Chapter 1:

Introduction and Conceptual Hydrogeologic Model

1.1 Background and Motivation

Groundwater resources on high volcanic islands serve several important functions. Because surface water supplies are commonly limited in these settings, groundwater is often the primary water resource available for human needs. Natural groundwater discharge to coastal and terrestrial-aquatic ecosystems supports biodiversity by providing baseflow to streams, moderating salinity, and delivering nutrients or other dissolved constituents to reefs. Because of the isolated nature of oceanic islands, the importance of effectively utilizing, preserving, and protecting their limited groundwater resources is undeniable. Developing a well-informed and data-driven understanding of groundwater quality and quantity in island settings is a prerequisite for supporting ecosystem services and for developing sustainable water resource management strategies.

On Tutuila, the main island in the U.S. Territory of American Samoa, groundwater provides drinking water to over 90% of the island's approximately 60,000 residents (AS-DOC, 2013). In the past, overuse of groundwater from some of the island's aquifers caused salinization of wells, reduction in water quality, and necessitated abandonment of entire well fields. At present, island wide groundwater extraction rates, minus transmission losses, often cannot keep pace with municipal and industrial water demand, resulting in frequent interruptions to water service. A large range of hydraulic conductivities in the island's rocks causes production rate limitations in extremely low-conductivity areas, and groundwater contamination issues in highly conductive zones. Groundwater under the direct influence of surface water in the Tafuna-Leone Plain region (ASEPA, 2010) has afflicted portions of Tutuila with one of the longest-standing boil-water advisories in U.S. history (ASEPA, 2016). Additionally, water quality in many of the island's aquifers is threatened by anthropogenic contamination caused by prevalent non-point pollution sources (Shuler et al., 2017). Excessive nutrient delivery to reefs via the process of SGD is a plausible, yet understudied threat to the health of coastal ecosystems (Houk et al., 2013; Whitall and Holst, 2015). Compounding these issues is the fact that the island's landmass is quite small (less than $1/10^{th}$ of Oahu, Hawaii); therefore, the total volume of freshwater storage is limited. To address these issues, quantitative hydrogeologic assessments are needed, and these assessments are fundamentally based on a well-informed understanding of the island's hydrogeology.

1.2 Dissertation Significance, Objectives, and Outline

The purpose of this work is to improve scientific understanding of hydrogeologic processes in tropical island environments, and on a local level, to address a set of American Samoa's most critical water resources management questions through applied scientific investigation of climatic, geologic, hydrologic, geochemical, and biological phenomena. American Samoa is located over 2000 miles away from the nearest continent, and with a total land area of only 199 km^2 (slightly larger than Washington, D.C.) any water resource challenge in the territory is a critical one. Currently the challenges faced in American Samoa include salinization of drinking water wells, anthropogenic contamination of aquifers, and degradation of environmental water quality. While these issues are complex and involve many stakeholders, this work seeks to contribute information towards their solutions by addressing a set of specific research questions that are carefully designed to consider some of the most pertinent needs of resource managers and stakeholders in American Samoa.

While the work presented in the following chapters is generally motivated by applied questions based on management priorities, the application of advanced, cross-cutting geochemical and numerical techniques as tracers of human impact provides a testing ground for these methodologies in this new setting, thereby furthering scientific knowledge regarding the utility of these techniques. However, the most significant contribution made by this work is in advancing the understanding of American Samoan hydrogeology. This may benefit future scientists, resource managers, and policy makers who strive to address the critical water resources challenges that lay ahead for the territory.

Chapter 1, *Introduction*, provides background on the study setting of Tutuila, American Samoa, and also introduces a conceptual hydrogeologic model to support the hydrogeologic framework upon which the other chapters are built.

Chapter 2, *Isotopes, Microbes, and Turbidity: A Multi-Tracer Approach to Understanding Recharge Dynamics and Groundwater Contamination in a Basaltic Island Aquifer*, applies geochemical and biological tracers including turbidity, fecal indicator bacteria, and water isotopes, to assess the mechanism of contamination in wells that have contributed to one of the longest-standing-boil water notices in U.S. history. The primary objective of this chapter is to determine if existing wells can be simply repaired or re-drilled, or if abandonment of the entire aquifer may be necessary.

Chapter 3, *Understanding Surface Water - Groundwater Interaction, Submarine Groundwater Discharge, and Associated Nutrient Loading in a Small Tropical Island Watershed*, shows how comprehensive, tracer-based field assessment of submarine groundwater discharge (SGD) can be complimented by watershed modeling to better understand groundwater-surface water interaction and watershed scale nutrient dynamics. The primary objective of this chapter is to quantify coastal nutrient loading from different anthropogenic sources as they contribute to terrestrial hydrologic pathways including surface runoff, lateral flow, baseflow, and SGD.

Chapter 4, *Assessment of Terrigenous Nutrient Loading to Coastal Ecosystems along a Human Land-Use Gradient, Tutuila, American Samoa*, expands the techniques used in Chapter 3 to four separate watersheds spanning a human-impact gradient, and also incorporates the assessment of macroalgal tissue parameters as a biological indicator of anthropogenic impact in these watersheds. The main objective of this chapter is to provide tools for coastal resource managers to detect or predict which nearshore areas may be at the highest risk of nutrient imbalance.

Chapter 5, *Groundwater Recharge for Tutuila, American Samoa Under Current and Projected Climate as Estimated with SWB2, a Soil Water Balance Model*, presents the development and results of a water budget assessment for Tutuila Island, specifically designed to estimate spatially distributed groundwater recharge. The main objective of this chapter, besides production of a groundwater recharge map, is assessing the effects of future climate change on groundwater resources.

Chapter 6, *Collaborative Groundwater Modeling: Open Source, Cloud-Based, Applied Science at a Small-Island Water Utility Scale*, takes a distinctive approach to groundwater modeling; instead of focusing on model results, this chapter focuses on a vertically-integrated, cloud-based, and process oriented collaborative modeling framework developed cooperatively between our research group and the American Samoa Power Authority. The main objective of this chapter is to present a case study that details the components in this process. These components include weather station and stream gauge installation, water budget modeling, and ongoing groundwater modeling. This case study shows how a collaborative approach can be applied to develop modeling products that have greater longevity and applicability to the needs of resource managers.

1.3 Geographic Setting

1.3.1 Regional Setting

Tutuila, the largest and most populous island in American Samoa, is located in the South Pacific Ocean near the coordinates of 14° 20' S and 170° 40' W (Fig. 1.1). The island has an area of 142 km^2 and a population of 56,000 residents (AS-DOC, 2013). Tutuila is within the South Pacific Convergence Zone, thus there is abundant rainfall year round. This region experiences some seasonality in precipitation with a wet season and a relatively less-wet season. Monthly average precipitation from November to March is roughly twice that of May to August's still significant rainfall amounts. Rainfall varies considerably with location and elevation (Fig. 1.2) and ranges between 1,800 to 5,000 mm/yr (70–200 in./yr) (Daly et al., 2006). Strong tropical storms and hurricanes also influence the region about once every other year, and an average of 25 to 30 significant thunderstorms affecting the island annually (Kennedy et al., 1987).

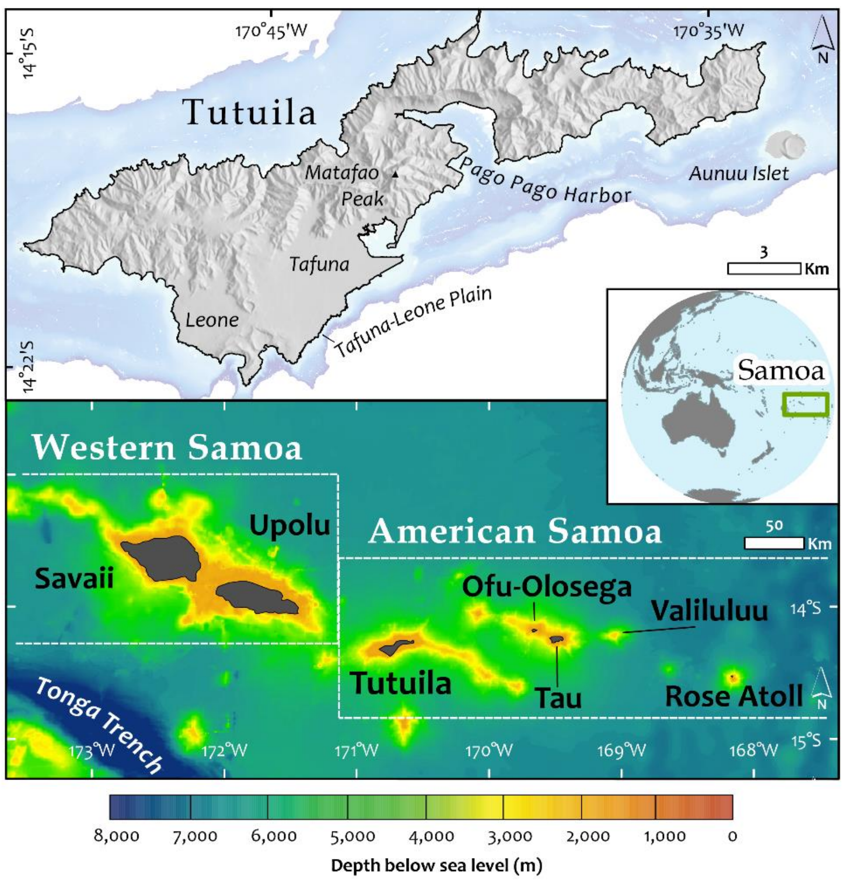

Figure 1.1. Bathymetric map of Samoan archipelago (bottom), and map of Tutuila Island (top). Divisions between Western and American Samoa are drawn to show political jurisdictions and do not constitute actual territorial boundaries. Regional location map shown in middle-right inset.

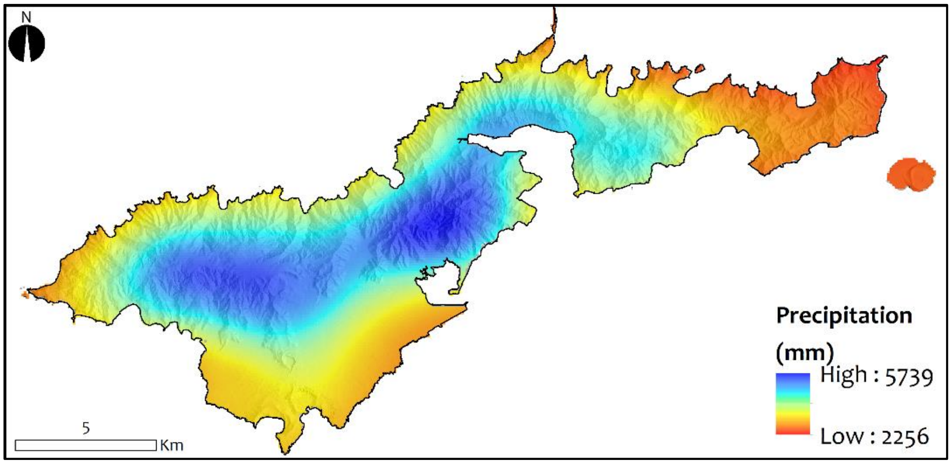

Figure 1.2. Average annual precipitation from climate data recorded from 1971 to 2000 (Daly et al. 2006).

Tutuila can be divided into two primary geographic regions: (1) an east-west trending series of Pleistocene age shield volcanoes that have 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. 1.1). A north-south trending ridge of cinder cones bisects the plain, 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 300 to 400 m above sea level 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%, 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.

1.3.2 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 begins to dip southward into the trench (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 volcanoes 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. 1.1). 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 (McDougall, 1985), and submarine eruptions from Valiluluu are ongoing (Johnson, 1977).

The second phase of Samoan volcanism is 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 shields' southwestern flank, and Aunuu Islet off of the eastern coast. Natland (2003) proposes 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 rejuvenated phase of volcanism is more voluminous on Savaii and Upolu and almost completely covered the original shields, thereby 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 the Savaii undersea 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 1-2 Ma 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. 1.3) were contemporaneously erupted over about a half-million years, starting around 1.5 Ma (Stearns, 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. At the end of the Pleistocene Epoch, the caldera was deeply eroded by surface water, and inundated by the rising sea level, creating the fjord-like feature of Pago Pago Harbor. Stearns (1944) interpreted the nearly vertical north wall of the harbor as direct evidence of this collapse. After the collapse, additional eruptive activity inside of the caldera created a distinctive lithology consisting of low-permeability ponded flows, tuffs, breccias, and trachyte intrusions that is 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 often have slopes of about 15°, which corresponds to the dip of many individual lava flows measured on Tutuila 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 the 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 the youngest. Stearns (1944) also notes that the Taputapu flows appear to overlie the Pago flows in Aasu Valley, and the geomorphology of the Taputapu Shield shows it is younger than the Pago Shield, with less erosional dissection.

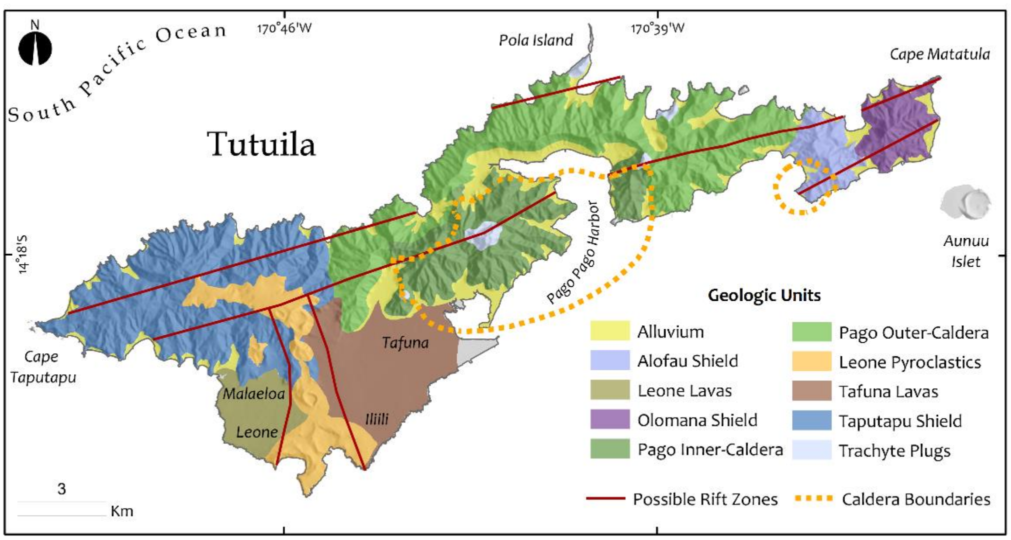

Figure 1.3. Simplified geology of Tutuila showing volcanic shields and inferred volcanic structures such as rift zones and caldera boundaries. Modified from Stearns (1944) and Knight Enterprises Inc. (2014).

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 (Stearns, 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. 1.4). In 2015, a deep borehole was drilled showing two carbonate horizons in the Tafuna-Leone Plain region. The lower horizon ranges from -58 to -74 m below sea level and is thought to be a part of the carbonate bench. Radiocarbon dating shows the middle of the horizon is 10,300 years old. Above this horizon, the Leone Volcanic flows continue up to a depth of -15 m 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 (Reinhard et al., 2019). 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 include 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 (Nunn, 1998) (dates and elevations are approximate).

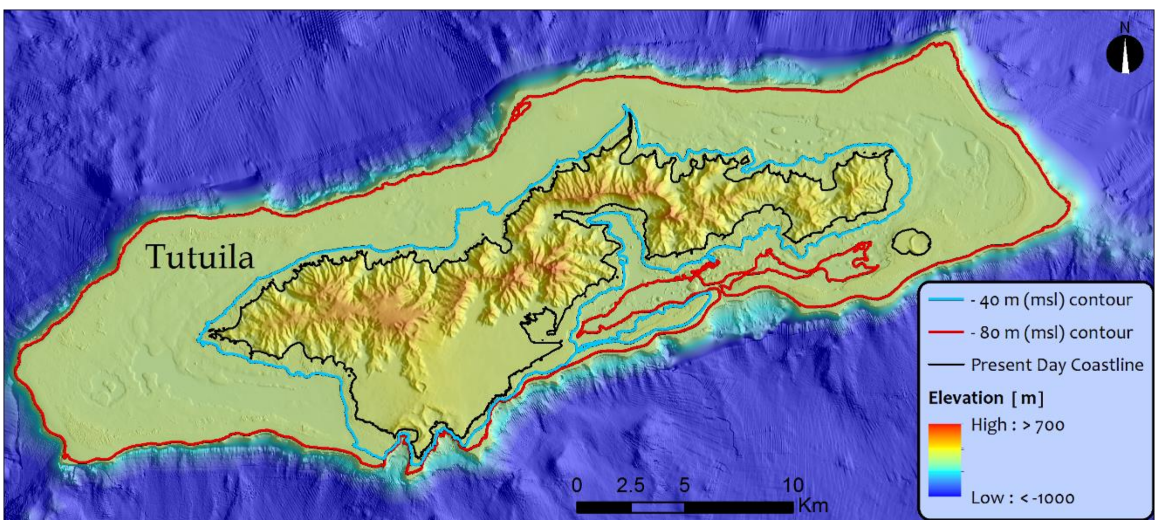

Figure 1.4. Bathymetry surrounding Tutuila (Lim et al. 2010). The sharp drop 3–7 km out from the coastline is interpreted as the former sub-aerial extent of the older shield volcano(s) prior to submergence. The flat area between -80 m and -40 m depth (*red and blue lines*) is the top of a carbonate rich 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 rising to 2 m above the current sea level, which correlates with sea-level highstands within the last 5,000 years (Nunn, 1998). These alluvial wedges provide some of the limited flat land around the island for building villages, and most probably contain at least a small basal-lens aquifer.

1.4.3 Holocene Leone Volcanics

After the last glacial period and until indigenous-historical times, Tutuila's rejuvenated volcanic phase produced eruptions along the southern flank and to the summit of the Taputapu Shield (Natland, 1980; Addison, 2006). Recent unpublished radiocarbon dates from the interbedded carbonate layers under the plain suggest that the rejuvenated phase eruptions began earlier than 10,000 years ago and continued until 4,000 years ago (Reinhard et al., 2019). Additionally, archeological excavation of a widespread red-ash layer throughout the plain indicates that pyroclastic eruptions were still occurring from around 650 to 750 years ago (Addison, 2014). These Holocene age lava flows, ash eruptions, and cinder cones, make up the Leone Volcanic Series.

The Leone Volcanic Series primarily originated from an approximately 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 erupted through the carbonate shelf, and ash deposits and lava deltas flowed down the flank of the older shields (Keating and Bolton, 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 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 Updated Conceptual Hydrogeologic Model of Tutuila, American Samoa

The foundation of any study involving groundwater, whether an analytical approach or a numerical model, inherently relies on basic assumptions of how water behaves in the subsurface. Unlike surface water resources, which can be observed, sampled, and measured with relative freedom, groundwater resources generally remain hidden beneath thick layers of soil and rock, making them difficult and expensive to observe directly. The qualitative or pictorial representation of groundwater properties, aquifer mechanics, and subsurface water flow invoked when one considers unseen subsurface processes is termed a conceptual hydrogeologic model (Betancur et al., 2012). Such a model is constructed by integrating direct or indirect measurements, results of exploration activities, and the general knowledge of aquifer construction and groundwater movement. An effective conceptual model ideally constrains all factors that significantly control groundwater quality or quantity, such as anthropogenic and natural-geochemical influences, underlying geology, surface water characteristics, and climatic variability. While conceptual models are a necessary foundation for building more quantitative analyses, such as numerical models, they also stand as perpetual works in progress, subject to update or revision as information becomes available through new observations or results.

This chapter attempts to compile all currently available hydrologic information with recently acquired subsurface datasets to inform an updated conceptual hydrogeologic model of Tutuila's groundwater and surface water resources. Published reports, recently collected data, and studies from similar basaltic islands were integrated to explain groundwater behavior in Tutuila's already developed basal aquifers, and to update various hypotheses of high level groundwater occurrence where data limitations exist. Additional data are detailed in Appendix A of this dissertation. Although this work attempts to integrate all of Tutuila's pertinent and available hydrologic information, much still remains to be discovered about the island's groundwater and its subsurface structure. Ultimately, this model is intended to support and inform future efforts to quantitatively assess the sustainability of Tutuila's groundwater resources; tasks that include numerical modeling, exploration for new uncontaminated groundwater sources, and decision support tools for water resources management.

1.5.1 General Conceptual Hydrogeologic Model of Basalt Islands

Generally, on basaltic oceanic islands, the primary freshwater resource is contained in a lens-shaped body near sea level within saturated rocks (Tribble, 2008). This basal freshwater lens is supported by the underlying seawater due to the contrasting densities between fresh water and salt water. The transition between fresh and salt water is marked by a zone of brackish water (the transition zone) that can vary in thickness and depth. A secondary freshwater resource described in basaltic island settings is high-level groundwater. It is distinctive from basal-lens groundwater as it is supported by low-permeability features such as dikes, perching layers, or low-conductivity country rock, and may or may not be hydraulically connected to underlying seawater. High-level groundwater has been observed and developed for use on other islands. However, on Tutuila no wells, except three in the village of Aloaufou have definitively tapped high-level groundwater and its occurrence remains generally unconstrained.

Various conceptual models have been proposed for groundwater occurrence on volcanic islands and these generally fall into two categories: Hawaiian models and Canary Islands models (Join et al., 2016) (Fig. 1.5). The Hawaiian Model describes groundwater occurrence in two distinct systems, basal groundwater and high-level groundwater (Lau and Mink, 2006). On the other hand, the Canary Islands model (Custodio, 1989; Custodio and Cabrera, 2008) — alternately described as the 'fully saturated vertically extensive freshwater body' model (Izuka and Gingerich, 2003) — describes a single hydraulically connected basal groundwater body extending from sea level and supported to high elevations by low-conductivity aquifer material. The average hydraulic conductivity distribution in this model is believed to decrease with depth, which is justified by an assumed loss of porosity due to compaction and secondary mineralization, as well as increasing age and weathering.

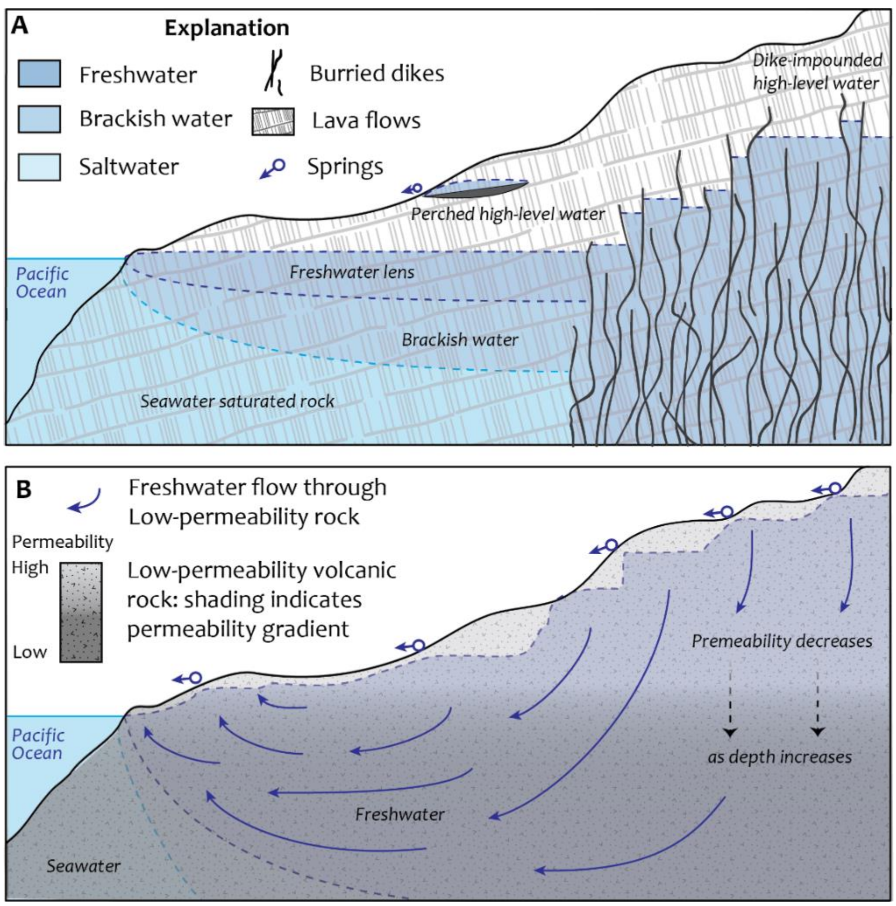

Figure 1.5: Two different conceptual models of groundwater occurrence on basaltic oceanic islands. The Hawaiian model (Lau and Mink, 2006), in *panel A*, consists of two disconnected groundwater systems, high-level and basal. The Canary Island model (Custodio, 1989), *panel B*, implies elevated and basal groundwater are hydraulically connected as a single system contained in low-permeability rock.

1.5.2 Hydrogeologic Units on Tutuila

Neither of the aforementioned conceptual models has been undeniably invoked to describe groundwater occurrence on Tutuila. However, they are not necessarily incompatible. Taken in perspective, a conceptual model is merely a simplification used to inform predictions or parameterization of numerical models. Real world subsurface conditions controlling groundwater movement and storage on Tutuila are heterogeneous and poorly constrained, thus it is possible and even likely, that different regions with distinct geologic histories may be more effectively parameterized on a regional scale by different conceptual models. This emphasizes the importance of interpreting data from different hydrogeologic units on an individual basis, as attempted in this work.

Izuka et al. (2007) delineated more than five hydrogeologic units for Western Tutuila based on what is known of the island's geologic construction (Fig. 1.6). 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 hydrogeologic units. The Leone Volcanics were separated into the more hydraulically 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 hydrogeologic conceptual model of Tutuila. However, new geologic and hydrogeologic data presented in Appendix A may provide evidence for proposed updates to this conceptual model, such as considering each shield in the lower-conductivity unit separately.

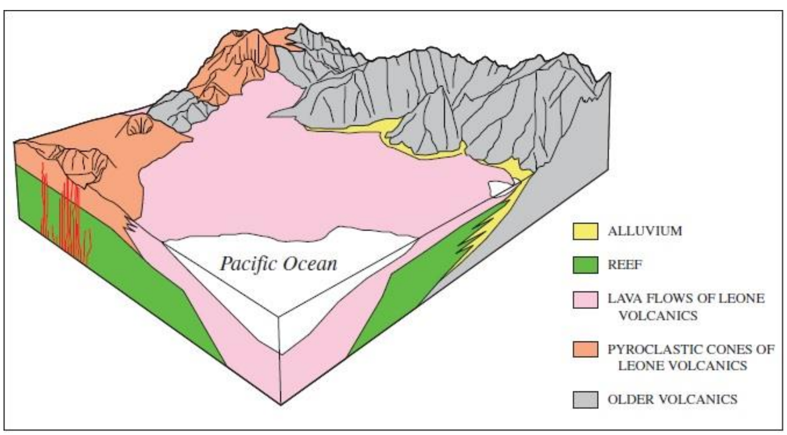

Figure 1.6. Conceptual hydrogeologic model of the Tafuna-Leone Plain region showing distinctive hydrogeologic units. Reprinted from Izuka et al. (2007) with permission.

1.5.3 Groundwater Occurrence in Tutuila's Hydrogeologic Units

1.5.3.1 Holocene Leone Volcanics

The young aquifers of the Tafuna-Leone Plain region are primarily composed of pahoehoe and a'a lava flows with localized interfingerings of ash beds and/or sedimentary carbonate layers. These materials sit above the weathered edifice of the Taputapu shield, though the degree of water movement between the Leone and Taputapu units is unknown. Due to their young age and lack of weathering, the Leone Volcanic aquifers are generally very hydraulically conductive and hold a thin basal lens. A prevalence of fractures, clinker zones, and lava tubes provides a high secondary porosity to the region, making it favorable for groundwater development (Bentley, 1975). However, these features also make the Tafuna-Leone plain susceptible to groundwater contamination (Kennedy et al., 1987). Currently, the 24 wells in the plain region produce about 70% of the island's municipal water (RCWW, 2002). Wells in this area are generally designed to skim the top of the unconfined basal lens that floats (due to its lower density) on salt water within the saturated rock. Because the plain's geologic units are so conductive, the water table in the region is typically about 1 to 3 m above sea level (Izuka, 1999b). The unsaturated zone above the water table is often less than 35 m thick, allowing only minimal travel time for contaminant attenuation. Within the plain there are three subregions, which can be distinguished into different hydrogeologic 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 seen in cores from two recently drilled deep exploratory boreholes (Tables A2 and A3). Visual inspection of the borehole core shows the Leone Series rocks in TGH-1 (on the Leone side of the plain) generally have a higher proportion of volcanoclastics (ash and cinder) than is seen in TGH-3 (on the Tafuna side), though the materials in both boreholes are still predominantly basalts from lava flows.

1.5.3.2 Tafuna Plain

The structure of the Tafuna region has been described by Eyre and Walker (1991) as a lava delta (Walker, 1991) formed as molten rock flowed from sub-areal vents downgradient via long tongues and subsurface tubes. Sub-flow-surface 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; when covered by successive flows it creates heterogeneity and preferential pathways for the movement of the water. When erupting, lava may flow over, around, or through topographic irregularities, which produces a heterogeneous subsurface distribution of less and more permeable zones. It should be noted that the Tafuna aquifer behaves as an unconfined aquifer, and the more permeable sections are probably still interconnected by fractures through the denser sections. The structural complexity of the Tafuna Lava Delta is enhanced by the fact that the lavas rest on the uneven topography of ancient buried ridges, valleys, pinnacles, and sedimentary basins of Taputapu's ancient erosional surface. Despite this heterogeneity, the water table in the Tafuna plain sits fairly uniform at about 1 to 2 m above sea level, and varies during drier or rainier periods.

1.5.3.3 Leone Plain

The Leone side of the plain is similar to the Tafuna side, though it contains more ash and pyroclastic material, blown westward by the southeasterly prevailing winds during explosive eruptions (Izuka et al., 2007). Extensive ash layers are observed in exposures on the Leone coast and in the borehole logs. These layers likely serve to reduce the vertical permeability of the unit, causing portions of the basal-lens to be locally or partially thickened, though no definitive measurements have 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, and the surface water contamination issues reported on the Tafuna Plain appear to be less prevalent on the Leone side (Kennedy et al., 1987). Water levels in the Leone Plain are similar to those on the Tafuna side and rise to about 3 m above sea level in wells near the Taputapu contact.

1.5.3.4 Leone Series Pyroclastics

The north-south trending ridge running down the center of the Tafuna-Leone Plain is comprised of ash and cinder cones. The ridge is considered to be a rift zone emanating from the rejuvenation stage of the Leone Series eruptions. A highly weathered rock outcrop found in a Futiga cinder quarry suggests the rift zone is underlain by at least one relic ridge of Taputapu rocks, mantled by Holocene age pyroclastic deposits and interbedded lava flows. The subsurface structure of the area has not been explored thoroughly, and there is only one well (Well 178) developed within the pyroclastic unit. This heterogeneous unit contains materials that range from highly-permeable unconsolidated cinder to nearly impermeable indurated tuff, which may have 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 pyroclastics 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 higher hydraulic conductivities. Also in the central section of this ridge a shallow valley is found, which may be 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 alludes to the presence of either perched groundwater or a fully saturated subsurface in this area.

1.5.3.5 Malaeimi Valley

Malaeimi Valley is a unique area on Tutuila. Its upper sections are carved from Pago Shield rocks, and its lower section was flooded (or potentially dammed) with basalts from the Tafuna Lava Delta. Currently, the interior of the valley has a flat bottom and is filled with alluvial material. Thus, wells in the valley might be tapping aquifers in lower-conductivity Pleistocene rocks, alluvial fill, or highly-conductive Tafuna lavas depending on their location and depth. Historically, water table elevations were seen to vary spatially and temporally, and large drawdowns in response to pumping were observed in some wells (Eyre and Walker, 1991). Some high water levels were observed to be unstable and declined rapidly when pumped. In general, high drilling water levels in the Upper Malaeimi Wells are found to rapidly drop off further down the valley at wells near the valley mouth. While these observations could help to constrain the subsurface boundaries of the valley's different geologic units, it remains unclear how hydraulically connected these different zones are to each other.

Another interesting feature of Malaeimi Valley is that it receives a significant amount of additional water from the process of mountain front recharge (MFR). Streams flowing off of the flanks of the less permeable Pago Shield rocks quickly infiltrate into the more permeable alluvial valley fill and Leone series lavas at the bottom of the valley and add to the area's total recharge. This additional water increases the thickness of the basal lens in this area, as well as providing additional water supply for the lens downgradient from the MFR zone (Fig. 1.7). The elevated lens thickness in this area may act as a freshwater fence, not only reducing the potential for saltwater upconing in the MFR zone, but also for wells upgradient in the valley.

Although the hydrogeology of Malaeimi Valley is complex, this region has long been recognized as one that contains valuable water resource characteristics; due to the unique geology and relatively high recharge rate. Malaeimi Valley has been recognized as possessing all qualifications needed for designation as a "Special Management Area" under American Samoan Law, and its protection as a special management watershed would be a significant step forward in water resources management on Tutuila (Pedersen Planning Consultants, 2004).

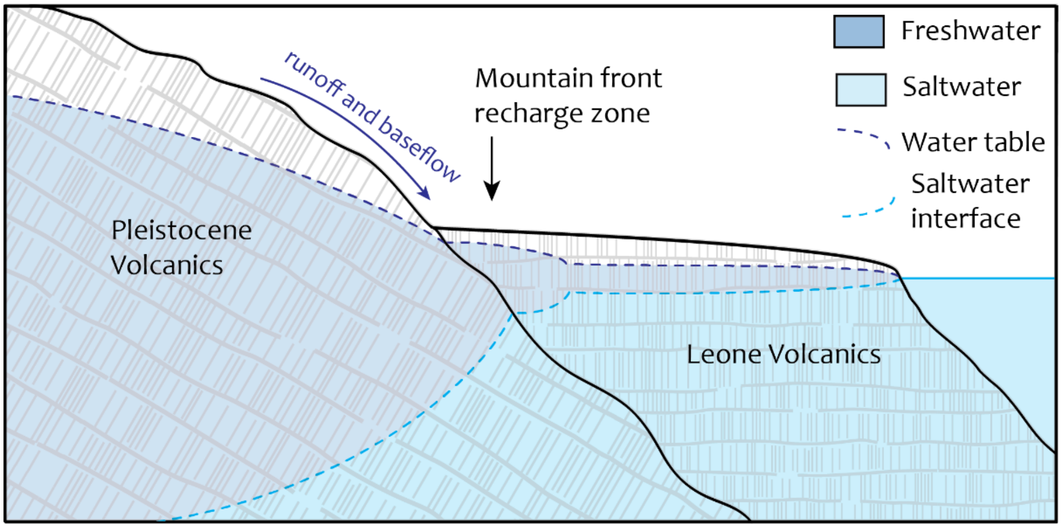

Figure 1.7: Diagram showing possible interaction of the basal lens in the mountain front recharge zone at the margin of the less-permeable Taputapu Shield and the more-permeable Tafuna-Leone Plain.

1.5.3.6 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 2.2). 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 may manifest hydrogeologically as a heterogeneous permeability fabric where variably sized compartments of high permeability rubble or cinders are adjacent to beds or tongues of massive lavas and other low permeability features that act as perching layers or barriers to water movement.

The shields likely contain both high-level and basal groundwater bodies. However, the basal supply probably makes up the majority of the developable groundwater in this unit. 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 be caused by overall low hydraulic conductivities (if a purely basal system was tapped) or by limitations in the aquifer extent. Previous workers have generally classified Tutuila's older shields into a single hydrogeologic unit with uniform properties. However, recent observations are beginning to provide sufficient data to characterize the region into separate hydrogeologic units.

The Pago Shield itself has two distinctive geologic units, the Inner-Caldera and the Outer-Caldera. The Outer-Caldera Unit contains thin and thickly bedded aʻa lava flows, numerous dikes, vitric tuff beds, and potentially buried cinder beds; 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 (Stearns, 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 and Bolton, 1992). In general, the composition and structure of the Outer-Caldera Unit suggests that it has better water transmitting properties than the Inner-Caldera Unit (Shuler et al., 2014). However, the available hydrological data does not show a clear difference in the performance of wells drilled in either unit, which is probably due to local scale heterogeneities.

Measured aquifer parameters and geologic information suggests that the Taputapu Shield may have a greater water development potential and higher average ***K*** values than the island's other shields. This hypothesis is supported by the following:

1. A limited number of recent aquifer tests show specific capacities and ***K*** values that are significantly higher than those measured in the other shields (Table 7).
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. 1.8).

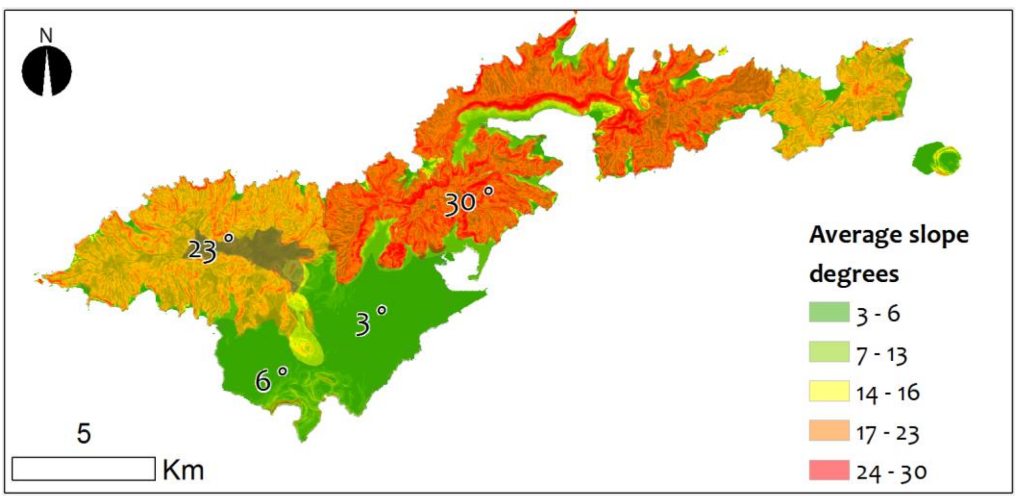

Figure 1.8. Average slope (°) of simplified geologic units. Taputapu shield slope excludes the subdued topography region covered by Holocene Aoloaou cinders (shown in grey).

3. McDougall (1985) hypothesizes that Taputapu and Olomoana are satellite shields of the main Pago Volcano, and therefore should have more high permeability flank lavas and less low permeability caldera related features (e.g., intrusives, ponded lavas, hydrothermal alteration). This is supported by gravity anomalies as measured by Machesky (1965). These show clear maxima (290 mGal) above the Pago Shield (Fig. 1.9), suggesting the Pago unit contains more impermeable intrusive bodies, such as

dike complexes or solidified magma chambers.

4. The inferred dike intensities as measured by Walker and Eyre (1995) and the locations of measured dikes by Stearns (1944) (Fig. 1.9) suggests a greater density of impermeable intrusive bodies in the Pago Shield.

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.

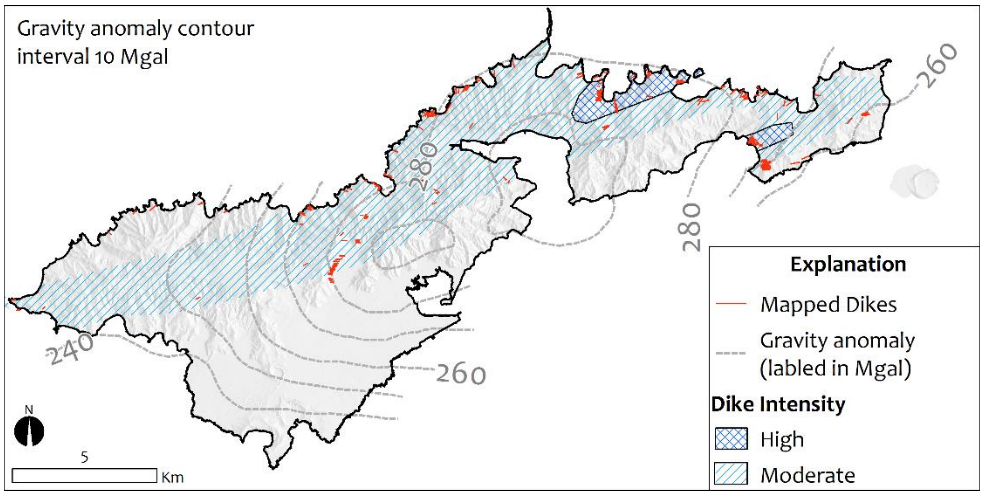

Figure 1.9. Geophysical and surface-mapping data showing inferred density of intrusive structures throughout Tutuila. Heavy cross-hatching indicates dike-complex areas and light hatching shows zones of moderate dike intensity from Walker and Eyre (1995). Bouguer gravity anomaly as measured by Machesky (1965) shows denser material nearer to the Pago Caldera. Also shown are locations of mapped dikes in outcrops by Stearns (1944).

1.5.3.7 Perched or Dike Impounded Aquifer at Aoloau

The 4.1 km^2 summit area at Aoloau is blanketed by layers of high permeability Holocene-age cinders. The permeable nature of this formation is indicated by observations of coarse cinder outcrops, domed topography, and a lack of runoff despite a high rainfall average (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. The extensive nature and unique geologic setting of this high-level aquifer makes it unique on Tutuila. Three wells—two out of production (Wells 127 and 129) and one that is still producing (Well 128)—were drilled into the cinder unit. Well 128 currently produces about 35 to 40 GPM (190 m^3/d). This elevated groundwater 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 (Appendix A, Fig. A10) indicate the potential for shallow perched aquifers of similar occurrence in both the eastern (Aoloau Village) and the western (undeveloped) portions of the cinder cap.

The thickness of the cinder is likely to be variable and dependent on the underlying Taputapu topography and 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 has not been fully explored, it is also possible that the Aoloau aquifer is supported by dike-impounded groundwater from within the underlying shield. Future subsurface exploration of any part of this unit will help to constrain the quality and the quantity of the available resource.

1.5.3.8 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 may 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 approximately 0.005 km^2 to 0.5 km^2. A dozen of the more populated valleys contain one to four municipal wells, drilled to provide water to the village as a satellite system. The aquifers that these systems tap are generally less hydraulically conductive than the Tafuna-Leone Plain aquifers, and their water quality varies greatly between areas. Many of the wells drilled in these units 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 indicate that materials and hydrologic properties are generally different between valleys, though in general, alluvial-valley fill has been inferred to typically have hydraulic conductivities that are higher than the older volcanics, but lower than the Leone Volcancs (Izuka et al., 2007).

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 affect the unprotected groundwater below. Nonetheless, the alluvial fill/Pleistocene volcanic aquifers provide an important source of water to isolated areas, and despite low observed and predicted yields from most of the formations, the demand in many of these small villages is currently fairly low.

1.5.4 Conceptual Model Summary

A two-stage eruptive history with shield-building and rejuvenated phases, compounded with high erosion rates, has made Tutuila's geologic structure complex and heterogeneous. This is seen by examining existing well performance with aquifer tests and water level observations. The presence of high-level water in the island's older shields is irrefutable, due to the presence of perennial streams, but the nature of the impounding structures remains poorly understood. A significant perched aquifer is observed below Aoloau Village, and numerous persistent springs support perennial baseflow throughout the island. Nonetheless, the type and locations of groundwater impounding structures remains unknown. These structures could be dikes, perching layers, low-connectivity matrix rock, or any combination of the above.

In general, the hydrologic connectivity between adjacent zones of variable permeability may be the primary controlling factor influencing the water resources availability of any given area. Conditions found during well drilling are likely to be site specific, in which case it will be difficult to predict the regional connectivity of any given location without extensive pump testing. In general, groundwater behavior in the Tafuna-Leone Plain region suggests that the connectivity between water bearing pockets is high. Therefore, the overall hydraulic conductivity of the region is probably controlled by the high-permeability zones resulting in a thin unconfined basal-lens. In the Pago, Olomana, and Alofau shields, connectivity between permeable zones is more variable but generally lower, which results in drilling and production head levels that vary greatly as well. Geologic and hydrologic evidence suggests the Taputapu Shield is more likely to display more favorable producing conditions than the Pago Shield. Nonetheless, the Taputapu region is large and heterogeneous, and the productivity of wells is predicted to vary greatly with site-specific conditions.

Long-term pump tests after drilling and continued collection of high-resolution water level data during production would be useful to assess the degree of connectivity between more permeable portions of the aquifers. However, interpretation of this type of data, which is always more limited than would be preferred, can be difficult and may yield non-unique solutions. If it is feasible for multiple exploratory wells to be planned and tested, the likelihood of finding a zone that sustainably produces a satisfactory volume of water will be increased. Continued collection of hydrologic data remains important for increasing the knowledge base that will ultimately contribute to further revisions of this conceptual hydrogeologic model.

References for Chapter 1 are included in Appendix B: References section.