probably the most conservative approach. As wells are deepened below sea level, the risk of dewatering a semi-perched system of limited extent is exchanged for the risk of drilling into or through a thin 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, and by utilizing angled drilling methods to further gain access to more inland parts of the lens. Based on available data, it would also be conservative to expect wells in the Pleistocene shields to yield an order of magnitude less water than wells in the Tafuna-Leone aquifers.

Recommended areas for exploration of new water resources in basal/parabasal aquifers are shown in Figure 27. Areas are listed in order of priority, which is based on hydrologic data, existing well data, and accessible distance from the coast, parameters which are summarized in Table 9. Although specific drilling sites are not defined, in all areas, site preference should be given to locations as far inland as possible.

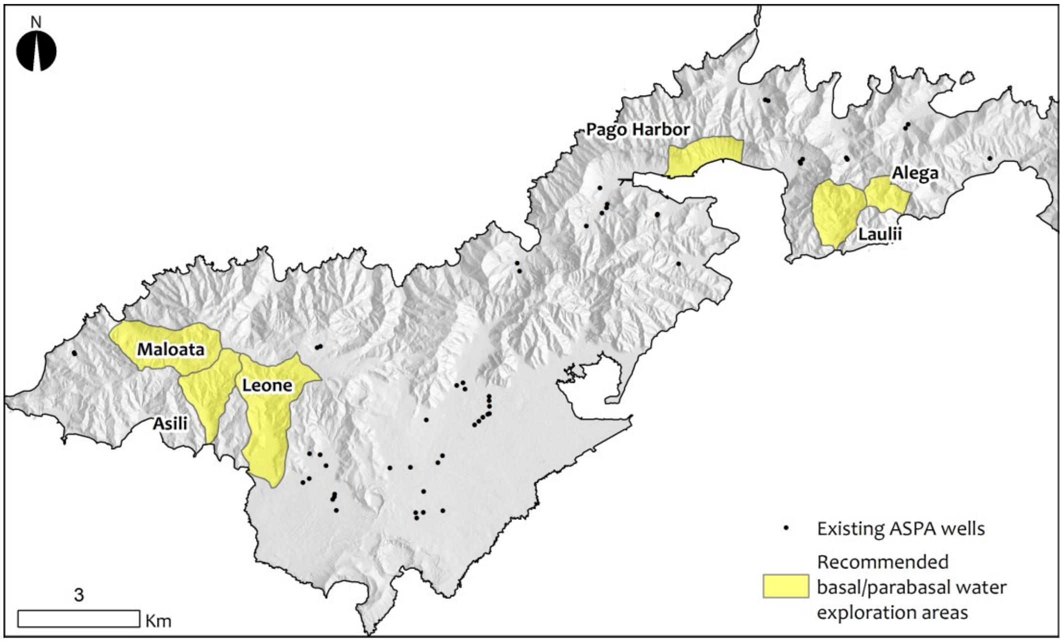


Figure 27. Location of recommended basal/parabasal exploration areas.

6.1.1 Leone Valley

Probably one of the better basins on Tutuila to explore for basal/semi-perched water. The large drainage area may also collect and direct additional recharge from losing streams discharging from perched aquifer above (Eyre and Walker, 1991). Located in the Taputapu Shield, which is inferred to have higher ***K*** values and water holding capacity than the Pago Shield.

- *Contamination potential*: Low, relatively pristine land use past last house.
- *Ecological/cultural significance*: Withdrawals could affect wetland salinities, and Submarine Groundwater Discharge (SGD) to Leone Bay may be affected by large withdrawals.

6.1.2 Asili Valley

Relatively large watershed, funneling to a narrow lower valley. Receives additional infiltration along stream reach supporting additional groundwater recharge, as shown by data in Wong (1996). Also located in the Taputapu Shield unit.

- *Contamination potential*: Low, relatively pristine land use past last house.
- *Ecological/cultural significance*: SGD to the bay may be affected by large withdrawals and basal water withdrawals may or may not affect streamflow.

6.1.3 Maloata Valley

Although Maloata watershed is located far from high demand areas, it likely has water development characteristics that are similar to those described for Leone and Asili watersheds. Nearby Fagalii Well 182 shows high values of $\boldsymbol{K}$ (192–312 m/d) and moderate specific capacity (62 gpm/m), indicating the local basal aquifer material is probably favorable for water development. Baseflow characteristics also encourage exploration in this area.

- *Contamination potential*: Low, pristine land use throughout much of valley.
- *Ecological/cultural significance*: Since the site was only gauged at one location, it is not clear if the stream is gaining or losing near potential exploration sites. Basal water withdrawals might affect streamflow, and SGD to Maloata Bay may be reduced by large withdrawals as well.

6.1.4 Laulii Valley

Basal/parabasal water has been developed in this watershed before. Low yields or rising salinities may have caused wells to be abandoned. However, with advances in angled drilling salinization problems could be reduced. The contact between the Inner- and Outer-Caldera Units of the Pago Shield runs through the valley, though the two units were not previously observed to have significantly different aquifer parameters. Based on older well data, low to moderate water yields should be expected from this area. Drilling logs from two now abandoned production wells identify a thick and massive lava flow throughout much of the valley's subsurface. A water yielding zone with about 6 m of head was found beneath this lava flow, more than 30 m below sea level. Pumping tests indicated that pumping rates exceeding 40 gpm are likely to cause saltwater upconing at the locations of previously drilled wells (Eyre and Walker, 1991). However, this lower confined aquifer may be thicker and located at a higher elevation farther inland, thus reducing the chances of salinization. Also, because the thick lava flow impedes the deep infiltration of groundwater recharge, semi-perched water on top of the massive lava flow could also be explored as a source of water.

- *Contamination potential*: Low, pristine land use past last house, and massive lava flow may protect underlying aquifer.
- *Ecological/cultural significance*: Basal water withdrawals may or may not affect streamflow above village limits. Any SGD reduction would have limited ecological effects on open coastline.

6.1.5 Alega Valley

Shares similar hydrogeological characteristics as the Laulii watershed. Alega Valley quickly gains elevation upstream, and thus there is less accessibility for drilling inland away from the coast. This steep elevation gradient is likely caused by a massive valley filling lava flow, noted by Eyre and Walker (1991), similar to the one in Laulii Valley. Since access above this flow is difficult, the basal or potentially confined water below it may be a good resource to explore. It is recommended that during drilling in both Alega and Laulii, careful attention should be focused on any changes in lithology or water bearing characteristics in order to constrain the extent of the geological structures.

- *Contamination potential*: Low, development density is very low in this watershed.
- *Ecological/cultural significance*: Basal water withdrawals may or may not affect streamflow above village limits where village water systems are currently in use.

6.1.6 Pago Pago Harbor Slope

Although this small and steep area is limited in its water development potential, high rainfall and proximity to a large water demand make it a viable location to explore. For cost-benefit planning purposes, a cautious estimate of yield from this area should be considered. In nearby Aua, total extraction of 600 gpm from several wells has dewatered the aquifer and caused chloride concentrations to rise above potable limits. At least one exploratory well on the Pago Pago Harbor slope is needed to refine an estimate of sustainable yield. Successful acquisition of a sustainable resource will be dependent on the ability to drill angled wells far enough into the hill slope to reduce the threat of seawater intrusion. It is possible that water bearing formations may be contained in the thinner bedded lavas of the northward sloping flanks of the Pago Shield, or potentially as dike-impounded water, since this area is located within a zone of marginal dike-intensity (Walker and Eyre, 1995). Lower angles of drilling will increase the chances of discovering sustainable resources in this area.

- *Contamination potential*: Low to moderate, depending on achievable horizontal distance away from the extensively developed area near the coast.
- *Ecological/cultural significance*: Withdrawals would only affect SGD to the bay as there are no perennial streams in this area.

Table 9. Hydrologic data for recommended basal/semi-perched exploration areas.

Watershed	Leone	Asili	Maloata	Laulii	Alega	Pago Harbor
Area (km^2)	3.6	1.8	2.6	1.6	0.73	1.1
RECHARGE ESTIMATES (Mgal/d)						
ASPA (2013)	6.1	2.6	1.8	1.8	0.8	1.9
Izuka et al. (2007)	7.1	2.8	4.2	–	–	3.5
Eyre and Walker (1991)	3.5	0.7	0.9	0.5	0.5	1.6
Mean	5.6	2.0	2.3	1.2	0.7	2.3
HYDROLOGIC DATA						
Area-weighted mean recharge (Mgal/d/km^2)	1.5	1.1	0.9	0.7	0.9	2.1
Geologic formation	Taputapu Shield	Taputapu Shield	Taputapu Shield	Pago Shield	Pago Shield	Pago Shield
Estimated *K* (m/d)	270–410	270–410	270–410	1–9	1–9	1–9
Existing wells	none	none	none	Well 96[a]	none	Wells 99 and 163[a]
Baseflow inde ($ft^3/sec/mi^2$)	2.7	1.9–2.1	1.2	1.9	2.2–6.0	–
Median stream discharge (ft^3/sec)	2.6	2.9	3.3	0.7	1.0	–
Road accessible distance inland (km)	1.3	0.76	0.55	0.8	0.25	0.2
Recommended priority	1	2	3	4	5	6

EXISTING WELL DATA[a]

Well Name	Pump Rate (gpm)	Cl^- Concentration (mg/L)	Specific Capacity (gpm/m)	Calculated *K* (m/d)
Laulii Well 96	70	25	8.2	6
Aua Well 99	160	653	10.5	3–5
Pago Pago Well 163	180	958	7.6	8

[a]Additional measurements from existing nearby wells for recommended development locations.

6.2 Groundwater Occurrence: High-Level Groundwater

High-level water refers to groundwater that is contained in zones of permeable material, which are bordered by adjacent low-permeability structural geologic features, such as dikes, perching horizons, or faults. If properly oriented, these structures can serve to support or retain pockets of freshwater at elevations that are discontinuous from the basal water system. Since high-level groundwater is separated from underlying saltwater, it is not at risk of salinization. However, the extents and locations of these reservoirs are difficult to constrain and it is likely that many reservoirs are too small to contain significant quantities of water. Exceptionally sized pockets or dike compartments may contain a developable water supply, but the locations of these water bodies are difficult to predict. Despite these reservations, such areas are attractive for water development on Tutuila because they are not as easily subject to contamination as the basal and parabasal water bodies discussed earlier. However, it is important to note that high-level water supplies are susceptible to overexploitation if pumping rates exceed recharge rates. Even small withdrawals will likely disrupt rates of discharge to springs and streams.

Natural discharge of high-level groundwater (as either stream baseflow or SGD) should not be considered to be an excess or waste, as it serves important ecological functions, creating habitat for aquatic organisms and maintaining riparian areas during dry periods. High-level water may also serve an important cultural function, because reliable streams or springs on Tutuila were often captured and routed to village water systems. Many of these systems are still in use today, and people who rely on them may be affected if high-level water development reduces stream or spring flow. Additionally, if a well is drilled too deep and penetrates a perching or retaining structure, the water resource may be drained away and lost into the underlying rock. It is recommended that the potential of disruption to village water systems and aquatic habitats is fully assessed prior to development of these sources.

Following are recommended areas for exploration of new water resources in high-level aquifers (Fig. 28). Locations are listed in order of priority based on hydrological parameters and quality of existing data, which are summarized in Table 10. It is also recommended that field investigations of these areas be conducted prior to development to constrain exact spring locations, flow rates, and elevations.

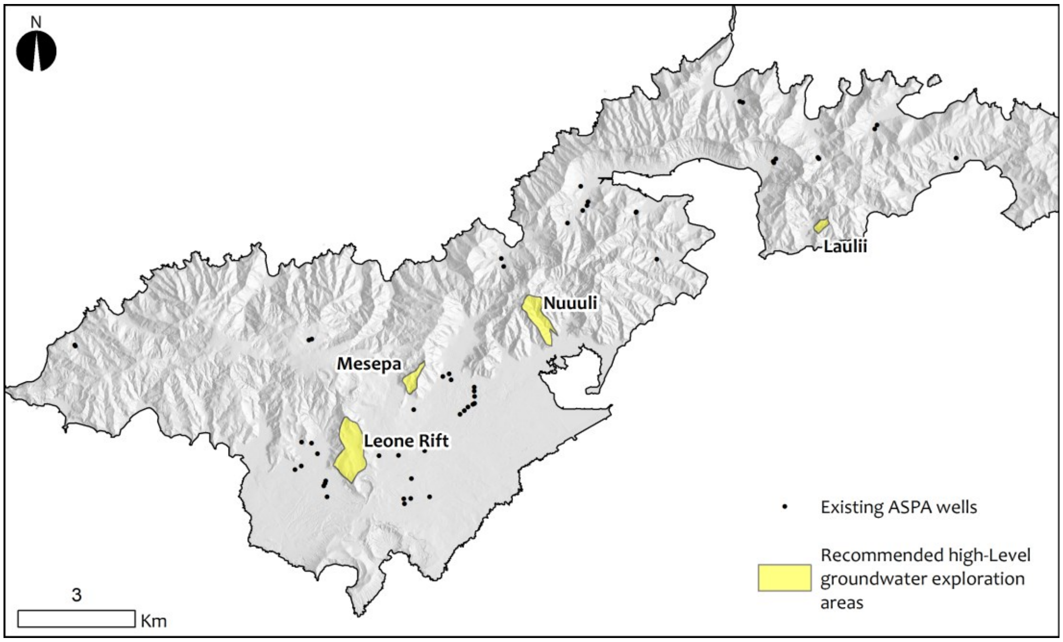


Figure 28. Location of recommended high-level groundwater exploration areas.

Table 10. Hydrologic data for recommended high-level groundwater exploration areas.

Hydrologic Parameters	WATERSHED			
	Laulii	Nuuului	Mesepa	Leone Rift
Area (km^2)	0.08	0.49	0.19	0.87
Normalized recharge ($Mgal/d/km^2$)[a]	1.0	1.9	1.8	1.4
Geologic formation	Pago Shield	Pago Shield	Pago Shield	Leone pyroclastics
Estimated K (m/d)	1–9	1–9	1–9	86–837
Baseflow index ($ft^3/sec/mi^2$)	5.6	3.36	2.29	1[b]
Median stream discharge (ft^3/sec)	0.32	0.6	0.23	0.03[b]
Recommended priority	1	2	3	4

[a] Normalized recharge based on ASPA (2013) data.
[b]Streamflow characteristics for Sigaloa drainage area (western side of unit), is not necessarily representative of all drainage areas from unit.

6.2.1 Laulii Valley Area, Lesea Stream Basin

A high BFI and median discharge (Table 10) indicate that this small drainage is fed by a substantial high-level groundwater resource. Davis (1963) also noted the existence of a high-level spring in this area. Access to upper elevations in this area may be difficult. Low-angle or horizontal drilling may increase chances of intercepting high-level water pockets.

- *Contamination potential*: Low.
- *Ecological/cultural significance*: Withdrawal of high-level water will likely reduce stream flow in the lower portion of the valley. Also the spring mapped by Davis has served as a village water supply in the past. Prior to development, the current use of this village water resource should be investigated.

6.2.2 Central Nuuuli Watershed, Mataalii Stream Basin

A moderately high BFI and a significant baseflow rate characterize the stream in this steep valley. Although access to upper elevations in this area may be difficult, utilizing low-angle drilling techniques could increase chances of intercepting high-level water pockets. Since the area above the streamflow measurement site (Wong, 1996) was fairly large, field investigations are necessary to constrain discharge locations, flow rates, and elevations.

- *Contamination potential*: Low to moderate. Limited agricultural use within the watershed creates some potential for nutrient or agricultural chemical contamination.
- *Ecological/cultural significance*: Withdrawals may affect streamflow which in turn will affect aquatic habitat along this short stream.

6.2.3 Mesepa and Mapusagafou Area, Taumata Stream Basin

This small basin is accessible from above via an unimproved plantation road that traverses a ridge from Mapusagafou Village. Although this basin is small, it has a noteworthy amount of baseflow and a reasonably high BFI. Perennial springs have been observed to issue from the southern and eastern exposures of the basin's southeastern ridge.

- *Contamination potential*: Low to moderate, plantations on nearby ridgetops create some potential for nutrient or agricultural chemical contamination.
- *Ecological/cultural significance*: Since this stream quickly infiltrates into the Tafuna-Leone Plain it does not support a significant amount of aquatic habitat. Mountain-front recharge from this area does feed Pavaiai Village well fields, however, reductions in streamflow will probably not significantly affect relatively larger basal groundwater sources.

6.2.4 Leone Rift Zone, Vaitai Watershed Area, Sigaloa Stream Area

The central portion of the Leone rift zone forms a shallow basin that may serve to concentrate local groundwater recharge. Geophysical cross-sections (Fig. 12) indicate that a small perched water resource could exist in this area. Also, small springs issuing from the eastern and western sides of the rift support this hypothesis. The size of this reservoir is unknown, but is likely to be limited considering the moderately low BFI and discharge issuing from Sigaloa Stream on the western flank. The area does support a number of other small ungagged streams radiating out on both sides, and their characteristics are unknown. Access to this area is quite good with road access partway up both the eastern and western flanks and also up through the center of the rift.

- *Contamination potential*: Moderate. Plantations and residential areas in the central valley create the potential for pathogen, nutrient, or agricultural chemical contamination.
- *Ecological/cultural significance*: Since the streams issuing from this area quickly infiltrate into the Tafuna-Leone Plain they do not support a large amount of aquatic habitat. However, streamflow from at least one of these streams has been observed to be used to irrigate taro crops. Effects on agricultural or domestic use of surface water from this area should be investigated prior to development.

6.3 Groundwater Occurrence: Aoloau Perched Aquifer

Perched water refers to high-level groundwater that is retained and supported above an unsaturated zone by low-permeability structural features. The most extensive known perched aquifer on Tutuila is located on top of the Aoloau Mountain (Fig. 29, Table 11). This area is 4.1 km^2 in area and consists of cinder cones, some lavas, and ash beds. Also welded tuffs in the unit probably acts as aquitards (Eyre and Walker, 1993). The unit sits on the summit of the Taputapu Shield, and can be delineated by the subdued topography created by the blanket of pyroclastic material. The thickness of these pyroclastics at Well 127 in Aasu has been reported to be over 50 m thick (Eyre and Walker, 1993). It is also possible that the aquifer is supported by high-level dike-impounded groundwater contained below in the Taputapu Shield. Exploration of the zone beneath the cinder unit would be useful for assessing this hypothesis.

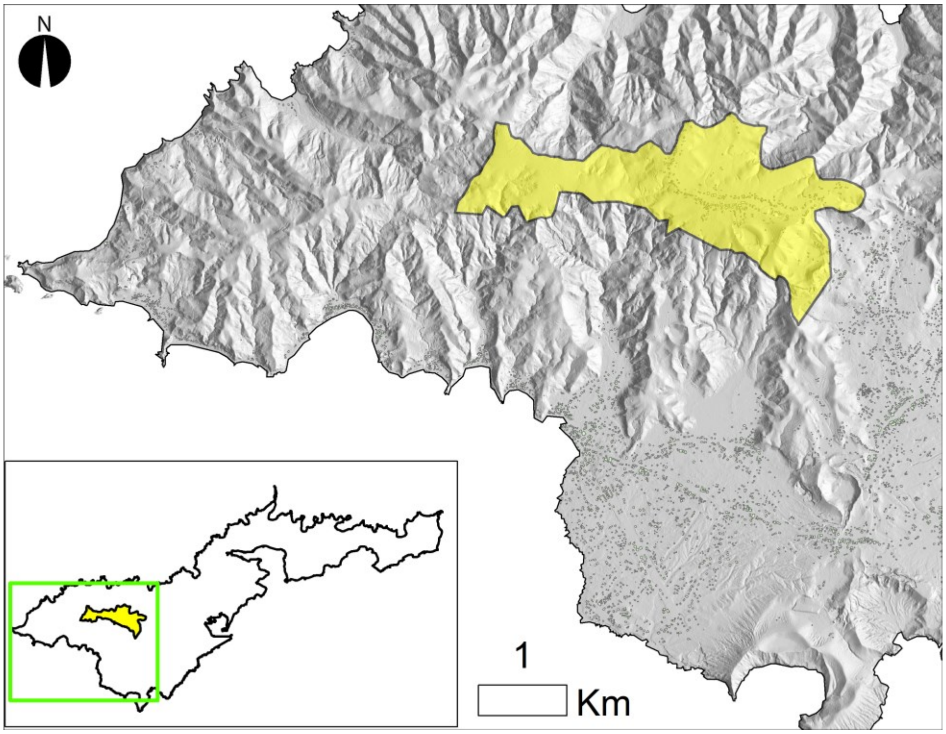


Figure 29. Location of Aoloau perched aquifer. This area is delineated by a subdued topography, and is inferred to be a cinder cap.

Table 11. Hydrologic data for Aoloau perched aquifer.

Area (km^2)	Total Recharge (Mgal/d)	Normalized Recharge (Mgal/d/km^2)	Elevation of Spring Discharge (m above MSL)	Geologic Formation	Estimated *K* (m/d)
4.1	6.5	1.6	335	Holocene pyroclastics	unknown

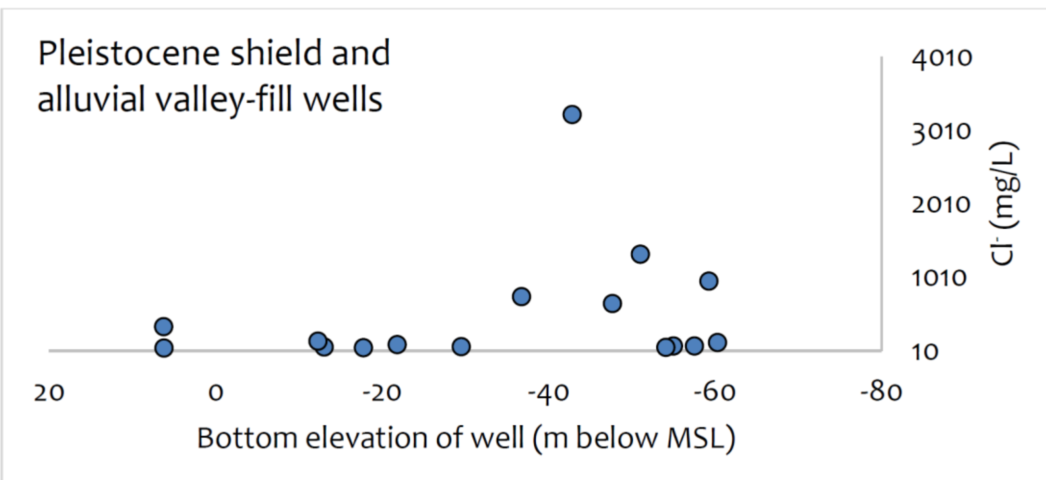
Note: Data for total and normalized recharge based on ASPA (2013).

- *Contamination potential*: 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 EPA limits.
- *Ecological/cultural significance*: Withdrawals of groundwater in this region will probably reduce natural spring discharge. Many of the springs that discharge from the sides of the unit feed perennial streams that in turn create aquatic habitats. It is unknown if springs serve village water systems. Additionally, springs and subsurface flows feed basal aquifers, primarily in the Malaeloa and Pavaii well fields, and if withdrawals are significant enough, they may affect basal water supplies.

7.0 RECOMMENDED DRILLING PROCEDURES

7.1 Drilling Depth

For exploration of groundwater occurrence in the Pleistocene Shields, initial exploratory well target depths depend on the groundwater source being targeted. To assess the development potential of higher elevation aquifers, an initial well target depth may be above sea level, depending on where water is encountered at the well site. Water level observations or aquifer tests may help to determine if groundwater occurrence in the elevated aquifer is basal or perched/semi-perched in nature. Once the characteristics of higher level zones are sufficiently understood, the decision to drill deeper might be made. If an assessment of basal water characteristics is desired, the well can be extended to sea level or to a depth not more than -20 m below sea level. Although well depth is not the only factor controlling groundwater Cl^- concentrations, an assessment of existing production wells in the Pleistocene rocks shows that, only wells deeper than approximately -20 m are currently producing water with elevated Cl^- levels (Fig. 30). 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 recommended, exploratory drilling below this depth would certainly be useful to assess the location of the saltwater-freshwater interface.



Note: 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 UH-WRRC data.

Figure 30. 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.

7.2 Data Collection Procedures

Capturing lithological, hydrological, and geochemical data for informing conceptual and numerical models of the subsurface is a high-priority for exploratory 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 which 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 likely indicates vertical downwards flow. Whereas a complete loss of water could indicate that a perching member has been punctured.
2. Accurate surveying of ground surface elevation, and through 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, core is best if available. If not, 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. The document provided in this report's data supplement titled, "CWRM Well Completion Report Part 1.pdf" provides a brief example of information to be recorded in driller's logs.
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 must be performed, at least upon well completion, but for exploratory drilling, could be performed repeatedly within different formations of interest. A step-drawdown test is the most important, followed by a constant-rate pump test, and then a recovery test. See Section 7.3 (Aquifer Test Recommendations) 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. To assess aquifer characteristics at different depths or in different formations, exploratory wells may be aquifer tested at multiple depths/open intervals. This could be accomplished by suspending drilling at predetermined depths, and performing aquifer tests using a portable pump. Reasonable depths could be (1) a depth between the first water table and sea level, (2) at sea level, and (3) at the final depth if planning to drill below sea level.
8. If there are other observation wells in the area, monitoring the effects of pumping in one well on the water level in another may indicate the degree of connection and hydraulic conductivity in the area between wells, and also can provide values for aquifer storage (a useful modeling parameter). Effects of groundwater withdrawals on the discharge of nearby streams could also be assessed.

7.3 Aquifer Test Recommendations

Upon completion of an exploratory well, or during exploration, the following tests are recommended to be performed in the following order.

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 logging intervals to capture the drawdown curve shape during transitions between steps. At least three, but more 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. More information regarding this test was extracted from the "Hawaii Well Construction & Pump Installation Standards" and is provided as a pdf in this report's data supplement.

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. Note that often the first log cycle (first 10 min) is unusable because the drawdown curve has not achieved a straight line in a semi-log plot. Also it is important to find a way to dispose of 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 for this test should be determined based on the results of the step-drawdown test. More information regarding this test was extracted from the "Hawaii Well Construction & Pump Installation Standards" and is provided as a pdf in this report's data supplement.

3. **Recovery test**

   During 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 pump discharge which may be a factor in the pumping test.

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APPENDICES

APPENDIX CONTENTS

APPENDIX A. DISCUSSION OF BOREHOLE AND OUTCROP DATA

A.1 Deep Exploratory Boreholes (TGH-1 and TGH-3)

Based on visual inspection of the rock cores, TGH-1 (northernmost borehole) shows a simpler lithological column as compared to TGH-3 (located closer to the coast). The column at TGH-1 shows a thick layer of mountain-front talus and alluvium covering the Leone Volcanic Unit, which overlies the Taputapu rocks; thus indicating that the well is probably located above a lava filled paleo-valley. At TGH-3, the alluvial overburden is relatively thin, and the Leone Volcanics are seen to contain two marine carbonate layers above the contact with the Taputapu Volcanics, indicating that the well is located above the lava covered inland margin of the carbonate bench that rings the island.

The Leone Series rocks can be distinguished from the underlying Taputapu rocks by distinctive geochemical signatures, whereas the Leone rocks have about 10% less magnesium oxide (normalized by weight) and about 20% more zirconium (normalized by weight) than contained in the Taputapu unit (Geologica Geothermal Group, Inc; unpublished data, 2016).

A.1.1 Leone Series Rocks

Upon visual inspection, the Leone Series rocks in TGH-1 generally have a higher proportion of volcanoclastics (ash and cinder) than is seen in TGH-3, though the material in both boreholes are still predominantly basalts from lava flows. In TGH-1, the Leone Volcanic rocks occupy the hole from 37.1 m above mean sea level (MSL) to 45.8 m below MSL (a total of 83 m in thickness). In this unit, the proportion of total sum of thickness of basalt layers to pyroclastic layers (here defined as ash and cinder/rubble) is 85% to 15%, respectively. Within just the basalts, the proportion of massive basalts (with or without fractures) to vesicular or soft/rubbly basalts is about even, 44% to 56%, respectively. Generally, cinders and soft/vesicular basalts are assumed to be more permeable while massive basalts and ash layers are less permeable. Therefore the TGH-1 ratio of more-permeable units (52%) to less-permeable units (48%) is about equal. These statistics were also compiled for the Taputapu rocks in TGH-1, and both the Leone and Taputapu rocks observed in TGH-3 (Table 3).

A.1.2 Taputapu Series Rocks

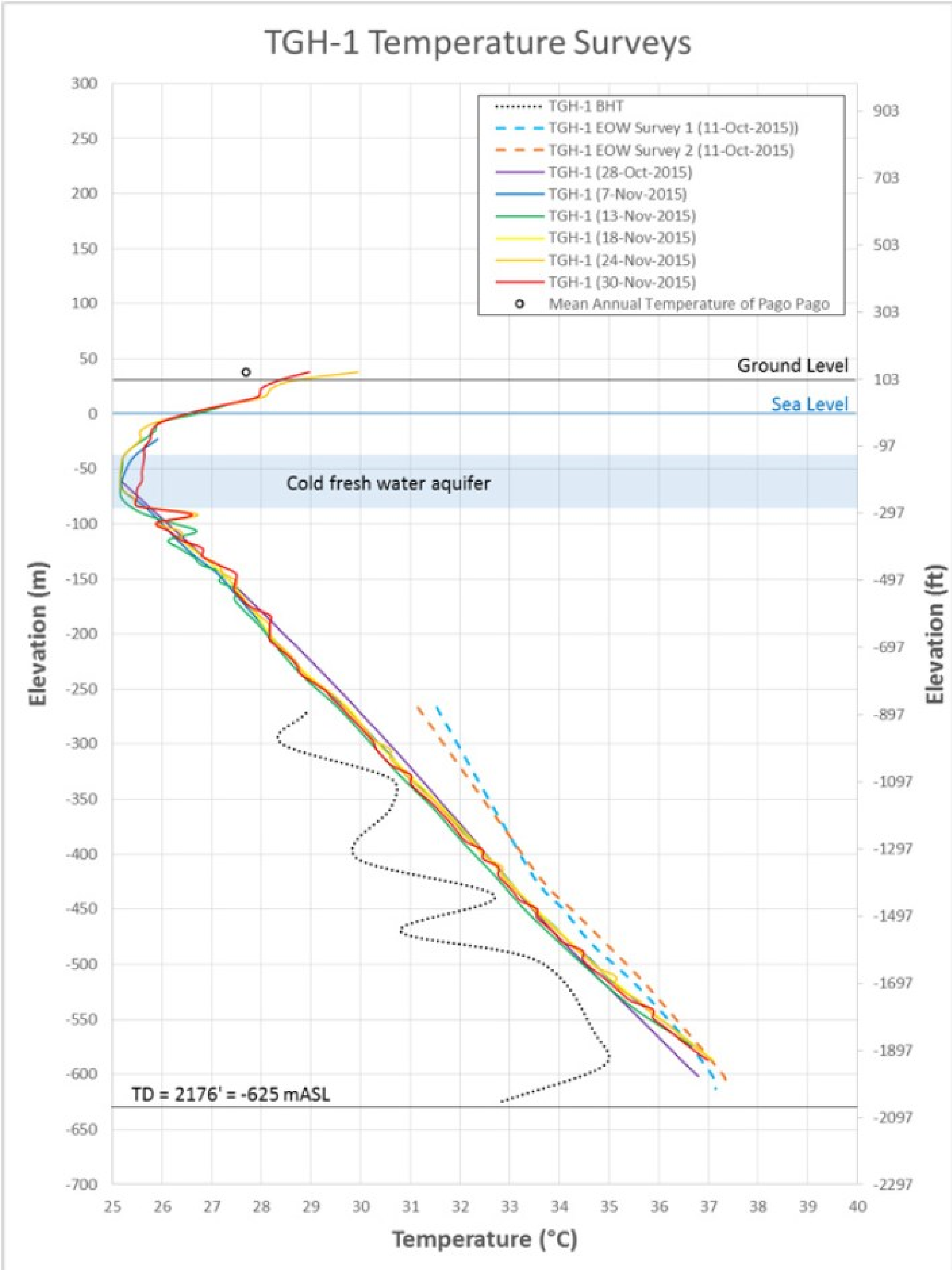
The younger units in both deep boreholes show abundant layering with common occurrence of fractured units, unconsolidated regions, or vesicularity. In contrast, the Taputapu Series, relative to the Leone Unit, generally has more secondary mineralization in voids and a higher proportion of clays or other minerals that reduce the porosity in rubble zones. The amount of void space is reduced below a large rubble zone in each borehole (below –236 m MSL in TGH-1, and below –232 m MSL in TGH-3). This boundary was used to differentiate upper and lower Taputapu sections. In the lower section the ratio of permeable to impermeable rock is reduced by 25–35%. The file “DeepBoreholeLogs.xlsx” in this report's data supplement provides raw data and these statistics. In both units, fairly thin distinctive lithological units of massive basalt, vesicular basalt, pyroclastic materials, and sedimentary horizons seem to alternate rather quickly in a non-regular sequence. The harmonic mean of the thicknesses of each distinctive layer in each series was calculated and does not seem to differ much between series, being generally between 1 and 3 m. This rapid alternation of units shows a high degree of both vertical as well as horizontal heterogeneity in the materials that make up the island. Additionally, it shows why aquifer characterization based on individual geologic layers is difficult, thus emphasizing the need to assess integrated hydrological properties based on aquifer tests.

A.1.3 Temperature Logging of Deep Boreholes

Unfortunately, aquifer tests were not performed during drilling, and TGH-1 and TGH-3 were grouted and cased down to –190 m and to –275 m deep, respectively. However, temperature logging was performed during and after drilling. Since surface derived freshwater is distinctively colder than the surrounding rock, borehole temperature logs can indicate areas of potential water flow. Survey results from Geologica Geothermal Group, Inc. (2016) are shown in Figures A.1 and A.2, indicating low temperature plateaus; thus, the presence of the known freshwater aquifer between about +3 to –85 m above MSL in TGH-1, and about +1 to –25 m above MSL in TGH-3. Interestingly, there may also be a low temperature plateau in THG-3 at 175 to 280 m below MSL; however, the interpretation of this anomaly is convoluted by a lost circulation event that required drillers to cement a small interval at about 225 m below MSL. Since the hydration of the cement releases heat, a corresponding temperature spike is seen on the temperature profile, coincident with the upper portion of the low-temperature plateau. Despite this complication, the temperature profile still shows this interesting plateau below the spike.

A.1.3.1 Iliili Borehole

The temperature profile with depth in Iliili at TGH-3 shows a decrease in temperature in the air-filled hole from the ground surface to near sea level where the water table is encountered (Fig. A.2). From near sea level to a depth of 15 m below sea level, the water temperature is relatively cool and constant, and represents the temperature of the water flowing through the unconfined freshwater lens. This water is recharged from cooler higher inland elevations. With one major exception, the temperature increases from –15 m to the bottom of the hole as the geothermal gradient heats the relatively immobile seawater that underlies the freshwater lens. The exception is from elevations of 175 to 280 m below MSL where the temperature is relatively constant except in the middle of that zone. Geologica Geothermal Group, Inc. (2016) notes that two cement plugs were placed in this zone to hold the hole open and that the heat of hydration during curing of these plugs caused the temperature to spike up. It was reported that the plugs were placed in an unstable zone of coarse volcanic "gravel" that occupies the local lithologic column from 200 to 230 m below sea level.



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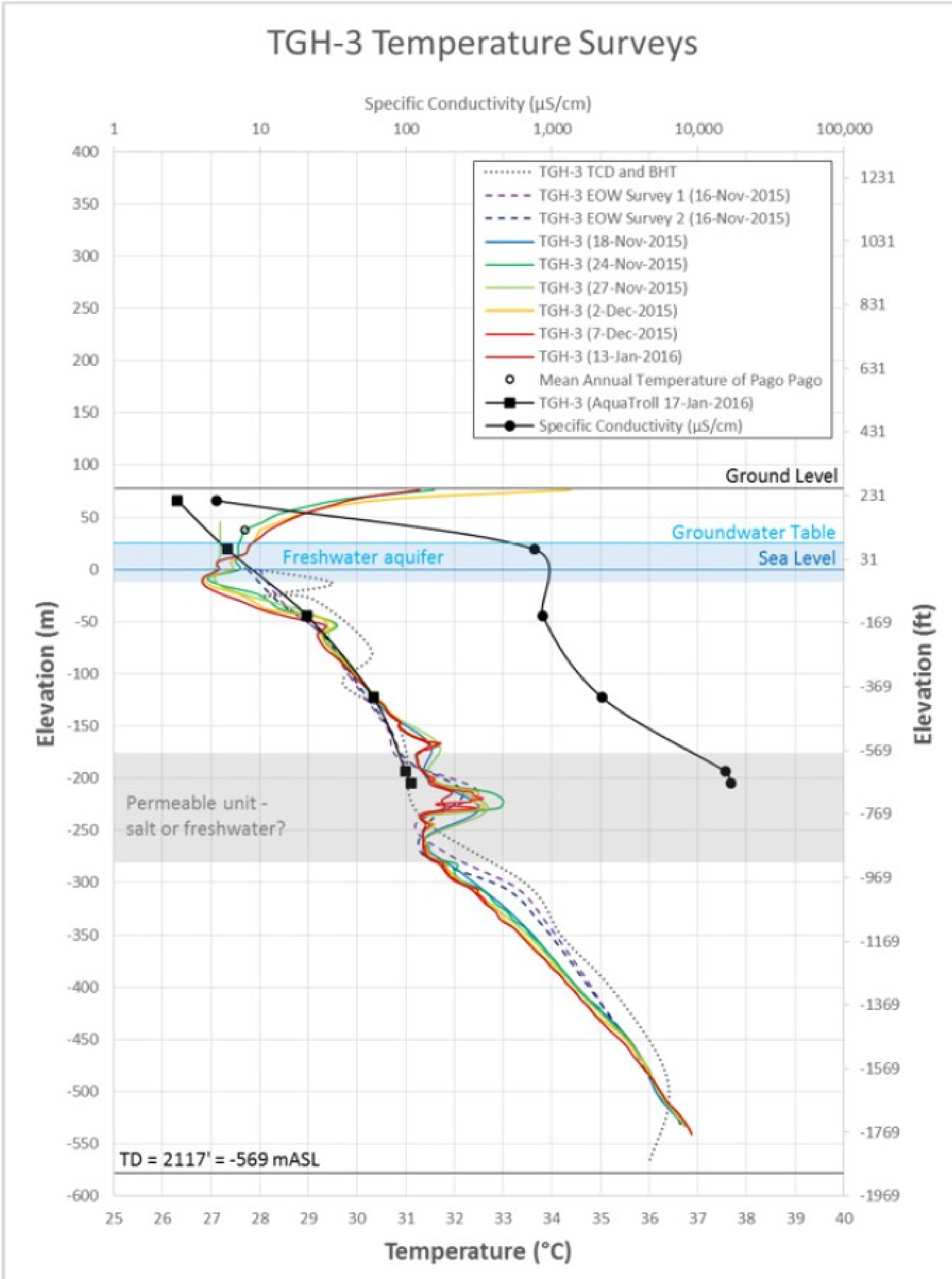
Note: Colored lines = repeated temperature logging measurements for TGH-1, dashed line = a series of Bottom Hole Temperatures (BHT) collected by maximum recording thermometers while drilling progressed downward.

Appendix Figure A.1. Temperature survey log data of TGH-1.



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Note: Colored lines = repeated temperature logging measurements for TGH-3, black line with circles = conductivity log in µS/cm, dashed line = series of Bottom Hole Temperatures (BHT) collected by maximum recording thermometers while drilling progressed downward.

Appendix Figure A.2. Temperature and conductivity survey log data of TGH-3.

The existence of a shallow freshwater lens, as indicated by the temperature profile, is verified by the wells in the Iliili well field, which pumps fresh water most of the time but becomes more salty during dry times, or when the wells are over-pumped. Heads in the Iliili well field range from 1 to 2 m above sea level and well depths range from 2 to 10 m below sea level. Although the temperature-depth profile may have some inaccuracies in exact elevations, it indicates that a flowing freshwater lens extends to about 15 m below sea level. Inaccuracies in the ground elevation data and equipment used to measure depth, the shallow penetration of the Iliili wells below the water table, and the potential for vertical flow within the aquifer only allow the elevation of the bottom of the lens to be approximated, which could potentially range from 15 to over 40 m below sea level.

A.1.3.2 Possible Confined Aquifer Below Tafuna-Leone Plain

The existence of a deep freshwater aquifer in the Taputapu Mountain is suggested by the zone of constant temperature from –175 to –280 m below sea level, indicating a zone where the flow of water is sufficient to overcome the geothermal gradient. The zone of flowing water does not extend deeper than –260 m below sea level and the geothermal gradient is reestablished at that depth. A head of 6.5 m is theoretically required for a basal lens to reach –260 m below sea level. Although there are no measured clearly basal heads in the Taputapu Mountain, the relatively low-permeability of the rocks and the substantial amount of groundwater recharge indicate that such heads are possible. However, this temperature anomaly might also be caused by tidally forced inflow of seawater. Water sampling from TGH-3 in this zone after extensive cleanout of the borehole would help to constrain the salinity of water in this zone.

A.1.3.3 Malaeloa Borehole

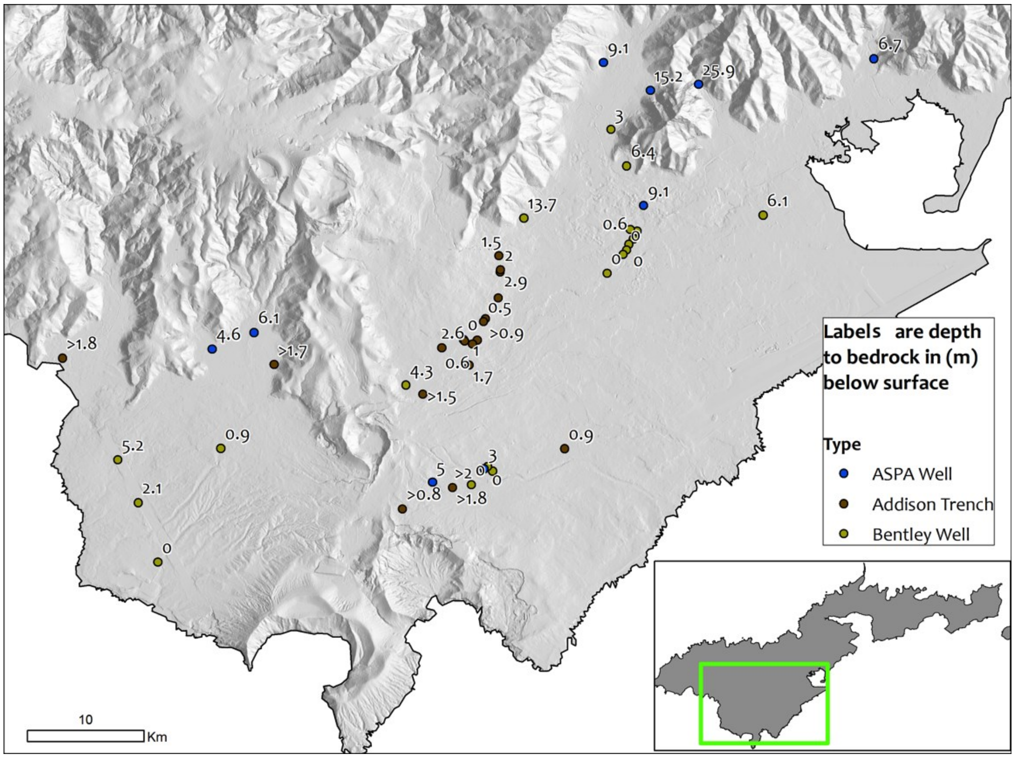
The temperature profile with depth in Malaeloa at TGH-1 is similar to the profile at TGH-3 except that a deep freshwater aquifer in the Taputapu Mountain is not indicated (Fig. A.1). In addition, there is better correspondence between the bottom of the shallow freshwater lens, indicated by the temperature profile (75 m below sea level), and the heads at the Malaeloa well field (1.5 to 2 m above sea level).

A.2 Shallow Borehole Logs

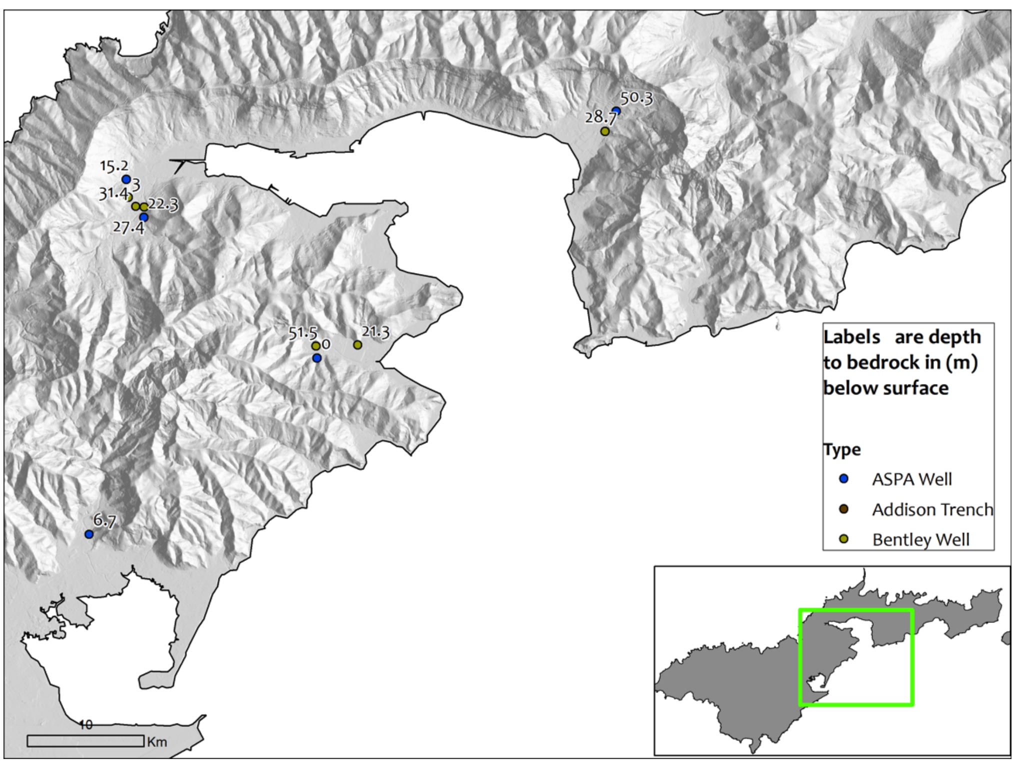
Borehole logs from production wells and archeological trenches also have value for comparing geologic features and properties between regions. A compilation of older driller's logs from mostly decommissioned wells was made by Bentley (1975) and published in a U.S. Geological Survey (USGS) water resources report. Here, these logs were compiled with more recent borehole logs directly from American Samoa Power Authority (ASPA) files (provided in data suppliment), as well as logs from shallow trenches dug for archaeological investigations (Addison, 2014). For this report, all logs were entered into a database where each logged formation was classified into one of eleven different lithologic types that are assumed to have different hydrological parameters. These types were unconsolidated, hard basalt, vesicular basalt, no circulation, clay, soft/broken/fractured rock, cinder, ash, non-carbonate sand, carbonate sand, or carbonate reef. Although other factors such as secondary mineralization and grain-size distribution can affect the permeability of a geologic type, each of the above classifications was assumed to be categorizable as either more-permeable or less-permeable based on the general characteristics of each material. Materials that were considered to be more-permeable were unconsolidated, vesicular basalt, no circulation, soft/broken/fractured rock, cinder, non-carbonate sand, and carbonate sand. Materials that were considered to be less-permeable were hard basalt, clay, ash, and carbonate reef.

A permeability-type for each meter of each well log was assigned, and the ratios of the total thickness of more-permeable units to less-permeable units were averaged for boreholes in each region. Logs from wells located in valleys around the Pago Shield were grouped into a single region, since there is uncertainty when distinguishing between layers in alluvium or the underlying volcanics. However, the results of this assessment are fairly inconclusive. No statistical differences in the permeability ratios of the logs from different regions are observed. On average, the summary indicates the ratio of materials found in the boreholes (more-permeable vs. less-permeable) is about equal. This result may also be a reflection of the uncertain quality of the log information, since the logs are from many different drillers, taken at different times, and are of variable quality in their interpretation of lithologic type. Nonetheless, this assessment does indicate that throughout the island the subsurface is generally constructed of similar materials with a high degree of flow-unit-scale heterogeneity, as would be expected in a volcanic island setting. Thus differences between unis may be more dependent on secondary factors such as, variability in weathering, secondary mineralization, or fracturing.

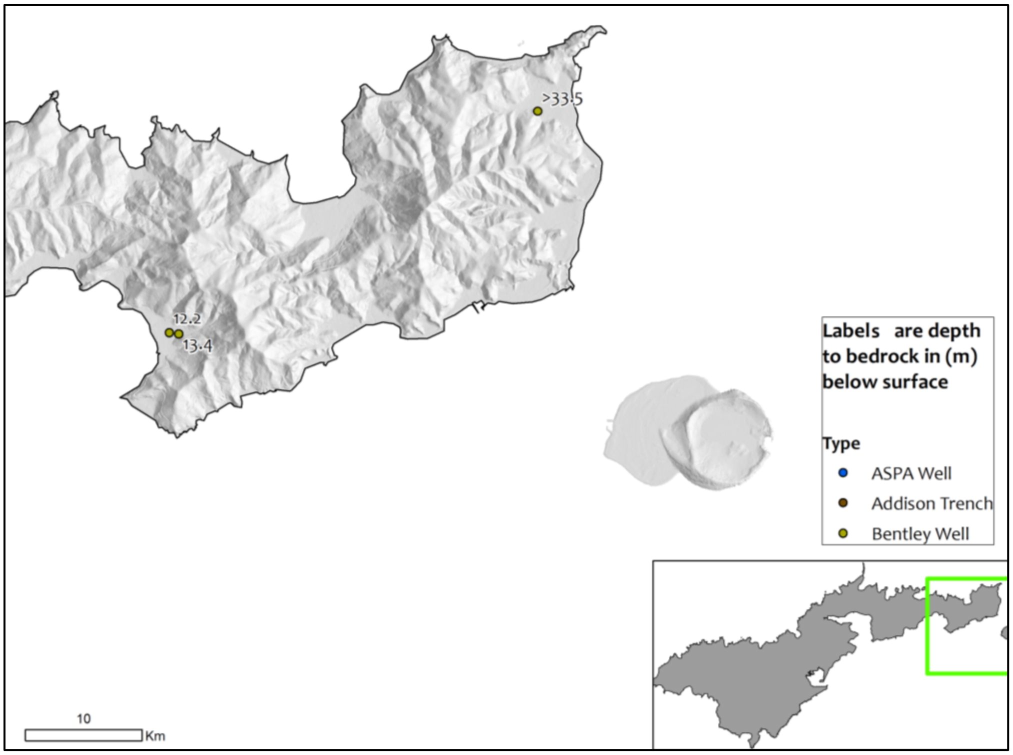
Although these logs do not seem to be useful for differentiating between aquifer units, they are still instructive for assessing the locations of recognizable geologic features. In the borehole and trench logs it was generally possible to estimate the location of the contact between alluvium or soil and the underlying bedrock. Though the lithologies were often ambiguous, it was assumed that the first mention of rock in the log—as opposed to soil, clay or sand—represented the top of the volcanic bedrock. This information is helpful when assessing regional hydrologic parameters such as permeability or infiltration rate, or for determining the practicality of installing subsurface infrastructure, such as septic systems or buried electrical or water lines. Generally, in the central Tafuna Plain area, the bedrock is shallow or often exposed at the surface, and areas closer to steeper slopes show variably thick layers of talus or alluvium. The Leone side of the plain seems to be richer with ash layers of highly variable thickness (Figs. A.3–A.5).



Appendix Figure A.3. Depth to bedrock seen in boreholes and trenches, western Tutuila.

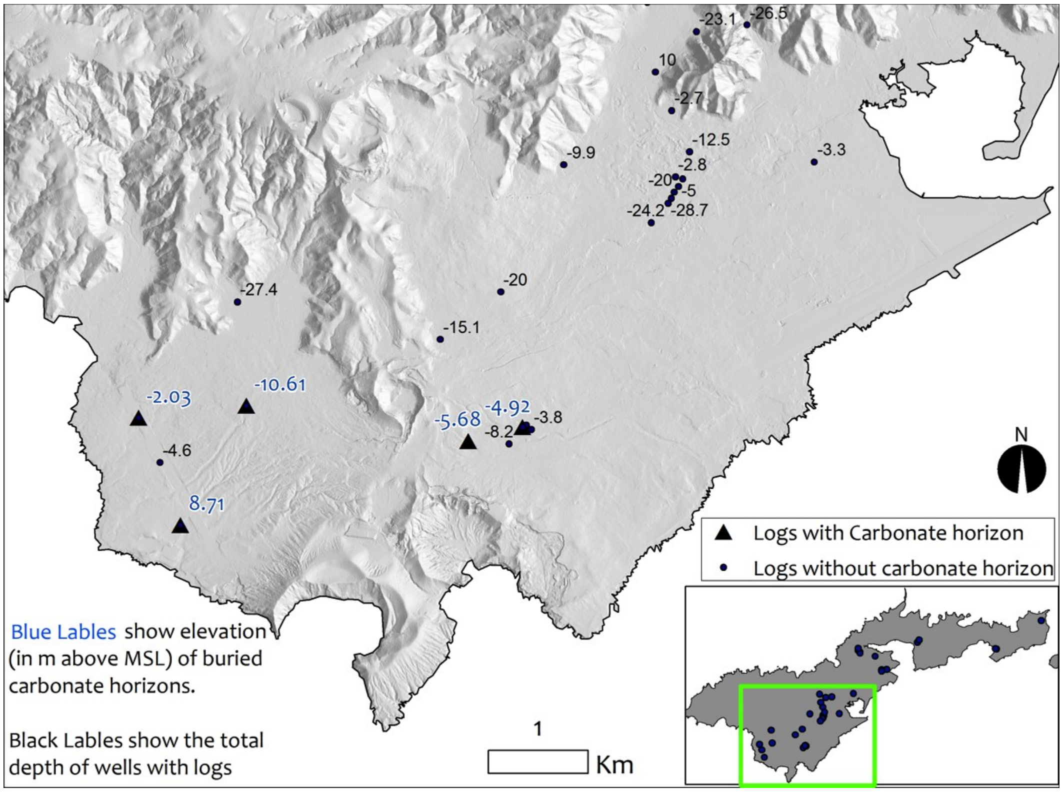


Appendix Figure A.4. Depth to bedrock seen in boreholes and trenches, central Tutuila.



Appendix Figure A.5. Depth to bedrock seen in boreholes and trenches, eastern Tutuila.

Another distinctive lithological feature observed in a few of the logs is the underlying marine carbonate layer(s) in the southern Tafuna-Leone Plain. Production wells in this region are drilled to a fairly shallow depth and only a few wells have reported carbonate materials in the very bottom. The elevation of the carbonate occurrence is quite variable, with the tops of these layers occurring between + 9 and -10 m above MSL (Fig. A.6). This lack of horizontality suggests that either drillers were unable to recognize the difference between carbonates and basalts, or that the carbonates are actually a series of discrete carbonate horizons or pockets deposited on uneven terrain and at varying elevations. Such a situation might result from various transgressive or regressive shorelines where carbonate material was deposited on the coast as the plain was built successively outwards, while sea levels continued to rise both globally and from Tutuila's slow subsidence. Carbonate horizons or pockets may subsequently have been unevenly paved over by lava flows from the Leone series. This package of volcanics and interfingered shoreline carbonates probably overlie what may be a more continuous and thicker carbonate/marine alluvial layer, which is seen at an elevation of about 60 m below MSL in TGH-3. This interpretation may help explain the observation of the two discrete carbonate layers seen in the lithologic column of the deep borehole.

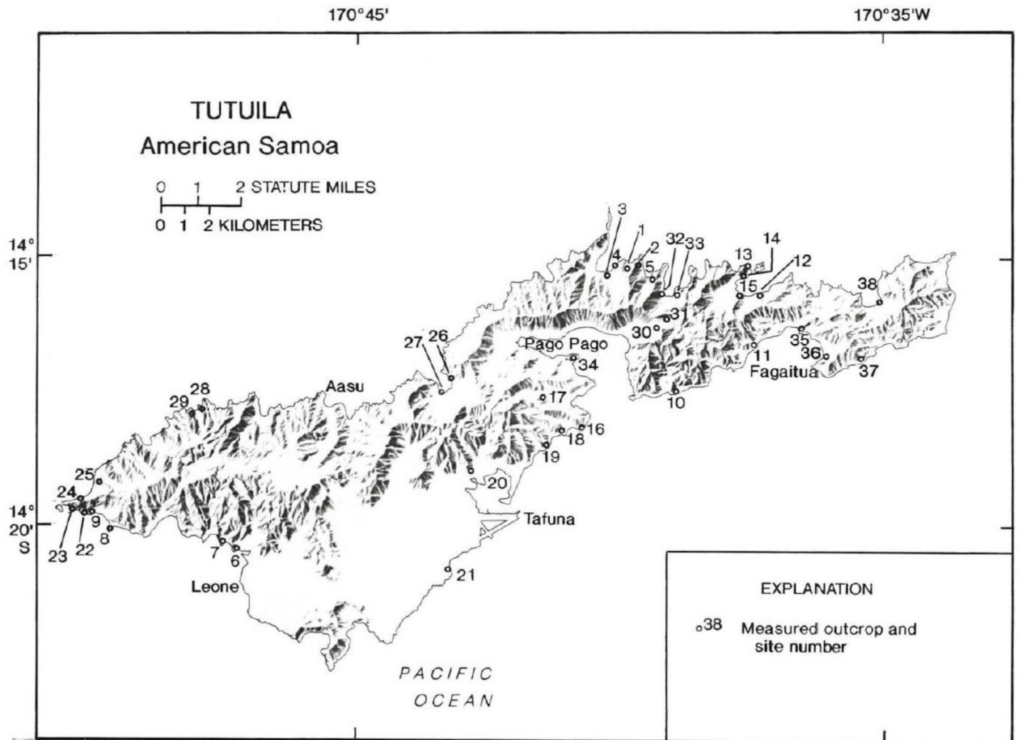


Appendix Figure A.6. Elevation of top of shallow carbonate horizons observed in Tafuna-Leone Plain boreholes.

The deeper carbonate unit that is visible in the TGH-3 core is also probably just the edge of a more extensive marine sedimentary wedge. The deep borehole in Malaeloa (TGH-1) did not recover any carbonate, which indicates that the northern extent of any contiguous carbonate deposits lies somewhere between the two deep boreholes. It remains unclear, exactly how these units affect the region's hydrogeology. It may be possible that they act as confining layers or it is also possible that they have a high-hydraulic conductivity and thus act as permeable aquifer units.

A.3 Additional Data for Pleistocene Volcanic Rocks

Figure A.7 shows the locations of Pleistocene Volcanic rocks on Tutuila, while data from lava flows are shown in Table A.1.



Base from Atlas of American Samoa, University of Hawaii Cartographic Laboratory. 1981

Note: Discussion of data given in Eyre and Walker (1991), and outcrop data shown in Appendix Table A.1.

Appendix Figure A.7. Locations of measured outcrops of Pleistocene Volcanic rocks from Eyre and Walker (1991).

Appendix Table A.1. Statistics from selected lava flows on Tutuila.

Site No.[a]	Location	No. of Measured Flows	Total Column Thickness (m)	A'a Unit Thickness: Massive Section (m)	A'a Unit Thickness: Rubble Section (m)	A'a Unit Total Thickness (m)	Pahoehoe Unit Thickness (m)	Dip Angle (°)	Rubble (%)[b]
1	Vatia	21	57.2	18.0	39.2	2.7	0.0	22	69
2	Vatia	2	10.9	5.2	5.7	5.4	0.0	23	52
3	Afono	1	8.2	4.2	4.0	8.2	0.0	20	49
4	Vatia	5	20.2	6.9	13.3	4.0	0.0	20	66
7	Leone	6	13.3	8.5	4.8	2.2	0.9	7	36
8	Amanave	11	17.0	12.2	1.7	1.5	0.0	small	28
11	Fagaitua	2	11.7	5.9	5.6	5.8	0.0	small	50
12	Masefau	12	55.0	33.0	22.0	4.6	0.1	small	40
13	Masefau	5	13.6	9.6	3.9	2.7	0.0	small	29
15	Masefau	2	9.9	8.8	1.1	5.0	0.0	small	12
18	Fatumafuti	2	13.1	6.3	6.8	6.6	0.0	<5	52
19	Faganeanea	3	9.8	4.5	5.3	3.3	0.0	15	54
20	Nuuuli	2	34.0	23.0	11.0	17.0	0.0	–	32
23 + 24	Cape Taputapu	6	30.3	17.2	13.1	5.1	0.0	small	43
25	Poloa	6	23.0	14.6	8.4	3.8	0.8	small	37
26	Fagasa	15	18.3	10.6	7.7	1.2	0.6	20	42
27	Fagasa	10	11.1	5.7	5.4	1.1	0.7	25	49
28	Fagamalo	6	14.1	6.8	7.3	2.4	0.0	10	52
29	Fagamalo	4	6.9	3.6	3.2	1.7	2.3	15	47
32	Afono	11	38.6	22.4	16.2	3.5	0.0	–	42
34	Utulei	1	5.9	4.0	1.9	5.9	4.1	–	32
37A	Amouli	4	27.6	14.0	13.6	6.9	0.0	15	49
37B	Amouli	5	2.3	1.5	0.8	0.5	0.0	15	34
38	Aoa	3	8.9	5.1	3.8	3.0	0.0	small	43

Source: Data from Eyre and Walker (1991).

[a]See Appendix Figure A.7 for site locations.

[b]Mean weight of rubble (%) = 45.4 (includes ~10% of thermally-welded rubble of low-permeability).

APPENDIX B. DISCUSSION OF AQUIFER PARAMETERS.

B.1 Water Levels

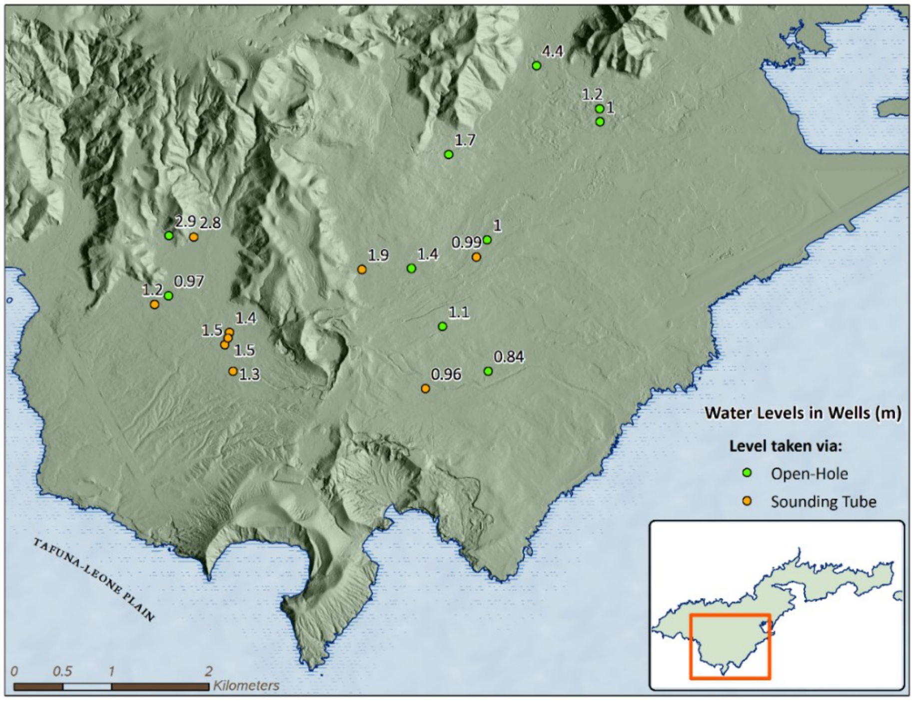
Since most of Tutuila's currently developed groundwater is thought to be basal in nature, the level of the water table in wells provides information that is useful for assessing the thickness of the freshwater lens and other hydrogeologic parameters. Inland static water levels near sea level generally indicate the well has tapped a high-permeability aquifer and thus a thin freshwater lens, whereas when the water table stands at a high elevation it suggests that some kind of geological feature is impeding the water's flow. Such features may be impermeable structures like dikes or perching horizons, or may simply indicate an aquifer with low overall conductivity. Opportunities to record static water levels are often limited on Tutuila, and a number of the static water levels recorded are from well development, prior to pumping. Also, some of the reported water levels are known to be affected by nearby pumping wells. Note that the discrete (one time) measurements compiled in this report are subject to uncertainties in recharge variation, previous pumpage, and tidal or atmospheric fluctuations. Ranges in historical records of water levels reflect these uncertainties and additional details are documented in Izuka (1996, 1997, 1999a). Nonetheless these measurements do show distinct and valuable spatial trends.

B.1.1 Pumping Water Levels

Presently, there are no dedicated monitoring wells on Tutuila. However, pumping water levels are taken monthly from sounding tubes and these records are kept by ASPA. Unfortunately due to the effects of variable aquifer drawdown and well losses (observed well losses in Tutuila are between 0.1 and 10 m) pumped water levels do not give a reliable indication of aquifer conditions. Additionally, accurate well-head elevations are not always available on Tutuila. These elevations should be derived from accurate survey data, however, a complete survey of the ASPA well system to this level of quality may not be available. Without an accurate understanding of the measuring point elevation (above MSL) at a well, water level measurements cannot be placed on a uniform datum, and levels in different wells cannot be compared.

B.1.2 University of Hawaii Water Resources Research Center (UH WRRC) 2014 Water Level Survey

Since there were no active monitoring wells on Tutuila, a synoptic static water level survey was performed by UH WRRC in order to obtain a regional sense of water level variation. The survey was performed one well at a time, during the dry season months of July and August 2014. Water levels were measured after recovery tests at roughly 27 pumping wells throughout the island (Fig. B.1, Table B.1). These water levels were assumed to be static based on the slope of observed recovery curve, however, these estimates are likely to be conservative level estimates (lower in elevation), due to potential effects of previous pumping, and current extraction from nearby online wells.



Appendix Figure B.1. Measured water level locations in the Tafuna-Leone Plain from UH WRRC 2014 water level survey.

Appendix Table B.1. Results of UH WRRC 2014 water level survey.

Well Name	Level (m)	Well Name	Level (m)	Well Name	Level (m)
Tafuna Region		**Western Malaeloa Region**		**Taputimu Shield Region**	
Tafuna-72	1.10	Malaeloa-70	1.18	Fagalii-182	0.22
Tafuna-77	1.00	Malaeloa-80	0.97		
Iliili Region		**Upper Malaeloa Region**		**Pago Shield Region**	
Iliili-167	1.12	Malaeloa-168	2.81	Masefou-242	4.59
Iliili-62	0.96	Malaeloa-169	2.89	Vatia-170	5.99
Iliili-84	0.84				
Upper Pavaiai Region		**Lower Malaeloa Region**		**Aluvial and Unrecovered Wells**	
Tafuna-177	1.37	Malaeloa-91	1.44	FTA-164	1.01
Tafuna-178	1.92	Malaeloa-92	1.49	AOA-152	-0.54*
		Malaeloa-93	1.45	PAGO-163	-4.46*
		Malaeloa-119	1.35	Afono-176	1.10
				AUA-99	-1.23*
Lower Pavaiai Region		**Malaeimi Region**			
Tafuna-172	0.99	Malaeimi-89	4.40		
Tafuna-171	1.02	Mesepa-85	1.74		

Note: Water levels are given in meters above sea level.

*Aquifer severely draw down from natural levels by over pumping.

B.2 Aquifer Transmissivity and Hydraulic Conductivity Analysis Methods

Available pumping test data (i.e., step-drawdown and recovery) were compiled from USGS records (Bentley, 1975; Eyre and Walker, 1991), archived ASPA records, and recently performed UH-WRRC aquifer tests. Aquifer data from Bentley (1975) and Eyre and Walker (1991) are estimates derived from pumping tests performed by the USGS or from data recorded during well development testing. The analytical methods used to obtain the values presented from the Bentley (1975) and Eyre and Walker (1991) studies are detailed in the aforementioned reports. Analytical methods for the computation of aquifer parameters from the UH-WRRC tests and ASPA records are provided in Section B.2.1 and B.2.2.

Aquifer tests are useful for developing estimates of aquifer transmissivity ***(T)*** and/or values of hydraulic conductivity (***K***). Analytical solutions such as the Thies or Thiem solutions can be applied to constant rate aquifer test data to calculate values of ***T.*** These values of ***T*** can then converted to values of ***K,*** if the aquifer thickness is known (or assumed), since ***T*** is defined as ***K*** times the thickness of the aquifer, (***b)*** (Freeze and Cherry, 1979). Since the thickness of Tutuila's aquifers are unknown, values of ***T*** reported in Bentley (1975) were converted to values of ***K*** by assuming the effective thickness of the aquifer ***b*** is equal to the saturated length of the well (i.e. well depth minus depth to water or bottom of casing, whichever is deeper).

B.2.1 Step-Drawdown Tests

In the ASPA files, the documentation for step-drawdown tests were more prevalent. These tests can be analyzed with the Jacob-Zangar Method to directly estimate ***K*** values without having to assume an aquifer thickness (instead, the well is assumed to be partially penetrating and only the hemispheric zone of influence from the well is considered in the analysis). The method first uses Zangar's (1953) equation to derive a rough estimate of the ratio of well-losses to aquifer losses, and then the single-well analytical solution, Jacobs equation, is used to calculate ***K***. This is also the method Eyre and Walker used to derive their estimates of ***K*** from older test records located in USGS files.

B.2.2 Recovery Tests

The UH-WRRC performed pumping and/or recovery tests on 25 production wells in the ASPA system from July to August 2014. These (constant rate) tests were first analyzed with the Cooper-Jacob Straight-Line Method to obtain values of ***T.*** This analysis was performed by plotting residual drawdown (***s'***), against pumping time over recovery time (***t/t'***) and using a computational template from Halford and Kuniansky (2002). Values of ***T*** were then converted to ***K*** values as above, by dividing ***T*** by the effective length of the well, as defined by the well depth minus the depth to the pumping water level. Additionally, the Jacob method (Eyre and Walker, 1991) was also applied to the UH-WRRC test data to develop an independent estimate of ***K*** for the wells that had either appropriate step-drawdown test data (using the Jacob (1947) method of well-loss estimation) or using examination of recovery curves to estimate well- loss, where well-losses were assumed to equal the preliminary recovery 15-30 seconds after pumps were shut off. Where both methods were used to calculate ***K***, the average percentage of difference in calculated ***K*** values between the two methods on UH-WRRC data (the most reliable of all data sets) was 112%. Values of ***T*** and ***K*** from all sources are given in the file "AquiferParameters.xlsx" in the supplementary material.

Additional transmissivity data from an unpublished study performed by the USGS prior to 1987 was presented in a report by Kennedy, Jenks, and Chilton Consulting Engineers (1987). The study examined data from water level loggers placed in monitoring wells on the Tafuna Plain that showed tidal efficiencies of more than one percent. By considering each well’s distance from the shore and relating tidal efficiencies to transmissivity, the authors determined very high values of $\boldsymbol{T}$ were needed to support such efficiencies in this region. These values were over 139,400 m^2/d. Though these values may be overestimates, they help to underscore the relatively rapid movement of water through the young volcanic aquifers.

It should also be mentioned that most of the estimates of $\boldsymbol{T}$ presented here are fundamentally based on the Theis non-equilibrium equation, which requires the following assumptions: (1) aquifer conditions are isotropic and homogeneous, (2) full penetration of the aquifer thickness by the well, and (3) the aquifer has an infinite areal extent. Many estimates of $\boldsymbol{K}$ rely on the assumption that all well-losses are adequately represented by the second degree Jacob equation. However, it has been shown that the degree of well-loss functions may in reality vary significantly from well to well due to differences in construction (Todd and Mays, 1980). Tutuila's wells seldom meet these ideal conditions, however, these estimates nonetheless represent the best available data regarding the relative differences in range and magnitude of Tutuila’s aquifer parameters.

B.2.3 Aquifer and Well Production Characteristics

Compiled aquifer parameter results from all data sources are summarized in Table 7. The summarized data is presented with three different measures of central tendency, these being the arithmetic mean [$\boldsymbol{\mu} = \boldsymbol{E}(\boldsymbol{x})$], the harmonic mean [$1/\boldsymbol{\mu} = \boldsymbol{E}(1/\boldsymbol{x})$], and the geometric mean {$\ln(\boldsymbol{\mu}) = \boldsymbol{E}[\ln(\boldsymbol{x})]$}; where $\boldsymbol{E}$ is the sum of individual values divided by the number of values.

In general, the arithmetic mean is representative of the central tendency of a dataset with a normal distribution, the harmonic mean is more representative of a distribution with a few large outliers, and the geometric mean is representative of a dataset that is not composed of independent measurements. In hydrogeological studies, each type of average has been used to estimate regionally appropriate $\boldsymbol{K}$ values that are representative of a larger part of the aquifer than that sampled, from a limited number of measurements from pumping wells. It has been shown that in an evenly layered aquifer where groundwater flow is parallel to the bedding, the average regional hydraulic conductivity is best represented by the arithmetic mean of the $\boldsymbol{K}$ values for the individual layers. Where ground water flow is across the bedding, the harmonic mean is a better representation of the large-scale hydraulic conductivity (de Marsily, 1986). Large-scale field studies of less ideal aquifers have shown that, in some cases, water levels are best predicted using the geometric mean of individual pumping test results.

At present, no single method satisfactorily uses aquifer-test derived hydraulic conductivities to determine a value that is representative of a larger part of the aquifer (e.g. Neuman, 1982; Carrera and Neuman, 1986; Dagan, 1989; El- Kadi and Brutsaert, 1985; Smith and Freeze, 1979). Considering the non-uniform character of the Pleistocene aquifers, it may be reasonable to assume that for the characterization of $\boldsymbol{T}$ and $\boldsymbol{K}$ for entire hydrologic units, the best estimate of these parameters is represented by the harmonic or geometric means, rather than the arithmetic mean, of individual values from well tests; whereas the more uniform character of the Tafuna-Leone flows could make the arithmetic mean a more representative value for this region (Eyre and Walker, 1993).

B.3 Conceptual Models of Groundwater Occurrence in the Pleistocene Rocks

B.3.1 Perched or Semi-Perched System

The Walters (2013) groundwater model suggests perched or semi-perched water overlies a separate zone of basal water. In an island setting, the lowest elevation feature on which freshwater recharge can accumulate is the higher density seawater within saturated rock. Therefore, the level of basal water is ultimately controlled by the level of the sea. However, since the overall permeability of the Pleistocene rocks is relatively low, and Tutuila experiences high recharge rates, it is likely that recharge accumulates on geologic structures within the permeability fabric of the rocks. If there were no unsaturated zones between the perched water and basal lens, this water could then be defined as semi-perched. Meinzer (1923) describes semi-perched water bodies as belonging to the same zone of saturation as the main (basal) water body, but separated somewhat by a negative confining bed (negative meaning that water flow is primarily downwards and vertical through the bed). In theory, semi-perched water would be distinct from basal water because it is supported by underlying rock, as opposed to underlying seawater. In practice, this water would only be observed as distinct if, when pumped, it lost hydraulic connection with the surrounding aquifer and developed an unsaturated condition that limited the spatial extent to which the cone of depression could extend. This condition would also limit the amount of developable water in this zone to the water in the localized saturated area, and would not extend across hydraulic barriers of unsaturated material. Semi-perched zones would be hydraulically disconnected from the main water body and thus would not be useful for assessing the thickness of the freshwater lens, even with more advanced techniques (e.g., Izuka and Gingerich, 1998). This disconnection would also suggest that pumping from the basal lens would not affect high-level streamflows. Because of this hydraulic discontinuity, and the complexity involved in modeling a perched/semi-perched system the ASPA model chose to only model the basal portion of the system.

B.3.2 Fully Saturated System

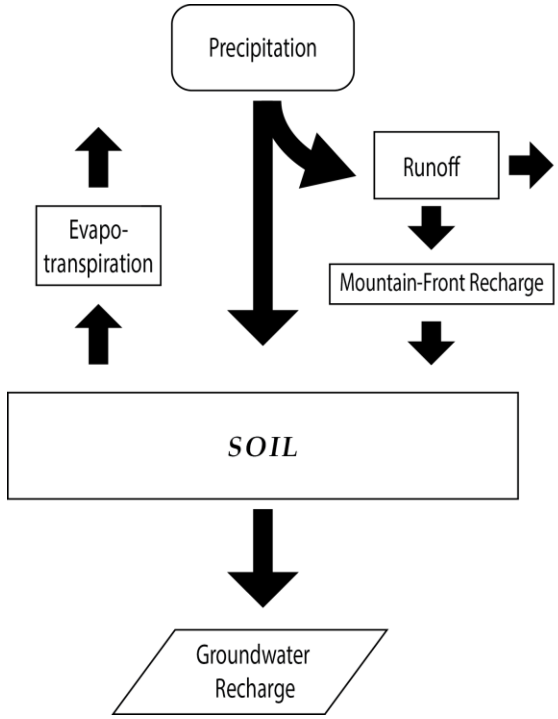
The conceptual model that the Izuka et al. (2007) model was based on contrasts the Walters (2013) conceptual model by considering the region as a hydraulically-connected fully-saturated aquifer with a main water table that sits several hundreds of feet above sea level. This high-water table is supported by a horizontally homogeneous aquifer material with an overall low-conductivity. This fully saturated, low-conductivity system considers any water within the basal zone of saturation as belonging to a single hydraulically connected water body, thus water may flow between areas wherever there is a hydraulic gradient. This body is also inferred as the source of much of Tutuila's high- to mid-level stream and spring flows. This model requires lower values of $\boldsymbol{K}$ in the older volcanics then the semi-perched model in order to achieve high observed head or spring levels, and thus it may give conservative estimates of sustainable yield from zones within the water body that are below sea level. Conversely, if the system behaves as a fully saturated model, pumping from the basal lens would result in the reduction of high-level streamflows. The key distinctions between these two models relates to the extensiveness of the high-level saturated zones and the hydraulic connection of these zones with each other, and with the main (basal) water body deeper below the ground surface. However, the existing hydrogeological data seems to indicate that the island's complex and heterogeneous geology creates a complex distribution of perched, semi-perched, and fully saturated basal water bodies throughout the island. Therefore, these two models may not be exclusive of each other, and each may be more or less representative in different areas of the Pleistocene Shields.

B.4 Groundwater Recharge Models

Since groundwater recharge is difficult and costly to directly measure, it is generally calculated with a water-balance/budget model of some sort. These types of models generally assume that groundwater recharge is the residual term after other outputs are subtracted from the measured amount of precipitation (Fig. B.2). In the most simplified model, Thornthwaite and Mather (1955) stipulated that:

RECHARGE = RAINFALL – RUNOFF – ACTUAL EVAPOTRANSPIRATION

Although simple in theory, there are some complications that make precise measurements of these parameters tricky to constrain. During periods when rainfall and soil moisture storage are not sufficient to supply the demands of plants, actual evapotranspiration (***AE***) is less than potential evapotranspiration (***PE)***, which is what has been traditionally been possible to measure with evaporating pan measurements. Proper constraint of runoff is difficult as well, especially on an island with over 140 perennial streams. Since direct runoff measurements cannot be recorded for every stream, assumptions are made regarding how runoff in measured watersheds correlates to runoff on ungauged streams. Other factors that add uncertainty to groundwater recharge estimates on Tutuila are strong spatial and temporal gradients in precipitation, runoff, evapotranspiration, anthropogenic effects such as crop irrigation (very limited), addition from on-site wastewater disposal systems, and leaking water delivery lines (≈50% of Tutuila's municipal water is lost to leaks).



Appendix Figure B.2. Schematic illustrating factors used to calculate water balance for Tutuila.

B.4.1 Recharge Estimates

Sufficient information is not available to constrain all of these factors, so past recharge estimates have primarily considered only basic hydrologic variables to inform recharge calculations. Despite this limitation, it is still useful to consider the three recharge estimates developed and detailed in Eyre and Walker (1991), Izuka et al. (2007), and Walters (2013). Though these estimates were published in different formats, this report compiles and standardizes them by total recharge volume within the areas of watersheds as defined in the American Samoa Department of Commerce (ASDOC) GIS database. Note that the recharge coverage calculated by Izuka et al. (2007) was focused only on the Tafuna-Leone Plain region and thus Eastern Tutuila was excluded from the result. Methods of calculation and input datasets used for these estimates vary between each study, and are fully described in the respective papers. Recharge calculations made by Izuka et al. (2007) and Walters (2013) were given in the form of water depth over an area in vector polygon, and raster formats, respectively. In order to standardize the Izuka et al. (2007) and Walters (2013) calculations with the Eyre and Walker (1991) method based on basin total volume, recharge depths were intersected with major watershed boundaries as recognized by ASDOC, and recharge amounts in each basin were multiplied by the watershed area. Basin geometries from Eyre and Walker were not always consistent with the ASDOC boundaries. Therefore, a percentage was calculated for the total sum of recharge from each basin, based on the proportion of each ASDOC watershed covered by an Eyre and Walker (1991) basin.

B.4.2 Sources of Available Long-Term Climate Data

Recharge estimate quality is generally limited by data quality and quantity. Known climatological datasets that exist for Tutuila are listed in Appendix Table B.2. Currently there are two permanent climate data stations having long-term records on the island: the National Weather Service (NWS) station at Pago Pago Airport and the NOAA Global Monitoring Division Baseline Observatory (NOAA GMD) at Cape Matatula. The NOAA National Climate Data Center (NCDC) has archived rainfall data for a number of partial record stations from various USGS efforts and three stations in the Western Regional Climate Center (WRCC) network, which also include temperature data. Two local organizations, ASPA and the American Samoa Community College Land-Grant are partnered with UH WRRC and are currently collecting climatological data. Parameters include rainfall, solar radiation, wind speed, relative humidity, and temperature at five sites; and runoff at six sites throughout the island. Unfortunately, many of these station's records contain gaps, and a small percentage of records are overlapping. Nonetheless, the previous hydrogeological monitoring efforts conducted by the USGS until 2008 were a great asset to the island. After a 6 year gap, hydrological monitoring efforts have again become a priority. New data from ASPA and UH WRRC efforts will be intended to feed a series of up-to-date water budget and watershed models designed to constrain groundwater recharge at a high temporal and spatial resolution.

Appendix Table B.2. List of long-term hydrological monitoring datasets for Tutuila Island.

Agency	No. of Stations	Record Range (variable)	Measured Parameters
NWS	1	1971–2015	Rainfall, temperature, wind speed, relative humidity, barometric pressure
NOAA-GMB	1	1974–2015	Rainfall, wind speed, relative humidity, solar radiation, temperature
NCDC	9	1955–2013	Rainfall
USGS	10	1980–2008	Rainfall
USGS	varies*	1959–2008	Runoff from stations operational at various times
USGS	9	1999–2004	Rainfall, wind speed, relative humidity, solar radiation, temperature, soil temperature and soil heat flux
WRCC	3	1980–2012	Rainfall, temperature
ASCC	1	2005–2017	Rainfall, solar radiation, wind speed, relative humidity, temperature
ASPA	11	2014–2016	Rainfall
UH-WRRC/ASPA	5	2014–2017	Rainfall, solar radiation, wind speed, relative humidity, temperature
UH-WRRC/ASPA	6	2015–2017	Runoff

*Runoff data from at least 11 continuous-record streamflow gauging stations, 75 low-flow partial record stations, and 49 miscellaneous sites is archived by USGS (Matsuoka 1978, Wong 1996).

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