A Hydrogeologic Survey of Santa Rita Spring, Guam: Engineering and Design Recommendations for Rehabilitation

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WERI

WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

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ABSTRACT

The Santa Rita Spring discharges fresh water from a hillside above the village of Santa Rita (pop. 7,500) in southwest Guam, and contributes to its municipal water system. It is a perennial karst spring that forms at the contact between a Miocene limestone aquifer capping Eocene-Oligocene volcaniclastic strata on the cuesta that forms the southwest edge of the island. The spring forms within a 30-ft-thick inter-bedded, depostionally-transitional unit mapped as the basal member of the overlying limestone. An impoundment was built by the U.S. Navy in 1929 and is still in service, producing up to 500 gpm. However, the persistence of wet ground, puddles, and piping around the structure, especially during wet weather, indicates the impoundment captures only part of the natural discharge. Past attempts to intercept the uncaptured water by modifying the existing structure were unsuccessful. This project undertook a comprehensive hydrogeological study of the spring and its watershed to determine the distribution of the discharge from within the complex contact, evaluate the spring's full potential capacity and responsiveness to recharge, and recommend economical options for capturing the entire flow. A 3-dimensional model of the spring's watershed was developed using previous electromagnetic survey data and current geospatial analysis tools. Watershed rainfall and spring discharge measurements showed the spring's potential capacity to be 250 to 1,200 gpm. Eleven boreholes were drilled at the site, from 20 to 90 feet deep. Cuttings were collected to characterize stratigraphy, and piezometers were installed to characterize site hydraulics from pump and slug tests of the impoundment. The new understanding of site hydrogeology provides the basis for design recommendations that will efficiently capture the entire capacity of the spring.

This report is derived from Paul Bourke's professional thesis, *A Hydrogeological Survey of the Santa Rita Spring, Guam: Engineering and Design Recommendations for Rehabilitation*, for which he was awarded a Master of Science degree in Environmental Science by the University of Guam, May 2020.

Keywords: ***Karst, hydrogeologic, spring, watershed, modeling, engineering hydrology***

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Glossary

Definitions derived from Freeze and Cherry (1979); Wilson and Moore (1998); Neuendorf et al. (2005); Merriam-Webster website).

Aquiclude: A geologic unit that is incapable of transmitting economically significant quantities of water under ordinary hydraulic gradients.

Aquifer: A saturated permeable geologic unit that can transmit economically significant quantities of water under ordinary hydraulic gradients.

Bung: A stopper made of wood or rubber used to prevent fluid flowing through a pipe.

Collection Box or Spring Box: A box made of concrete or other material approved to be in contact with potable water, which collects spring water. It may be sealed and buried, or it may extend above grade.

Collection System: A system typically including a collector pipe, a spring box, and a cutoff wall used to capture spring flow.

Collector Pipe: A perforated or slotted pipe that collects spring water.

Cutoff Wall: A well-tamped, wing-shaped wall of impervious material that shunts spring water into the collection system.

Diversion Ditch: A ditch above the spring box that diverts surface flow around the spring facility.

Evapotranspiration: The sum of evaporation and plant transpiration from the land or water surface to the atmosphere.

French drain: An underground passageway for water removal typically through the interstices among stones placed loosely in a trench.

GPM: Gallons per minute.

GWA: Guam Waterworks Authority.

Hydraulic Conductivity: The volume of water at the existing kinematic viscosity that will move in a porous medium in unit time under a hydraulic gradient through a unit area measured at right angles to the direction of flow. In contrast to permeability, it is a function of the properties of the liquid as well as of the porous medium.

Hydrograph: A graph that shows some property of groundwater or surface water as a function of time.

MGD: Millions of gallons per day.

NAVFACMAR: Naval Engineering Facilities Command Marianas.

NCE: Navy Corps of Engineers.

Ordinary Flow: Spring discharge induced by rainfall other than from tropical cyclones.

Peak Flow: Spring discharge induced by tropical cyclones.

Perennial Spring: A spring which flows continuously all year.

Santa Rita Facility: The system that captures, collects, stores, and supplies water from the Santa Rita Spring to the GWA system.

SRS: Santa Rita Spring

Stratigraphy: The arrangement of strata, esp. as to geographic position and chronologic order of sequence.

Transmissivity: The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer. It is a function of properties of the liquid, the porous media, and the thickness of the aquifer, and is defined as aquifer thickness times aquifer hydraulic conductivity.

USGS: United States Geological Survey.

Water Budget: An accounting of the inflow to, outflow from, and storage in, a drainage basin, aquifer, soil zone, lake, reservoir, or other hydrologic unit.

Watershed: A region or area bounded peripherally by a divide, and draining ultimately to a particular watercourse or body of water.

Scope of Work

1) Existing facility evaluation: a) Evaluate the flow of spring water currently being captured at the Santa Rita Spring (SRS) site. b) Estimate the amount of spring water being delivered to the site by the natural system.
2) Watershed evaluation: Delineate the watershed area of the SRS, calculate its mean annual water budget, and characterize the seasonal (wet-season-to-dry-season) and episodic (i.e., storm-driven) variations in flows delivered to the SRS site by the natural system.
3) New impoundment collector design concept: Propose a design concept that will maximize the amount of water collected at the SRS site.
4) Additional considerations: Identify nearby sites with additional potential for development.

For original proposal documentation see appendix A

Executive Summary

PURPOSE: This technical memorandum describes Santa Rita Spring (SRS) hydrology and hydrogeology, as investigated from June 2016 through May 2018, and recommends engineering design concepts to maximize production capacity (Figure ES.1), (See Section 5, page 46).

HISTORY OF THE SPRING: The current SRS facility was built by the Navy in 1929. It has been occasionally renovated and modified, most recently in 2011 and 2019 (See Section 1.1, page 1).

CONFIGURATION OF THE CURRENT FACILITY: Current collection capacity is limited to the portion of spring flow captured by a single 9-foot-long perforated 8-inch-diameter pipe laid perpendicular to the hillslope and in only partial contact with the zone of discharge (Figure ES-1A). Water collected by the pipe is stored in a 47,500-gallon compartment, then transferred to a second 47,500-gallon compartment where it is mixed with imported, chlorinated water from the Navy's Fena water system, and then piped into the GWA distribution system (See Section 1.2, page 1).

PRODUCTION FROM CURRENT SYSTEM: Reported production of the existing facility ranges from an annual minimum of 80 gpm[1] during dry seasons to an annual maximum of 500 gpm during wet seasons.[2] At least 80 gpm of these volumes is believed to be seeping up through the floor of the first storage compartment. Subtracting this minimum insurgence of 80 gpm from the reported maximum discharge of 500 gpm leaves a maximum of 420 gpm that can be attributed to the 8-inch-diameter collector pipe at maximum production. In addition to 80 gpm seeping into the first storage compartment, an additional 80 gpm may be seeping into the second compartment. Another 60 gpm is estimated to be flowing around the facility and another 30 gpm into the booster pump wet well. Thus, the minimum flow delivered to the site by the natural spring, only part of which is captured by the current facility, is estimated to be 250 gpm (0.3 MGD), (See Section 1.2, page 4).

POTENTIAL CAPACITY: The estimated daily mean recharge of the spring's watershed is 1.5 MGD (1050 gpm), based on: 1) 0.62 sq. mi. of watershed catchment area; 2) evidence that recharge is mostly confined to the wet season, for which the 10-yr (2008-2018) watershed annual average rainfall[3] is 86 in, and 3) estimated wet-season evapotranspiration rate of 40%[4]. Assuming that at least 70% of the 1050 gpm average recharge is reaching the Santa Rita Spring site, the potential mean capacity should be about 735 gpm (1 MGD). The 420 gpm maximum captured by the current spring collector pipe is thus about 60% of the ordinary capacity of the site. Peak discharges, *i.e.*, responses to major storms, could be much higher, but are not likely to be much higher than 1220 gpm (1.7 MGD), (See Section 2.4.2, page 16).

DESIGN CONCEPT FOR OPTIMIZED SPRING IMPOUNDMENT: The design concept is based on an annual mean discharge of 735 gpm (1 MGD), with flow varying from a low of 250 gpm (0.2 MGD) to a maximum of 1220 gpm (1.7 MGD). (See Section 4, page 40.)

We recommend a two-phase design approach:

- Phase 1(Figure ES-1B): Collection System Improvement—Cutoff Wall and French Drain
  - A cutoff wall spanning the breadth of the site with its foundation in the aquiclude layer.
  - A French drain placed at the bottom of the wall flush with the water-bearing horizon of the aquifer designed to collect and deliver up to 1220 gpm to the spring box by gravity flow.
- Phase 2(Figure ES-1C): Spring Box Construction
  - A new spring box set deep enough to preclude backpressure on the spring flow. The water captured in the spring box is pumped up and into the existing SRS holding tanks.

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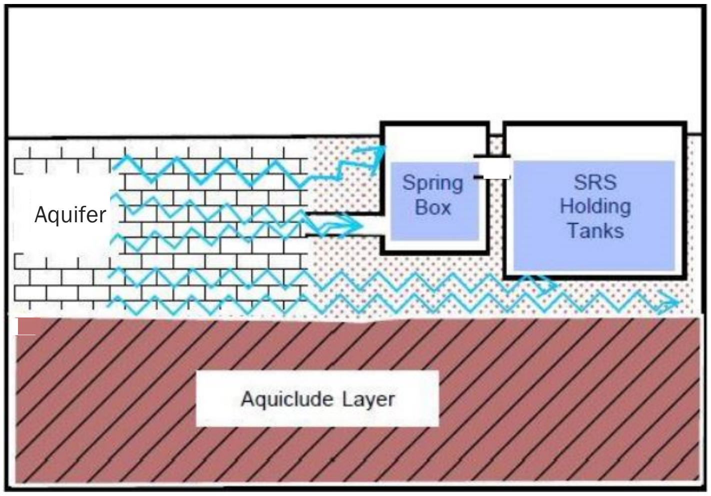
[1] GWA reported minimum, stated in the Power Point presentation given to WERI by GWA April 23, 2015

[2] The maximum discharge rate of 500 gpm was recorded by GWA on 29 November 2019, after 9.21 inches of rain fell within a three-day period (NOAA data). GWA reported maximum, stated in an email from Clint Huntington 11/29/19.

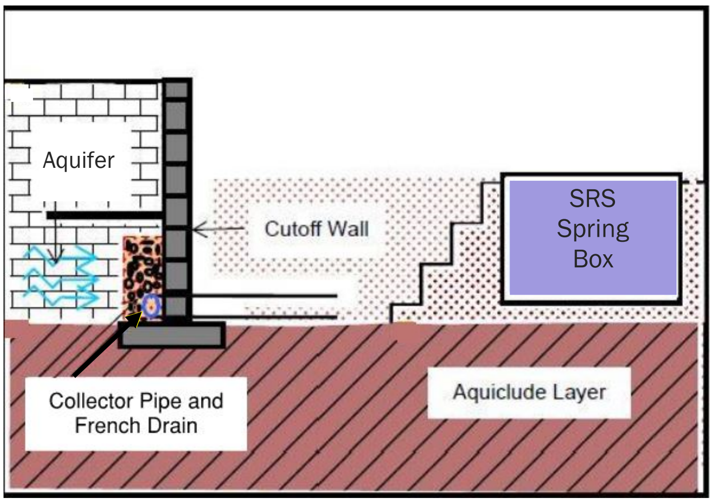
[3] Average annual precipitation 2008 -2018 for the southern highlands of Guam is 110 in, (USGS Fena Reservoir Pump Station Gauge).

[4] Johnson, A., 2012, A water-budget model and estimates of groundwater recharge for Guam.



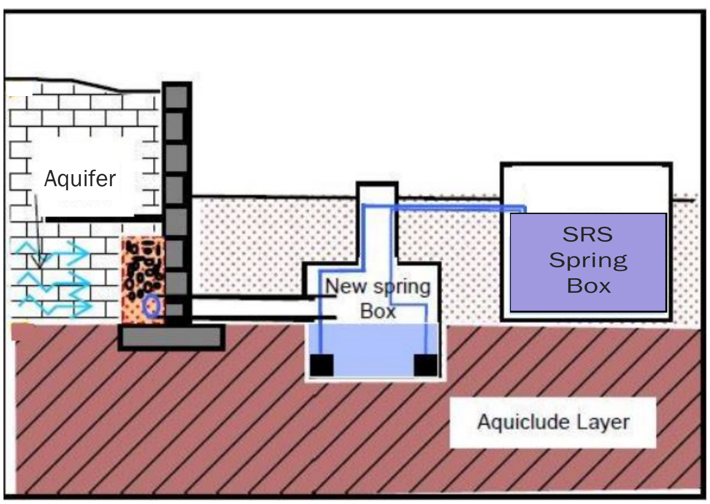
A) Current Facility

1) Captures only part of spring flow.
2) Current elevation of spring box puts back pressure on flow.
3) Water escapes around holding tanks.



B) Improvement Phase 1: Cutoff Wall & French Drain

1) Base of cutoff wall set into aquiclude.
2) Captures all of natural flow.



C) Improvement Phase 2: Lowered Spring Box

1) Spring box set below level of collector pipe eliminates backpressure on spring discharge.
2) Water captured in new spring box is pumped up into existing SRS facility.

Figure ES.1. Schematic of recommended design concepts and phases of construction for maximizing capacity and efficiency for the Santa Rita Spring impoundment, (Diagrams not to scale).

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Section 1: Existing Santa Rita Spring Facility

This section describes the configuration and performance of the existing Santa Rita Spring (SRS) facility.

1.1 Santa Rita Spring History

The Santa Rita Spring (Figures 1.1 and 1.2) discharges freshwater from a hillside above the village of Santa Rita, in southwest Guam (see map in Appendix B). The spring has supplied people living in the Santa Rita area with freshwater for as long as Guam has been inhabited. Nearby archeological excavations to the south and the east of the current SRS facility show evidence of Pre-latte Period (400 to 1000 AD) human occupation (Allen, 2011).

The SRS facility dates from 1929 (Figure 1.3), when the US Navy Corps of Engineers (NCE) built a concrete impoundment and reservoir to capture and store spring discharge. Originally called the Agat Reservoir, the facility provided water to the nearby settlements of Sumay and Old Agat. After World War II, the residents of Sumay were relocated from the area of the newly formed Navy Base on Apra Harbor and the Orote Peninsula, to the newly created village of Santa Rita (Allen, 2011). To our knowledge, the SRS facility has been in continuous service since 1929, though it has occasionally been renovated or modified.

1.2 Current Facility Hydraulics

With the current configuration (Figures 1.4, 1.5, and 1.6), a portion of the water springing from the hillside on the southwestern side of the site is collected by a 9-foot-long, perforated 8-inch-diameter PVC pipe (Figure 1.7, and Section 1.2.1) running from the spring box back into the hillside, with the open end buried about 8 feet beneath the surface, and abutted by limestone cobbles (Figure 1.8). Collection capacity is thus limited to the flow that can be accommodated by this single 8-inch diameter pipe in this limited contact with the natural spring discharge. Water collected by the pipe is impounded in a 1,000-gallon spring box (Figures 1.5 and 1.6), from which it is exported through a filtered pipe into a 47,500-gallon storage compartment, Compartment 1 (Figure 1.9). Upon filling Compartment 1, the spring water cascades across an internal weir (Figure 1.10), into a second 47,500-gallon compartment, Compartment 2 (Figures 1.5 and 1.6) where it mixes with imported, chlorinated water from the Navy's Fena water system. The mixed water is then injected in the municipal water distribution system from the booster pump station.

Figure 1.1. Santa Rita Spring facility, looking northeast, 27 Dec 2019.

Figure 1.2. Aerial view of the current Santa Rita Spring site, 10 May 2018.

Figure 1.3. Plaque on the southern-facing wall to commemorate its construction. The encryption reads: "Agat Reservoir 1929, Captain Shapley USN Governor, Lt. E. D. Graffin CEC USN public works officer."

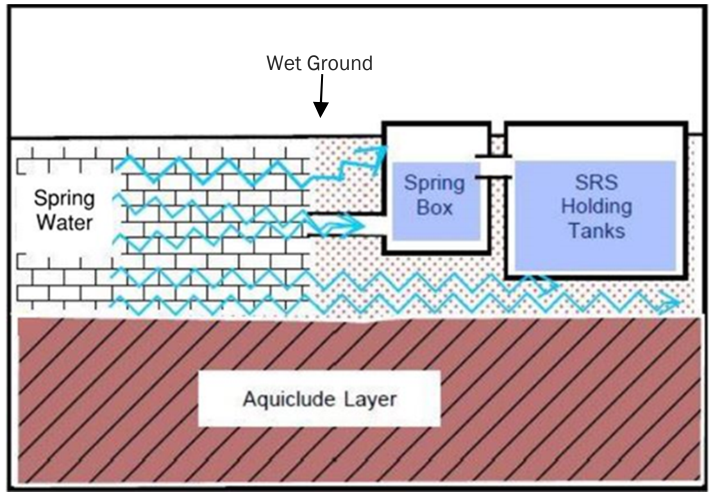

Figure 1.4. Current facility schematic diagram (not to scale).

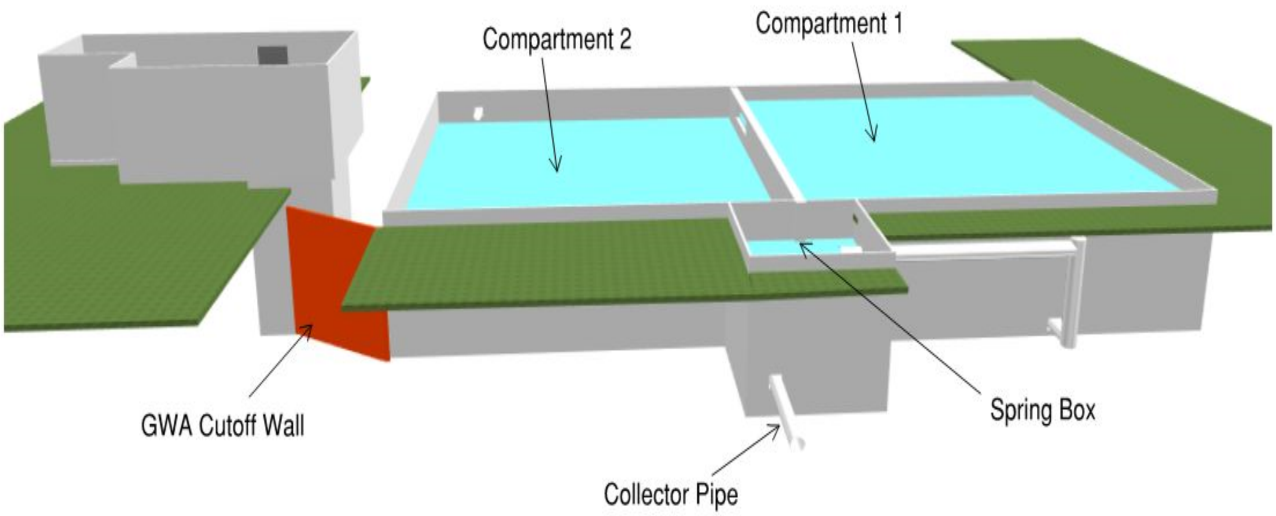

Figure 1.5. Current configuration of the Santa Rita Spring facility.

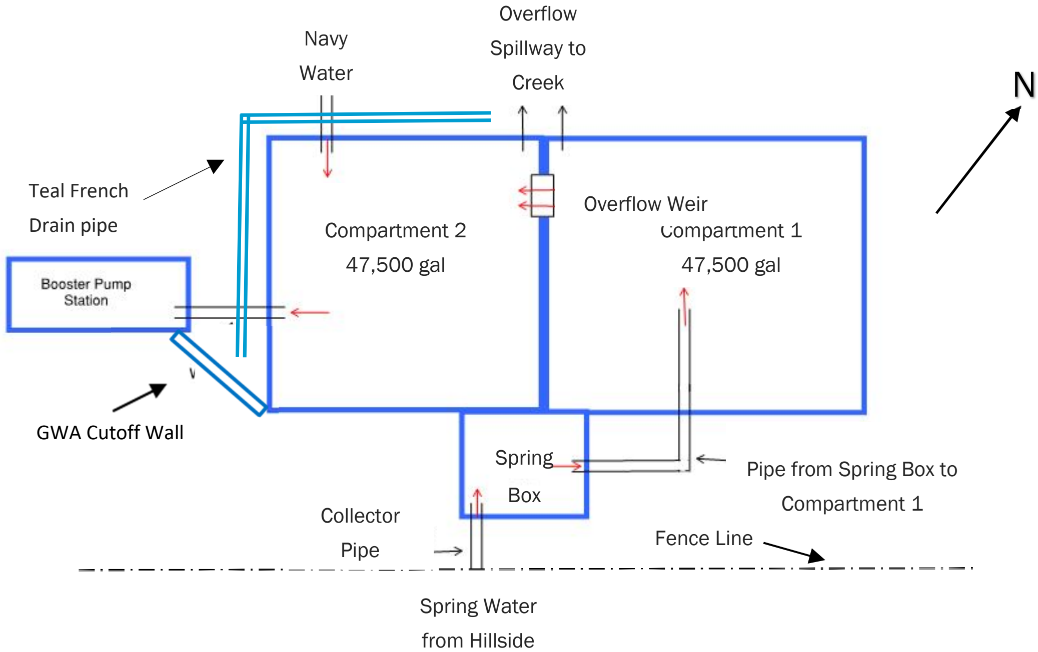

Figure 1.6. Water-flow schematic of the current Santa Rita Spring facility (plan view, not to scale).

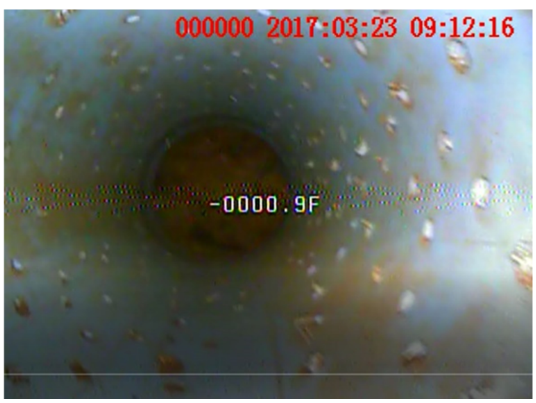

Figure 1.7. Perforations on PVC collector pipe.

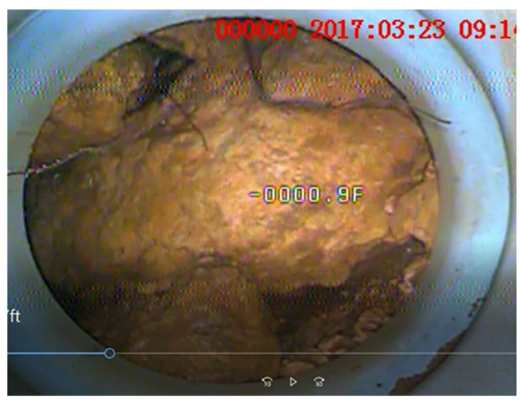

Figure 1.8. Spring collector pipe terminates against limestone cobbles.

Figure 1.9. Spring water in Compartment 1, Santa Rita Spring.

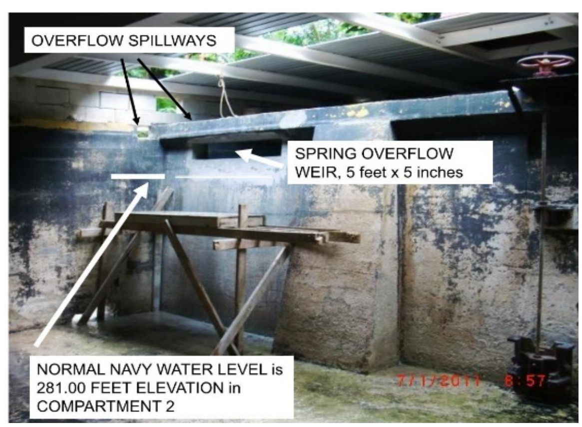

Figure 1.10. Weir between compartments 1 and 2. (GWA picture and measurements.)

Production from the current facility: Spring production is measured by a Hach SC200 Ultrasonic Flow Meter ® from the flow of the spring water from Compartment 1 over the weir into Compartment 2 (Figure 1.10), rather than from flow though the collector pipe. Production measured at the weir is reported to range from an annual minimum of 80 gpm during dry seasons to an annual maximum of 500 gpm during wet seasons (see Appendix C). Flow at the weir could be assumed to represent what is captured by the 8-inch diameter collector pipe were it not that during minimum-flow (80 gpm) conditions, the water level inside the spring box has been observed to stand *below* the level of the outlet pipe that carries water out of the spring box and into Compartment 1. This indicates that even when there is *no* flow from the spring box into Compartment 1, at least 80 gpm continues to flow *out* of Compartment 1 via the weir. With no flow coming from the spring box, the 80-gpm minimum flow out of Compartment 1 must therefore originate *inside* Compartment 1. Significantly, it has been documented (Figure 1.11) that spring water flows *up* into Compartment 1 through cracks in the floor. GWA attempted to seal the cracks in 2011.

It is thus conceivable that the 80 gpm of minimum flow recorded at the weir is entering Compartment 1 through its floor. Subtracting this minimum insurgence of 80 gpm from the reported maximum flow over the weir of 500 gpm thus leaves a maximum contribution of 420 gpm that can be attributed to the 8-inch-diameter collector pipe.

Figure 1.11. Spring water rising up through the floor of compartment 1 during 2011 GWA upgrade work. Photograph provided by GWA.

1.2.1 Collector Pipe Camera Survey

To determine the condition, length, and configuration of the existing SRS collector pipe, we adapted and inserted a Geo-Vision® borehole camera into the collector pipe (Figure 1.5and 1.7). The survey revealed that the current SRS collector pipe, which was installed by GWA during a previous rehabilitation effort, is a 9-foot-long, 8-inch-diameter perforated PVC pipe (Figure 1.7).

The collector pipe terminates 9 feet from the spring box against cobble-sized limestone fragments (Figure 1.8). Broken shards of a previous terracotta collector pipe were seen lodged by the mouth of the existing PVC collector pipe. The end of the pipe lies just beyond the current fence location, approximately 40 ft short of the limestone outcrop on the southeastern side of the site. Flow through the pipe is evident in the video footage; particles of debris can be seen transiting rapidly through the video frames. We could also see inflow coming from the joint between the collector pipe and the wall of the collection box.

1.2.2 Overflow Springs at the Santa Rita Spring Site

On 23 October 2017, before drilling began that day, and following a 22-day period of substantial rainfall (17.79 inches of rain recorded between 01 to 23 October 2017), we discovered water rising from the ground around the SRS collection box wall (Figure 1.12) and outside the fence line. Using hand tools, we tracked the surface water to two sources. We excavated these sources, exposing two overflow springs in the limestone (Figure 1.13).

Figure 1.12. Water rising to the surface up along the wall of the spring box, above the spring collector pipe.

Figure 1.13. Overflow springs (a) Natural overflow conduits excavated outside of the southeastern fence, and (b) the V-notch weir installed to measure the flow rate.

We constructed a V-notch weir and placed it in the largest overflow spring (Figure 1.13b). A flow rate of 60 gpm was measured from this spring on 30 October 2017, one week after the discharge began. These overflow springs continued to flow until 20 November 2017, 28 days after their discovery. The discovery of the overflow springs, the relatively young geologic age of the Alifan Limestone, and the multiple conduits observed at a representative exposure of the SRS geology (see Section 3), support the hypothesis that there are several small distributed conduits, as opposed to one large conduit, discharging water at the SRS site.

1.2.3 Field Investigation of the Water Discharging behind the SRS Site

GWA has long been aware of water escaping around the catchment system at the SRS site, and previous efforts have been made to capture some of this escaping water. In 2011, a cutoff wall was constructed between Compartment 2 and the booster pump house at the site (Figures 1.5, 1.6, and 1.14) in the hope that this wall would retain the spring flow for capture by the collector pipe by blocking water escaping around the holding tanks. An 8-inch-diameter teal pipe had previously been installed to act as a French drain to direct water around the base of the SRS structure (Figures 1.6 and 1.14). During the 2011 facility upgrade work, a collar with a stopper was placed on the end of this teal pipe where it discharged into the spillway (Figure 1.15). By preventing the flow discharging from the teal pipe it was hoped that the water could be redirected with the help of the newly constructed cutoff wall between the southwestern corner of Compartment 2 and south-eastern corner of the booster pump station building, towards the collector pipe. The collar succeeded in preventing the water discharging from the end of the teal pipe temporarily. However, the water found a new path, channeled around the pipe, and continued to discharge into the spillway (Figure 1.15). We installed a temporary weir to quantify the discharge rate of this flow. Dry season discharge was estimated to be between 40 to 60 gpm.

Figure 1.14. Construction of the cutoff wall between Compartment 2 and the booster pump building, 2011. The teal pipe can be seen at the base of the excavation (GWA picture).

Figure 1.15. Spring water discharging from the teal pipe before flowing into the natural creek on the western downslope side of the SRS site.

To rule out that this water discharging around the teal pipe was coming from a leak in the Navy supply line to Compartment 2, we tested the water for chlorine. (The water supplied by the U.S. Navy arrives treated with chlorine, which is added at the Fena Filtration Plant). The groundwater from the spring is chlorine-free. Using a Thermo Scientific AQ3070 Free and Total Chlorine Colorimeter, water samples from the spring box, Navy inlet pipe, the teal pipe, and the water surrounding the teal pipe were tested for chlorine. Results from Table 1-1 clearly show the absence of chlorine in the water discharging around the teal pipe. This water is apparently spring water.

Table 1-1. Chlorine concentration of water samples

Location	Chlorine Concentrations (mg/l)
Navy inlet pipe	2.80 2.79
Spring box	0.00 0.00
Inside teal pipe	0.00 0.00
Around the teal pipe	0.00 0.00

Section 2: Santa Rita Spring Hydrology

This section describes the methods used to delineate the watershed that feeds the Santa Rita Spring, evaluate the water budgets for the watershed and the spring, and obtain a rainfall- discharge hydrograph for the spring.

2.1 Field Investigation of the Watershed Area

At the beginning of this project, from May to June 2016, we conducted three field traverses to document the terrain, vegetation, and relevant geologic features of the SRS watershed (Figure 2.1). We examined exposures of Alifan Limestone outcrops and quarry cuts we found in the field (Figure 2.1a). The limestone terrain behind the SRS is covered by a thick jungle canopy of trees and shrubs (Figure 2.1b). Above the old Alifan Quarry, the terrain is covered with limestone karst pinnacles, and the vegetation is characteristic of a disturbed limestone forest (Figure 2.1c).

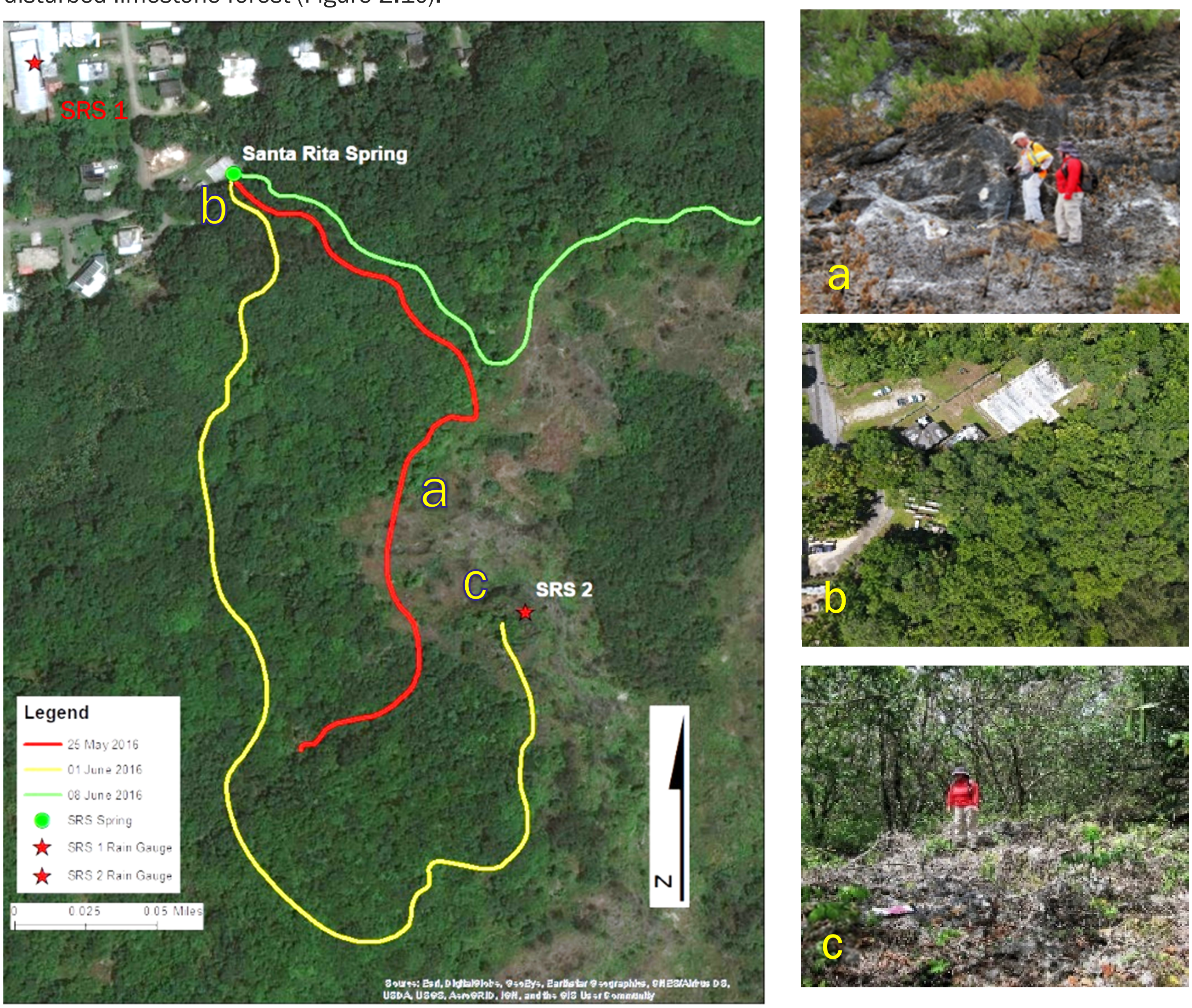

Figure 2.1. Field traverses on 25th May, 1st June and 8th of June 2016, a) Exposure of the Alifan Limestone in a cut within the old Alifan Quarry behind the SRS. b) Aerial picture of the jungle canopy behind the SRS site. c) Karst pinnacles and limestone forest

vegetation on the hill to the east of the SRS site. Watershed rain gauge locations are northwest and downgradient of the SRS (SRS1) and southeast and upgradient (SRS 2).

During our first traverse, on 25 May 2016, we explored the geology and the terrain directly upslope behind the SRS site and on the ridge. Approximately 800 feet behind the site a fire had recently burned the vegetation, exposing the limestone walls of the old Navy quarry (Figure 2.1a). On the second traverse, 01 June 2016, we explored the region to the southeast of the SRS and up to the summit of the hill behind the site. We installed a rain gauge (SRS 2) at the top of this hill (Figures 2.1 and 2.2). On the third traverse, 08 June 2016, we examined the area to the east of the SRS to examine the contact between the limestone aquifer and the underlying volcanic aquiclude, and the terrain up to the fence line of the Naval Magazine. The surface of the Alifan aquifer is dominated by rugged pitted terrain (karrenfeld) which is both highly porous and very rough (Figure 2.2). No streams form on the terrain, and there is no surface runoff even during the heaviest of storms.

Figure 2.2. The rugged karrenfeld terrain on the hilltop to the southeast of the SRS site, looking west towards Orote peninsula. Rain gauge SRS 2 is in the center of the photo.

2.2 Delineation of the Santa Rita Spring Watershed Area

Delineating a karst spring's watershed (i.e., the terrain that recharges the limestone aquifer that feeds the spring) presents special challenges (Bonacci, 1993). The conventional approach, for non-karst watersheds, is to delineate the watershed from the hydrologic divides formed by the surface topography using contour maps, aerial photos, or LIDAR imagery. Karst watersheds, in contrast, must be delineated by hydrologic divides in the underlying non-soluble, hydrologically tight basement substrates. For the SRS, the underlying aquiclude is the 30 ft thick Talisay Member, of the Alifian Limestone and the underlying volcanic Alutom Formation which comprises the basement beneath the limestone bedrock. The limestone Alifian cap is draped on the original topography of the Alutom Formation and grades downward into it (Section 3 and Appendix B). Fortunately, basement topographic data were available for the SRS watershed area because the USGS conducted a geophysical survey in the mid-1980s to determine the thickness of the Alifan Limestone that caps the Southern Mountain ridge from Mount Alifan to Mount Lamlam (Kauahikaua, 1985). Figure 2.3 shows their findings. Using the data from the USGS survey and LiDAR data of the surface topography, we built a 3D model of the Alifan Limestone cap (Figure 2.4). From this model, we created the digital elevation model (DEM) of the basement aquiclude topography using Arc Scene® 10.4 (Figure 2.5). The model in Figure 2.5 shows the topography of the aquifer-aquiclude contact that forms the subterranean watershed for the SRS. Note that the conventional surface watershed that would be associated with the SRS, enclosed by the dashed line, contains only 0.19 sq. mi., whereas the actual watershed formed by the aquiclude surface is three times larger, 0.62 sq. mi. (Table 2-1). This watershed area is used in Section 2.4 to calculate the water budget for the SRS watershed.

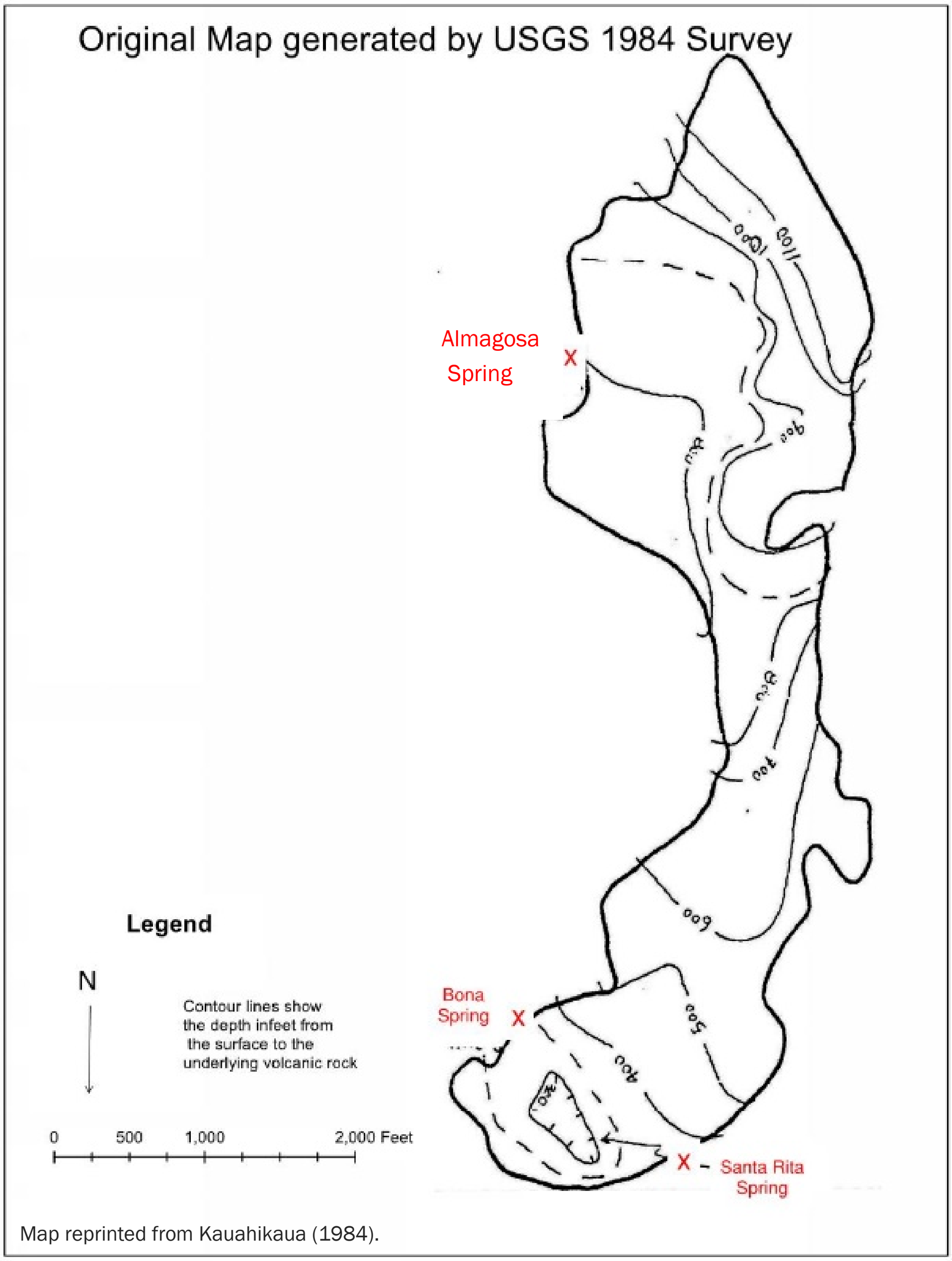

Figure 2.3. Map (looking south) from the USGS electromagnetic survey of the Alifan Limestone cap (Kauahikaua et al, (1985) showing the depths from the surface to the underlying volcanic basement rock. Between January and April 1984, measurements were taken every 300 ft. along the cap using a Max/Min II loop-loop system in a horizontal planar mode at 600 ft. between loops. The SRS, Bonya Spring and Almagosa Spring, are approximately marked to show known discharging sites around the base of the Alifan Limestone cap.

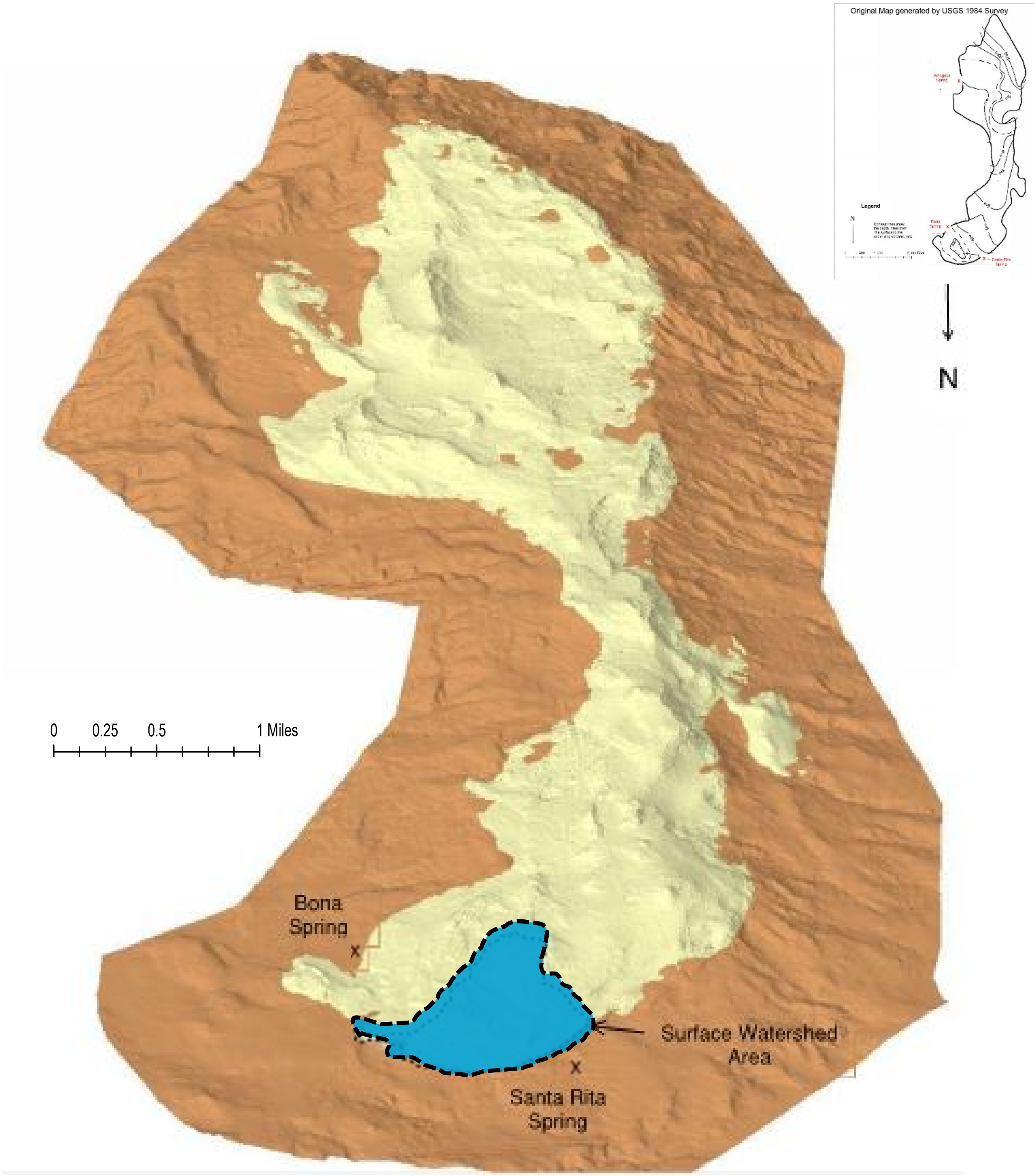

Figure 2.4. 3D model (looking south) of the Alifan Limestone cap (light yellow) that forms the ridge on this part of the Southern Mountains of Guam. Dashed blue area would be the size of the SRS watershed using surface topography.

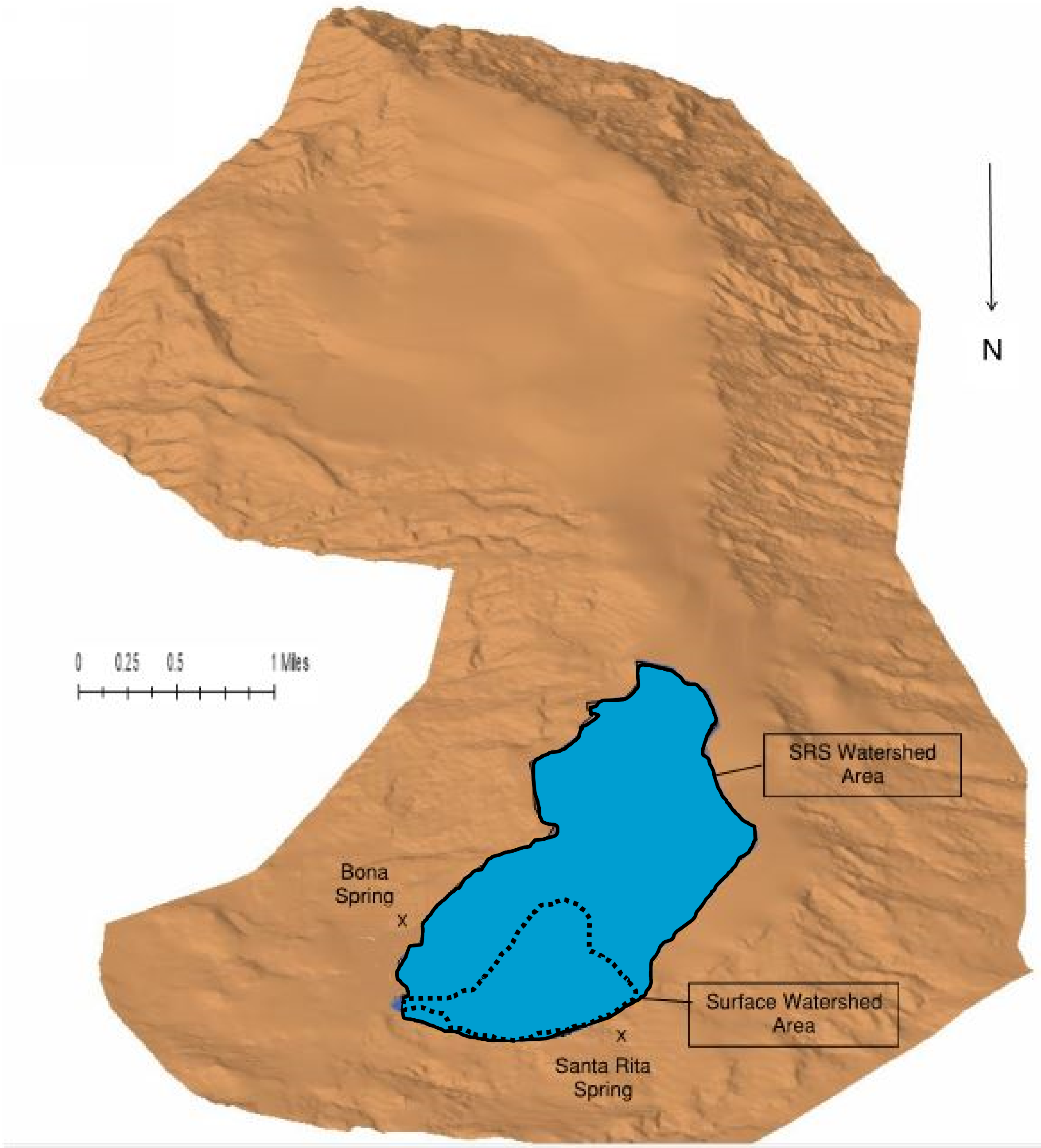

Figure 2.5. Detail of the SRS watershed as delineated from the Kauahikaua (1985) data and the geospatial analysis of this study. The area enclosed by solid line is the inferred subterranean watershed that feeds the SRS. The area enclosed by the dashed line is the area beneath the notional surface watershed (Figure 2.4).

Table 2-1. Santa Rita Spring Watershed area

Location	Size (mi^2)	Line
Apparent (surface) watershed	0.19	Dotted
Actual (basement) watershed	0.62	Solid

2.3 Watershed Hydrology

2.3.1 Watershed Rainfall

To estimate recharge for the aquifer feeding SRS, we compiled historical rainfall data of the past 10 years from the nearest long-term-record rain gauge, the USGS Fena Reservoir Pump Station Gauge, located about 3 miles southeast of SRS (Figure 2.6). Ten-year-monthly average rainfalls from January 2008 through June 2018 are shown in Figure 2.7. Average annual and seasonal totals are shown in Table 2-2.

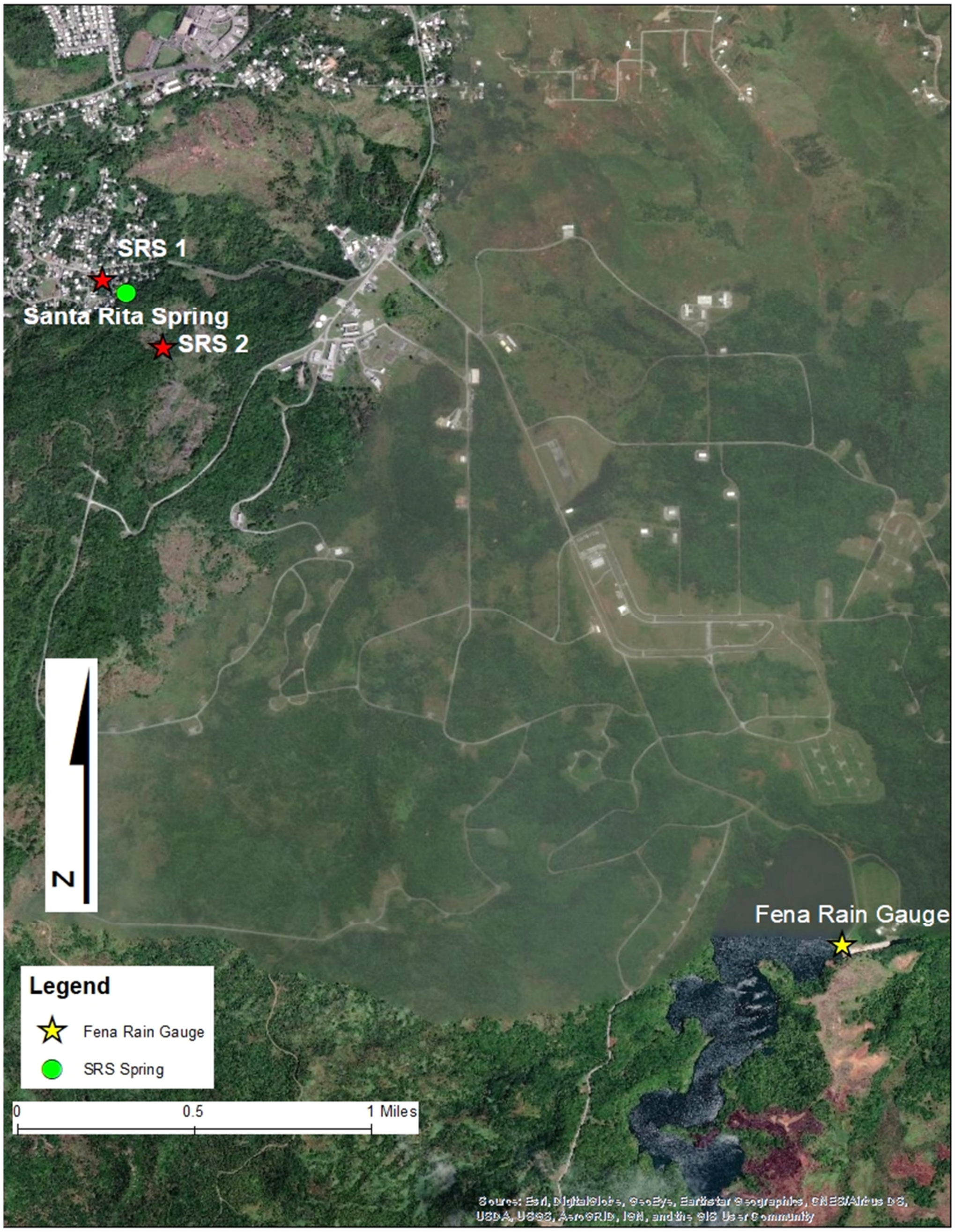

Figure 2.6. Location of the Fena Reservoir Pump Station Rain Gauge relative to Santa Rita Spring. Rain gauges installed for this study, SRS 1 and SRS 2 (described in Section 2.4.2) are also shown.

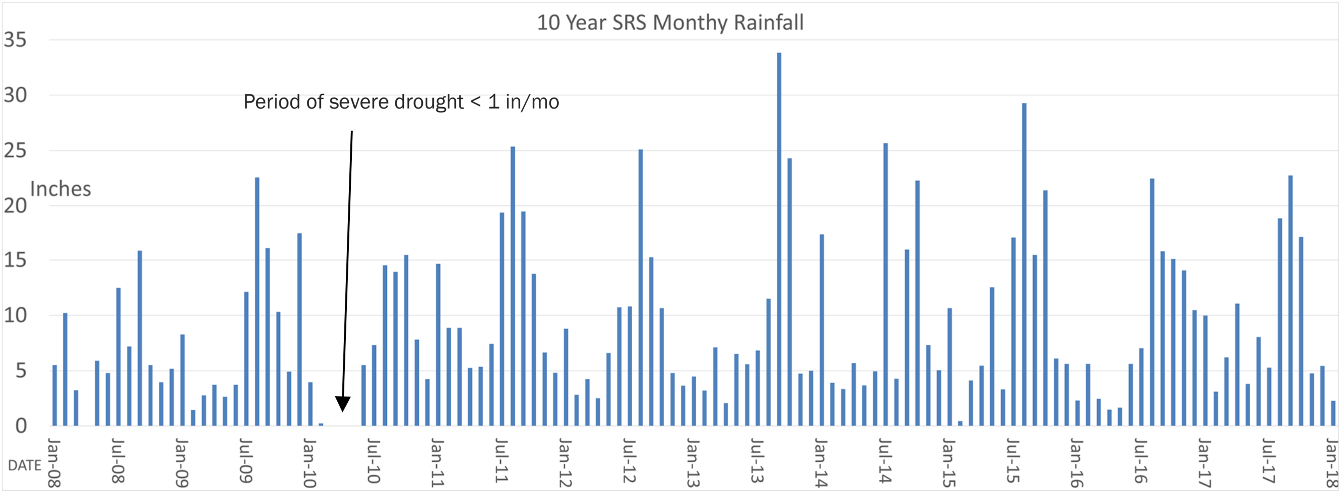

Figure 2.7. 10-year rainfall data collected from the USGS Fena Reservoir Station rain gauge, Jan 2008 to Dec 2018.

Table 2-2. Ten-year rainfall statistics

Period	Annual Average Rainfall (in)	Wet Season (Jul- Dec) Average Rainfall (in)	Dry Season(Jan- June) Average Rainfall (in)
2008 – 2018	110	86	35

2.3.2 Real-Time Rainfall Measurement

To interpret the real-time spring responses to ongoing rainfall, provide redundancy, and gain some insight into the geographical distribution of rainfall within the watershed, we installed two rain gauges inside the watershed (Figures 2.1, 2.6, and 2.8), SRS 1 at its lowest elevation (Figure 2.8a), and SRS2 at its highest (Figures 2.2 and 2.8b). Rain Gauge SRS 1 was installed on the roof of Our Lady of Guadalupe Church, next to the SRS site. Rain Gauge SRS 2 was installed on the summit behind the SRS site in the old Navy quarry. The gauges were active from June 2016 to July 2018. Measurements by the two gauges are effectively identical; differences appear to be random, with an average daily difference of only 7.5% (appendix D). At least one gauge was functional at any given time. Monthly total rainfall is shown in Figure 2.9. Annual and seasonal totals are shown in Table 2.3. This record of rainfall was used to interpret spring hydrograph data (Section 2.5).

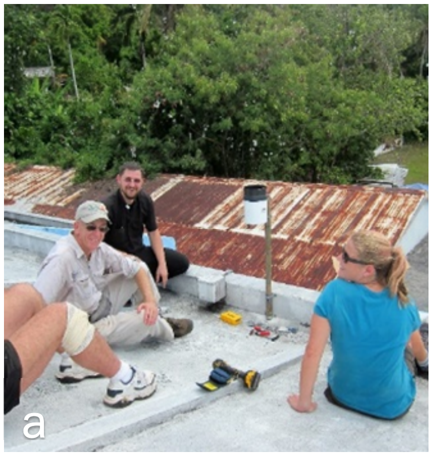

Figure 2.8. Rain gauges installed for this study. (a) SRS 1, on top of Our Lady of Guadalupe Church. (b) SRS 2 on the summit of the watershed, overlooking Orote peninsula, to the northwest, center of photograph.

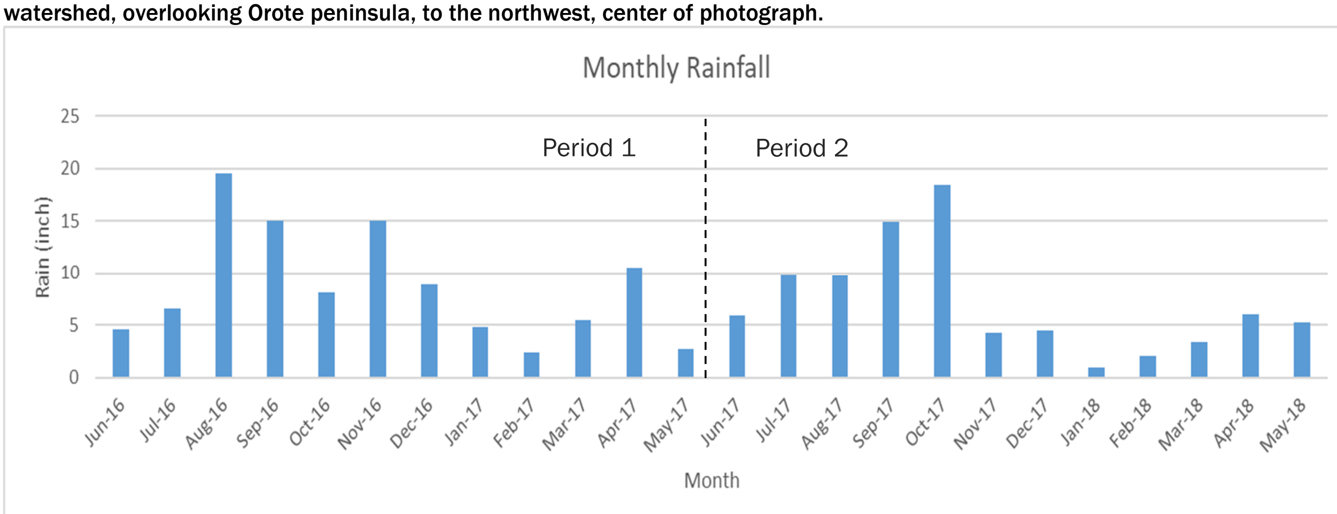

Figure 2.9. Monthly rainfall from the SRS watershed rain gauges SRS 1 and SRS 2, inside the watershed, June 2016 through May 2018. Data shown are composite: When both gauges were in service, the average is used. When one was out of service the data are from the active gauge.

Table 2-3. Summary of the rainfall data collected at the Santa Rita Spring Watershed.

Gauges	Period	Total Annual (in)	Dry Season (Jan – June) Total (in)	Wet Season (Jul – Dec) Total (in)
SRS 1 and 2	June 2016 to May 2017	103.79	31.94	73.17
SRS 1 and 2	June 2017 to May 2018	85.33	33.83	61.70
SRS 1 and 2	2-year average	94.56	32.89	67.44

2.4 Water Budgets: Watershed and Spring

The water balance equation for karst aquifers contains no runoff component since streams do not form on the porous surface. The water balance equation may therefore be written simply as:

$$P - ET = R = Q \qquad \text{(equation 1)}$$

Where,

P = Rainfall, ET = Evapotranspiration, R = Aquifer recharge, Q = Aquifer discharge.

2.4.1 Watershed Water Budget

We estimated the watershed water budget from the following parameters and assumptions:

1) The area of the aquifer watershed is 0.62 sq. mi. (Section 2.2; Figure 2.5).
2) The aquifer is recharged only during the wet season (Beal et al., 2019; Johnson, 2012; Partin et al., 2012), for which the mean annual wet season rainfall is 86 in. (Section 2.3.1; Figure 2.7, Table 2-2).
3) The evapotranspiration rate for the wet season is assumed to be 40%, the low end of the annual range for southern Guam estimated by Johnson (2012).

Table 2-4. Watershed water budget

SRS watershed area (mi^2)	0.62
Rainfall (in/yr)	86
Evapotranspiration Rate (%)	40
Recharge (in/yr)	51.6
Recharge volume (ft^3/yr)	7.41 $\times 10^7$
Recharge (MGD)	1.52
(gpm)	1050

To obtain a notional estimate of maximum daily aquifer recharge, from which to estimate maximum spring discharge associated with ordinary rainfall (*i.e.*, from other than tropical cyclones), we assumed a linear temporal distribution (Figure 2.10) of daily recharge from a minimum of 0.0 MGD to the maximum constrained by the mean recharge of 1.5 MGD (1050 gpm). The assumed ordinary maximum aquifer recharge is thus twice the mean: 3.0 MGD.

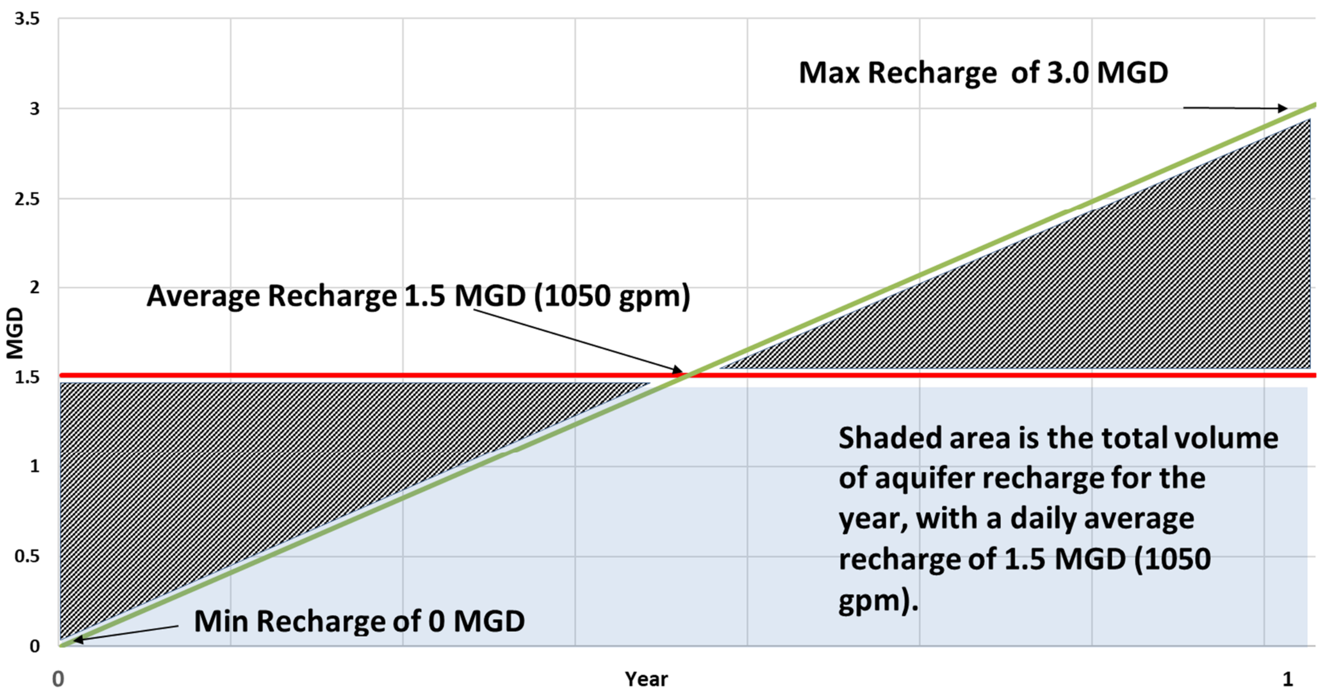

Figure 2.10. Watershed recharge, linear distribution, MGD.

2.4.2 Santa Rita Spring Facility Water Budget

To obtain reliable parameters for design of the improved SRS facility, we proceeded from the following observations and assumptions:

1) The SRS never runs dry. The aquifer thus has sufficient storage to distribute spring discharge over the entire year, even when it is receiving no recharge.
2) During minimum-flow conditions, at least 80 gpm is seeping into facility storage Compartment 1 (Section 1.2; Figure 1.11).
3) Another 80 gpm is likely seeping the floor into Compartment 2, since it is co-located and has identical construction (Section 1.2; Figure 1.5).
4) We measured 60 gpm channeling around the structure at the end of the dry season (19 June 2017), through and around the teal pipe French drain which discharges into the overflow channel to the northwest of the SRS site (Section 1.2.3; Figure 1.15).
5) Another 30 gpm is reported by GWA staff to be seeping into the booster pump wet well.

Thus, we estimate the dry-season minimum flow delivered to the SRS (not all of which is captured by the current facility) to be the sum of the above: 250 gpm (0.3 MGD).

To estimate the maximum ordinary (non-tropical cyclone) discharge from the spring, we began with the assumption that at least 70% of total annual aquifer recharge for the SRS watershed is discharged through the SRS site. This assumption is based on the age of the limestone formation which is not old enough to have developed a concentrated conduit system. The recorded GWA maximum discharge at the site 500gpm plus the known amount of water going uncaptured at the SRS 250 gpm further corroborates this assumption. Proceeding as in Section 2.4.1 (for aquifer recharge), we assumed a linear temporal distribution of spring discharge, with a daily minimum of 250 gpm, constrained by a mean of 735 gpm (70% of mean aquifer recharge). The assumed maximum is thus 250 gpm higher than mean discharge: 1220 gpm (Figure 2.11). This estimate of maximum ordinary discharge provides a reasonable benchmark for design.

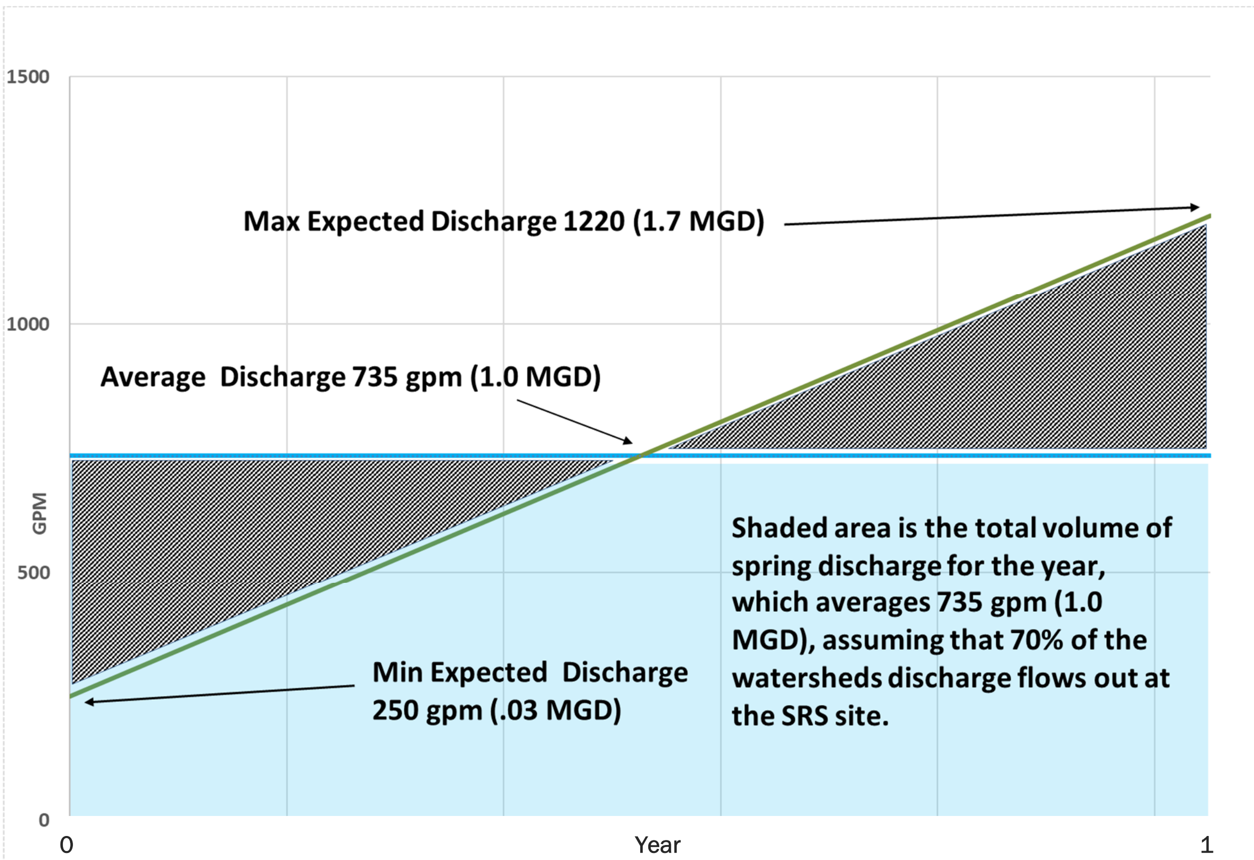

Figure 2.11. Spring discharge, linear distribution, GPM.

Historically, the existing collector pipe appears to capture 0 to a maximum of 420 gpm. If this estimate is correct and if the mean ordinary flow to site is 735 gpm, then the maximum captured by the existing facility is about 60% of mean ordinary flow to the site. Definitive determination of peak (as opposed to maximum ordinary) discharge requires measuring spring flow during and immediately after typhoons. No typhoons occurred during the study period of June 2016 to May 2018.

2.5 Rainfall Discharge Hydrograph Analysis

Karst spring hydrographs can be used to infer the characteristics of the route the rainfall takes as it passes through the catchment surface and travels to its natural exit at the spring (Bonacci, 1993; Kresic and Bonacci, 2010). The unique plumbing of each karst spring, however, means that hydrographs are distinct. Nevertheless, there are some common modes of behavior. During periods of heavy rain, for example, water flows turbulently though otherwise dry networks of conduits and dissolution-widened fractures, which typically induces turbidity. During gentle rainfall, infiltration is slow and diffuse, and the dominant mode of aquifer flow is laminar flow through small cracks and pores, which is typically clear.

The storm hydrograph for the 2017 dry season (Figure 2.12) shows rainfall on the right axis in inches (in/hr and in/day), and hourly spring discharge on the left axis in gallons per minute (gpm) as measured by the flow meter sensor at the overflow weir from Compartment 1 into Compartment 2 (Figure 1.10). We concluded that there is no naturally occurring cause for the saw-toothed nature of the raw spring discharge data, the light gray line. We determined rather, that this saw-toothed discharge curve was the result of the thermo-expansion of the instrument’s mounting within Compartment 1. This artificial noise was removed by using a sixth order polynomial trendline, (the red line) to smooth the data.

The spring’s discharge rate declines throughout the season until the first significant rainfall, on 24 April 2017, when within a 24-hour period, 2.97 inches of rain fell on the SRS catchment. This provided an informative test of the spring’s responsiveness to intense rainfall under dry conditions (Figure 2.12b). Before the pulse of rain arrived at the SRS facility, the dry season base flow of water coming from the SRS watershed was 150 gpm. Had this storm not happened the base flow rate of the spring would have continued to trend down (see blue trendline Figure 2.12) towards 80 gpm, which is the reported minimum SRS discharge.

Table 2-5 summarizes the storm hydrograph (Figure 2.12b). There was a lag time of 28 hours between the storm and the watershed response. During the storm, the peak discharge was 220 gpm, an increase of 30% from the pre-storm base flow of 150 gpm. Post peak, the spring hydrograph exhibits a typical recession curve, with a 30 days base flow recession to the pre-storm baseflow level. 27. During the storm the current SRS system captured 58% of the watershed discharge (appendix E). If the new SRS collection system captures all the available water, then the peak discharge for a similar storm will be approximately 500 gpm.

Table 2-5. Summary of hydrograph analysis

Duration of Storm	24 hr
Time to Peak	120 hr
Lag Time	28 hr
Rising Limb	4 days
Flood Recession	28 days
Peak Discharge	220 gpm
Original baseflow	150 gpm
Total storm discharge volume	7.43×10^6 gal
Aquifer recharge volume with 40% recharge.	1.28×10^7 gal
Percentage capture by SRS	58%

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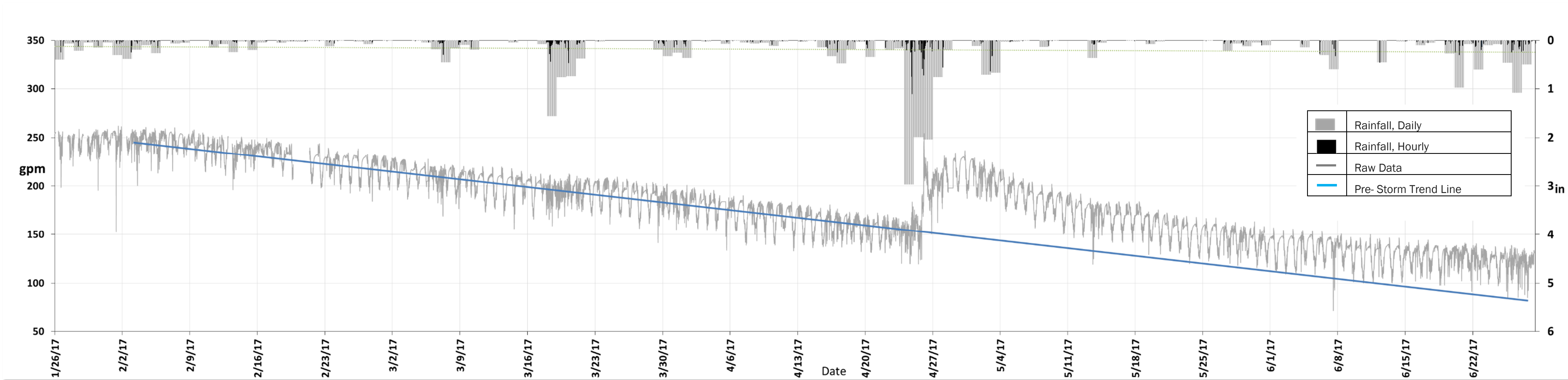

Figure 2.12a. Spring discharge hydrograph from January 26th to June 28th, 2017, with the spring discharge on the bottom axis and rainfall on the top axis.

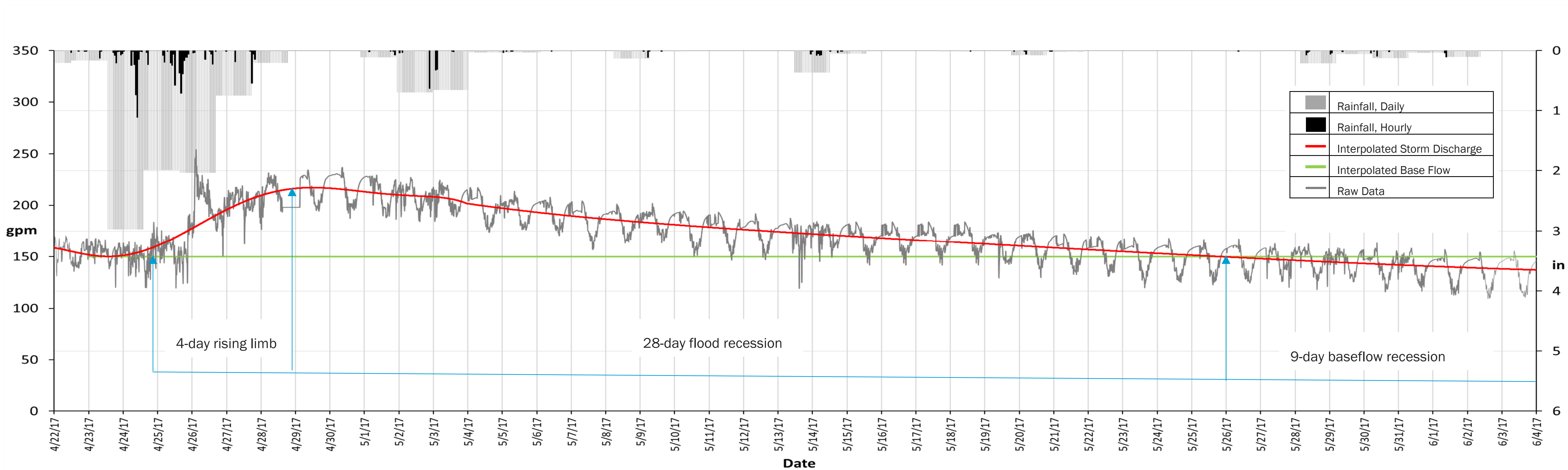

Figure 2.12b. Storm hydrograph analysis with discharge in gallons per minute of the SRS spring from the 24th of April when the first major rain event began until the 4th of June 2017.

Section 3: Santa Rita Spring Site Hydrogeology

This section describes the methods and results of the fieldwork we undertook to characterize and evaluate the natural plumbing of the spring. Fieldwork included 1) visiting the type locale of the aquiclude unit; 2) studying the hydrogeologic characteristics of an accessible nearby exposure of the water-bearing contact between the overlying aquifer and the underlying aquiclude; 3) drilling at the SRS site to determine site hydro-stratigraphy; 4) installation of boreholes by which to observe water-table responses to intense rainfall events; and 5) hydraulic testing to evaluate the hydraulic properties of the water-bearing zone at the SRS site.

3.1 Santa Rita Spring Notional Model

The Santa Rita Spring is a perennial spring formed along the contact between Guam's Alifan Limestone and its basal unit, the Talisay Member (appendix B). The Alifan Limestone consists mostly of dense, hard, crystallized limestone (Figure 3.1), which forms a mature, classic karst aquifer (Figure 3.2). The Talisay Member is a transitional unit, composed of marls, clays, and conglomerates, with occasional inclusions of coral fragments and lignites (Tracey Jr. et al., 1964). Together with the older, underlying volcanic Alutom Formation, it comprises an aquiclude at the base of the Alifan aquifer. Water descending to the base of the aquifer has formed networks of caves and conduits along the contact with the aquiclude. Spring water discharges from these conduits where they intercept the hillsides.

Figure 3.1. Sample of dense, hard, recrystallized Alifan Limestone collected at the old Navy quarry behind the SRS.

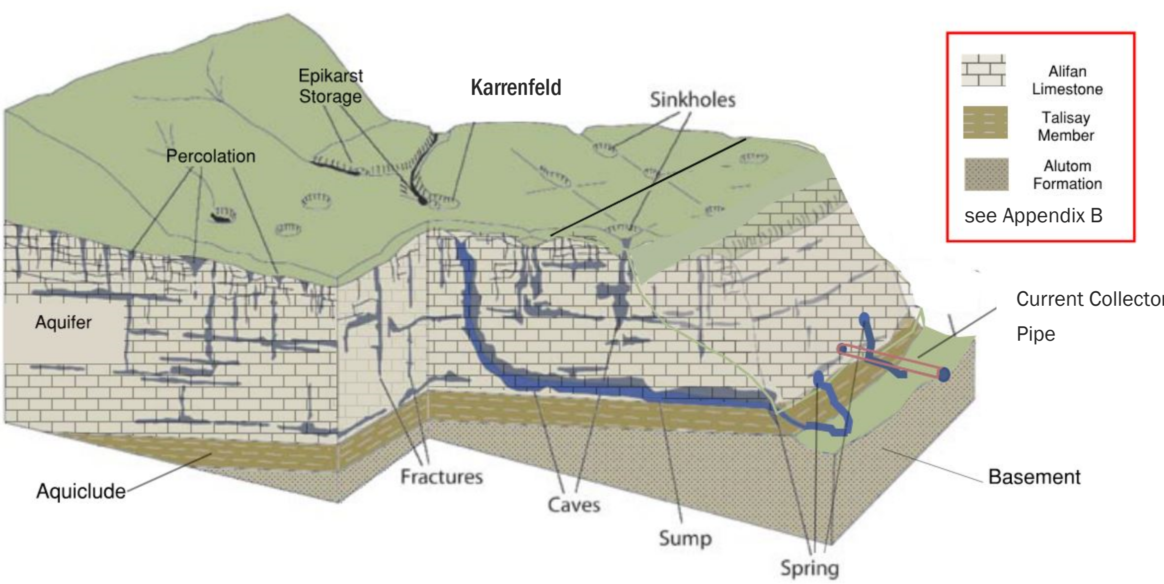

Figure 3.2. Notional model of the Santa Rita Spring stratigraphy and hydrology

3.2 Site Stratigraphy

3.2.1 Field Study of the Talisay Member Type Locale

The position of the SRS on the geologic map of Guam (Appendix B) indicates that spring discharge is located at the contact of the Miocene Alifan Limestone and the Early Miocene Talisay Member, which comprises its basal unit. The Talisay Member is a transitional unit, no more than 30 feet thick, containing clays, marls, and lignite associated with the Early Miocene marine transgression onto the subsiding terrain of the Oligocene Alutom Formation. The Talisay Member grades upward into the pure limestone formed in the overlying reef sequence that comprises the Alifan Limestone (Reagan and Meijer, 1984; Taborosi et al., 2004; Tracey Jr. et al., 1964). Relative to the overlying Alifan Limestone, the Talisay Member is an aquiclude. The SRS is thus a contact spring that forms primarily at the contact between the permeable Alifan Limestone and the relatively impermeable Talisay Member at its base. Beneath the Talisay Member is a weathered clay-rich, low-permeability saprolite formed in the upper portion of the Alutom Formation.

To gain an understanding of the composition and hydrologic properties of the Talisay Member, we attempted to visit the type locale (Tracey et al., 1964) on 23 April 2018 and 14 May 2018, accompanied by UOG Emeritus Professor Richard Randall, and NAVFACMAR environmental staff member Maria Lewis. The type locale is mapped one-half mile southeast of the entrance to the Naval Ammunition Depot, about 250 meters north of the Talisay River, in an excavation behind the loading ramp of a building apparently used as a warehouse. (Figure 3.3; Location Fj5). After extensive hiking however we determined that we failed to find the original location designated by Tracey et al. (1964), (Appendix F).

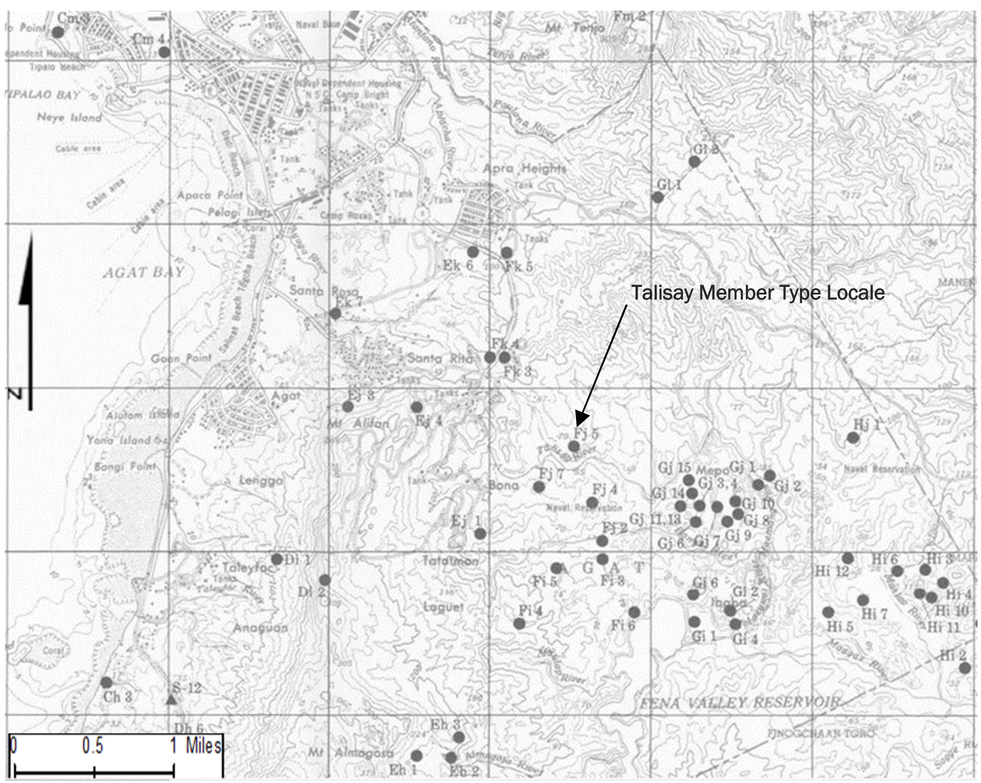

Figure 3.3. Excerpt from the Sample Locality Map of Guam (Tracey et al., 1964).

3.2.2 Field Study of a Representative Exposure of the Talisay Member

On 25 June 2018, we visited an exposure of the Alifan-Talisay contact mentioned in Tracey et al. (1964), in a roadcut 0.85 miles north of the main entrance gate to Naval Base Guam (Figures 3.4 and 3.5). The cut has intercepted and exposed a cross-section of a network of open conduits that have formed at the contact between the soluble, high-permeability Alifan Limestone above and the insoluble, low-permeability clayey layer beneath in the Talisay Member (Figure 3.5C). Conduits such as these drain the water from the overlying limestone aquifer and can be expected to be exposed at the SRS when the contact is excavated.

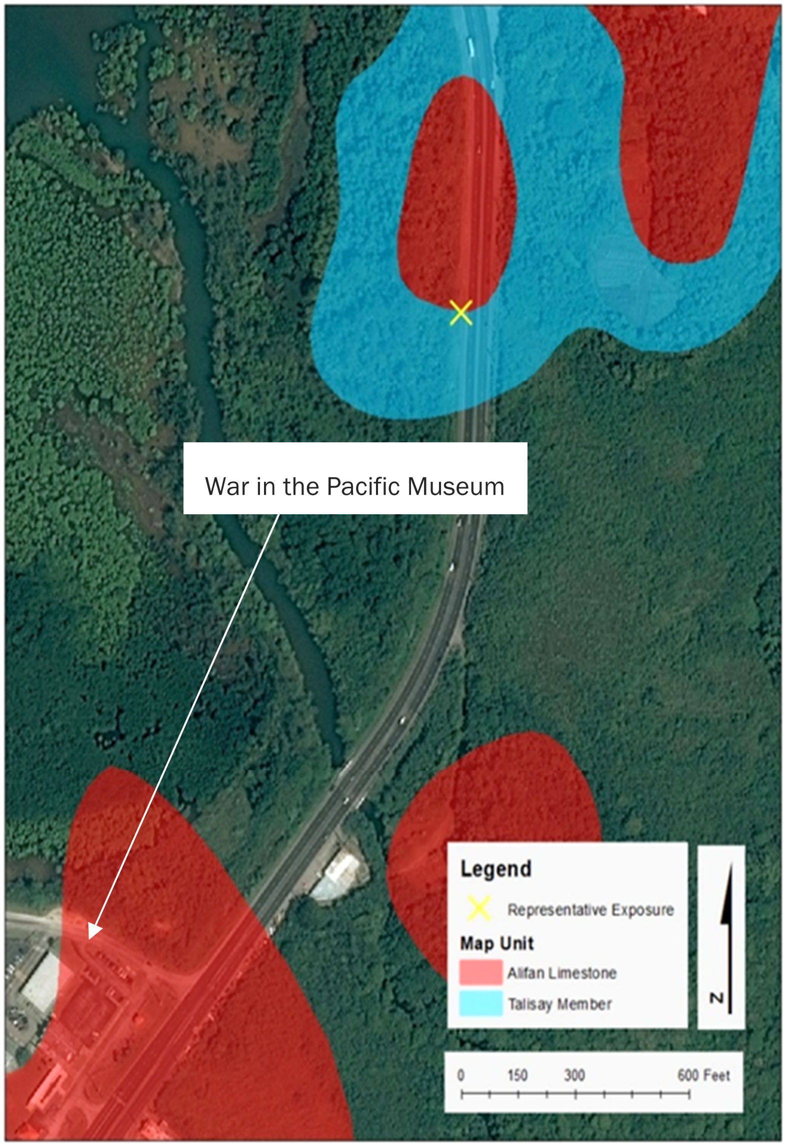

Figure 3.4 Representative exposure of Alifan-Talisay contact. The contact is well exposed in a roadcut on the west side of Marine Corps Drive, about a half-mile north of the main entrance to Naval Base Guam (Figure 3.5).

The recent installation of a new water main along the side of the road presented an opportunity to learn even more at this site, so we returned on Saturday, 11 January 2020 to study the site again and take the series of photographs shown in Figure 3.5. The texture and color of the layers seen in this exposure matched those found at the SRS site during our drilling study (Section 3.2.4).

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Figure 3.5. (a). Route 1 southbound shoulder showing Alifan-Talisay exposure. Yellow boxed area contains the contact between the overlying Alifan aquifer and the underlying Talisay aquiclude. The teal pipes in the foreground are new 16-in, water main for the Navy water system serving the base.

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Figure 3.5 (b) Closer-in view of the Alifan- Talisay contact, marked by dotted yellow line.

Figure 3.5 (c) Detail, showing distributed hand-scale cavernous porosity at the contact. The cut has intercepted and exposed the cross-section of a network of open conduits that have formed at the contact between the soluble, high-permeability limestone above and the insoluble, low-permeability clayey layer beneath. Although the ones seen here are inactive, conduits such as these drain the water from the overlying limestone aquifer and can be expected to be exposed at the SRS when the contact is excavated.

Figure 3.5 (d). Detail of trench cut in the low-permeability Talisay Member, in which the new Navy water main is being installed. Note the standing water in the trench, from recent rainfall.

3.2.3 Ground Penetrating Radar at the Santa Rita Spring Site

The first attempt to discern the hydro-stratigraphy of the SRS site was the application of a ground penetrating radar (GPR) provided by GWA. A GSSI model SIR 3000 GPR® controller, with both a 400 MHz and a 270 MHz antenna were used to carry out the survey from September to December 2016. Unfortunately, the surveys provided no resolvable data. The soft geologic materials at the site have high clay and high moisture contents, which when combined with the high water table at the site, apparently prevented the radar signal from penetrating more than a few inches into the ground.

3.2.4 Borehole Drilling at the Santa Rita Spring Site

To discern the hydrogeologic characteristics of the site—in particular, the depth to the aquiclude—we used a Lonestar LH200® portable drilling rig[5] (Figure 3.6) to install 11 boreholes. In order to characterize the hydrology of the site, for each borehole, cuttings were collected and analyzed (Figure 3.7), and standpipes were inserted.

Figure 3.6. The Lonestar LH200 portable well drilling rig drilling hole 5 at the SRS.

Figure 3.7. Collecting drilling samples with a sieve.

Borehole locations (Figure 3.8) were initially marked using a Trimble Geo 7x GPS® mapping grade unit, and post-processed using GPS Pathfinder software. However, due to the thick canopy cover, locating the GPS points of the boreholes using this method proved unreliable. To accurately locate the boreholes, a range finder was used to triangulate the location of each borehole from the known location of specific points that were referenced on the original GWA site plans (Table 3-1). The elevation of each borehole was measured with a Theodolite, using the USGS elevation reference plate used as a base by the original GWA site plans.

Borehole locations were deliberately chosen to maximize data on stratigraphy and hydrogeology around the site from a manageable number of holes. The holes are numbered in the order in which they were drilled. The 11 boreholes are divided into three groups:

[5] The Lonestar LH200 is a portable 20-hp hydraulically driven hollow-stem drill rig, with a 5-hp mud pump. The rig can drill a 4-to-6-inch borehole to a depth of 200 feet.

1) Located on the spring side of the existing SRS structure, close to the walls of the structure, are boreholes 1, 3, and 4 (white circles).
2) Located behind the buried cutoff wall and behind the spring holding tank on the west side are boreholes 5 and 11 (blue squares).
3) Located along the suspected contact between the Alifan Limestone and the basal Talisay Member are boreholes 2, 6, 7, 8, 9, and 10 (yellow triangles).

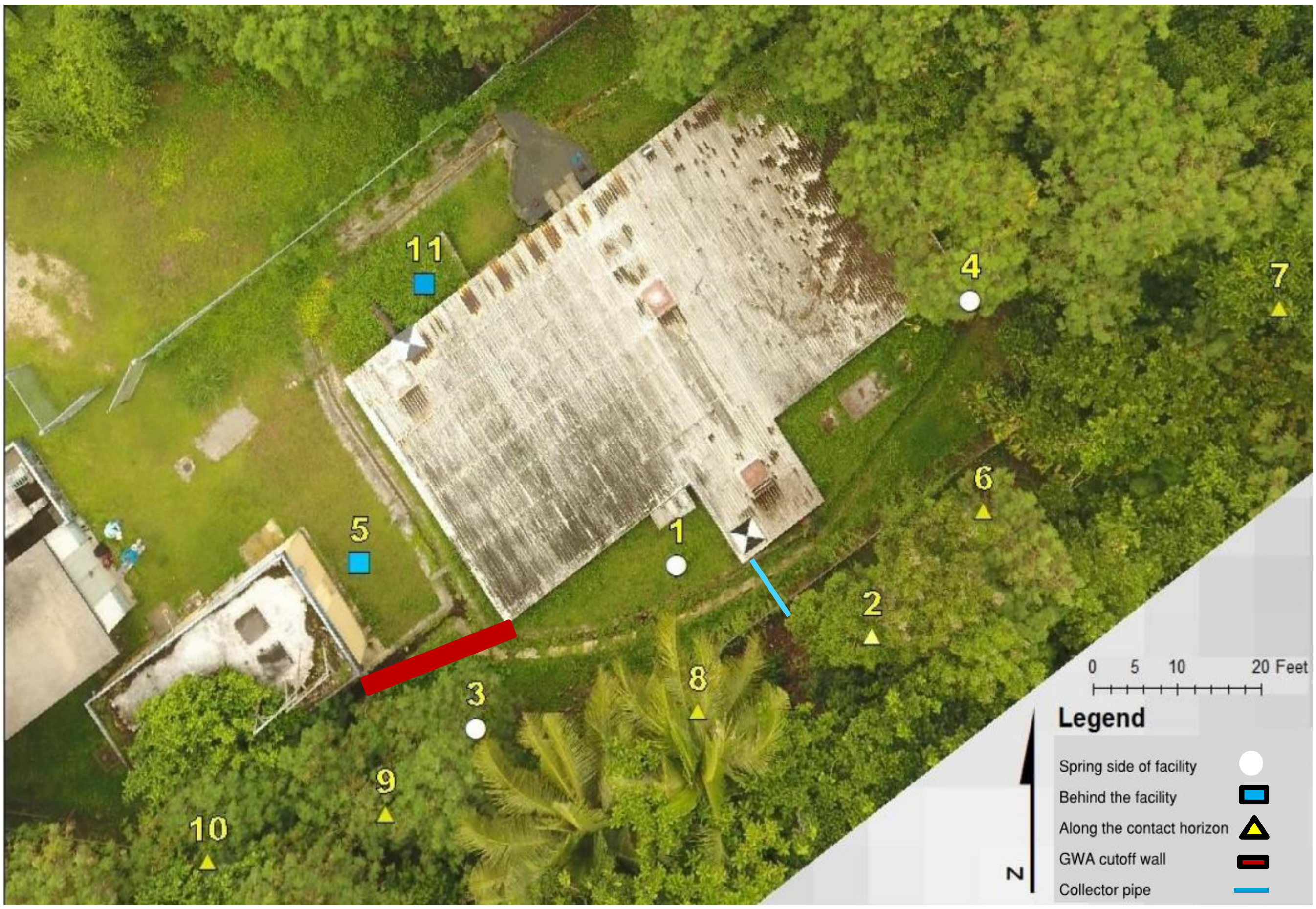


Figure 3.8. Locations of the Santa Rita Spring boreholes.

Drill cuttings were sampled at each borehole every 2.5 feet (half the length of the drill stems), using a sieve (Figure 3.7). The samples were taken from the water circulated through the hollow drilling stems and up the borehole to the surface by the mud pump. Casings were installed at each borehole to keep the boreholes from collapsing. The casings were comprised of 2-inch diameter PVC pipe, jointed and perforated with half-inch holes drilled every foot of the casing length below the surface. The length of the casing differs from the depth of the borehole drilled because of partial collapse in some of the boreholes, even in the time it took to remove the drilling stems and replace them with the PVC casing. To preserve the hydraulic properties of the site we did not use bentonite or drilling mud to stabilize the boreholes. The drilling log for each borehole and the stratigraphic interpretation of each location is provided in Appendix G

Table 3-1. Borehole location and depth

Borehole	X-Coordinates [a]	Y-Coordinates [b]	Surface Elevation [c] (ft)	Depth Drilled (ft)	Depth of Casing (ft)
1	814499.616	4858875.490	284.0	30.0	27.0
2	814522.886	4858867.410	285.3	30.0	6.0
3	814475.700	4858857.068	284.7	20.0	18.0
4	814534.521	4858905.548	238.4	20.0	17.0
5	814461.802	4858875.813	283.5	30.0	7.5
6	814536.137	4858881.631	285.0	25.0	23.5
7	814571.366	4858904.578	291.1	27.5	25.0
8	814502.202	4858859.007	285.1	67.5	55.0
9	814465.034	4858847.373	288.7	47.5	45.0
10	814443.703	4858841.878	284.3	35.0	33.0
11	814469.559	4858907.487	281.7	90.0	16.0

a: X and Y Coordinates in UTM ft b: Geographic coordinate system used WGS 1984 UTM Zone 55N C: All elevations are above mls

3.2.5 Stratigraphic features at Santa Rita Spring site

Each sample was examined, and preliminary findings were recorded in the drilling logs at the site (Appendix G). The samples were examined in more detail subsequently at the WERI lab. The texture and grain size of the soil found in each sample were described using the Unified Soil Classification System (USCS), (Table 3-2). The samples were found to be fine-grained inorganic clay (C) with a liquid limit of less than 50%. The soil samples from the SRS site may thus be classified as CL type soil, i.e. inorganic clays of low-to-medium plasticity. While the texture and grain size found throughout the site was nearly uniform, the color of the samples differed. The three major units found at the site, comprising 90 to 95% of the samples, collected are summarized in Table 3-2, below, using the Munsell colors and the USCS classifications. A representative picture of each unit is shown in Figure 3.9. At the SRS site the Olive Gray; 5Y 5/1 soil was identified as the aquiclude layer. It is on average 12 ft below the surface.

Table 3-2. Sediment Descriptions

System Used	Munsell Color Charts		Unified Soils Chart		Interpretation
No.	Number Designation	Description	Description	Category	
1	5Y 6/3	Pale Olive	Yellowish Orange	CL	Artificial fill
2	10Y 6/2	Light Greenish Olive	Greenish Gray	CL	Soft weathered saprolite
3	5Y 5/1	Gray	Olive Gray	CL	Firm saprolite aquiclude

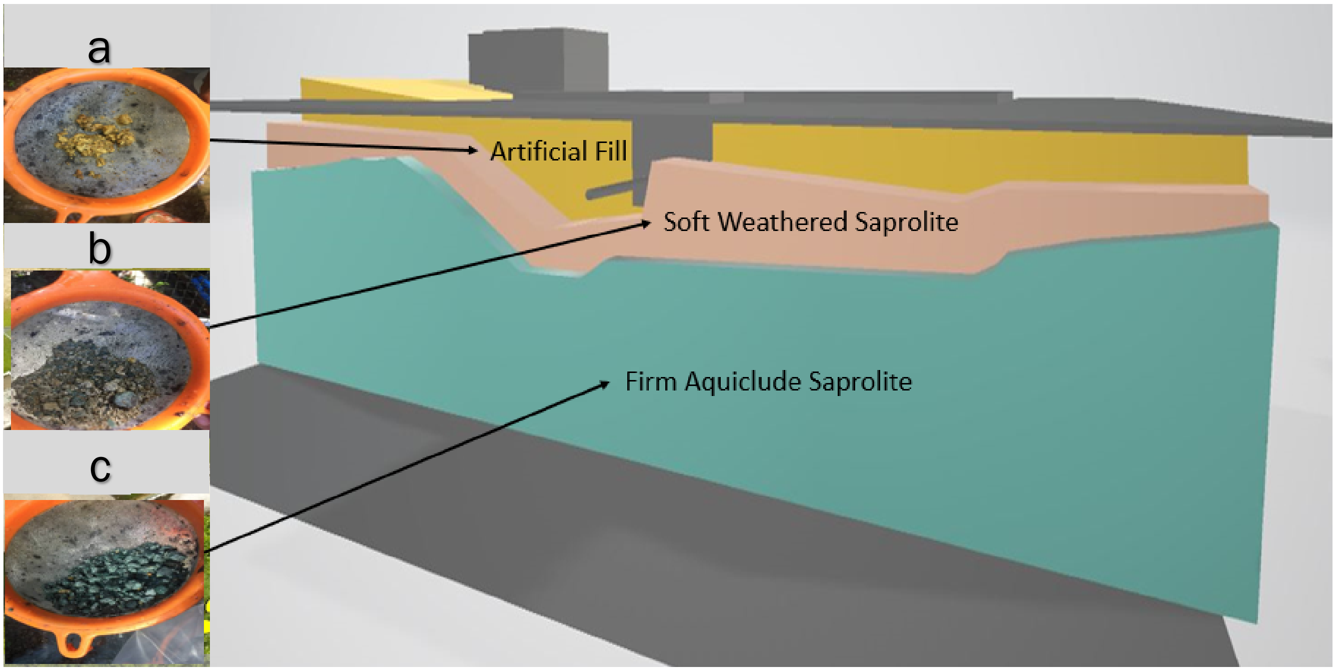


Figure 3.9. 3D model of the site stratigraphy and the three soil colors found and identified from the dilling at the SRS site. a) Pale Olive; b) Light Greenish Olive; c) Gray

3.3 Hydrography at the Santa Rita Spring Site

3.3.1 Installation of Standpipes

Onset Hobo® level loggers were placed inside boreholes 1 to 10 (Figure 3.10) to record pressure (kPa) every five minutes. No logger was placed in borehole 11 because it is located behind the current SRS holding tanks, beyond the influence of the spring hydraulics. A logger was placed inside the booster pump house to record atmospheric pressure (see Appendix H). The recorded standpipe logger pressure minus the locally recorded atmospheric pressure gave a more accurate water level calculation because atmospheric pressures can vary greatly geographically. The location and elevation of each logger was recorded using a Solinst® water-level tape sounder. Table 3-3 summarizes the location and elevation of each logger placement. The water table response in each standpipe can be seen in Appendix I. The level loggers remained in place for use during the subsequent hydraulic testing carried out at the SRS (Section 3.4).

Table 3-3. Depth of level loggers below the surface elevation of the borehole

Borehole	Surface Elevation (ft)	Depth of Casing (ft)	Depth of Loggers (ft)	Elevation of Loggers (ft)
1	284.0	27.0	16.5	266.9
2	285.3	6.0	1.9	282.1
3	284.7	18.0	10.3	272.8
4	238.4	17.0	10.2	271.9
5	283.5	7.5	3.1	276.2
6	285.0	23.5	12.8	269.6
7	291.1	25.0	9.9	272.4
8	285.1	55.0	5.9	277.4
9	288.7	45.0	21.4	261.7
10	284.3	33.0	2.3	278.1
11	281.7	16.0	0.0	281.7

3.3.2 Testing and Standpipe Data Analysis

On 21 May 2018, 1.49 inches of rain fell from 1200 to 1600 within the SRS watershed area. The following graphs show the response of the water table in each borehole (Figure 3.10). The shape of the response curve can be used to infer the type of flow that may be affecting the water level in the area around each borehole:

1) Barely to Non-Responding (Figure 3.10 (A): The water levels in borehole 2 and 5 show very little response to the pulse of water created by the storm. Borehole 5 is located behind the cutoff wall installed by GWA in 2011 to redirect the groundwater towards the collector pipe. Borehole 2, which is located close to the current SRS collector pipe showed little response probably because the pulse of water was captured by the nearby collector pipe and fed into the SRS facility, dampening the water level response.

2) Slowly Responding (Figure 3.10 (B): The water levels in boreholes 1, 4, and 7 were slow to react to the pulse. Water levels rose gradually and receded gradually. Boreholes 1 and 4 are located in disturbed materials, backfilled with artificial granular material. Borehole 7 responded slowly probably due to its position in undisturbed ground above the SRS site.

3) Rapidly Responding (Figure 3.10 (C), Boreholes 3, 6, 8, 9, and 10 each show a very rapid response, indicated by a spike in the water level at these locations. After this spike, the water levels recede rapidly. This water level behavior suggests the presence of conduit flow. Conduits deliver the pulse of water rapidly resulting in an immediate and rapid spike in the water levels. The likely presence of multiple conduits (such as shown in Figure 3.6) at the SRS site forms the basis for the design recommendations proposed in Section 4.

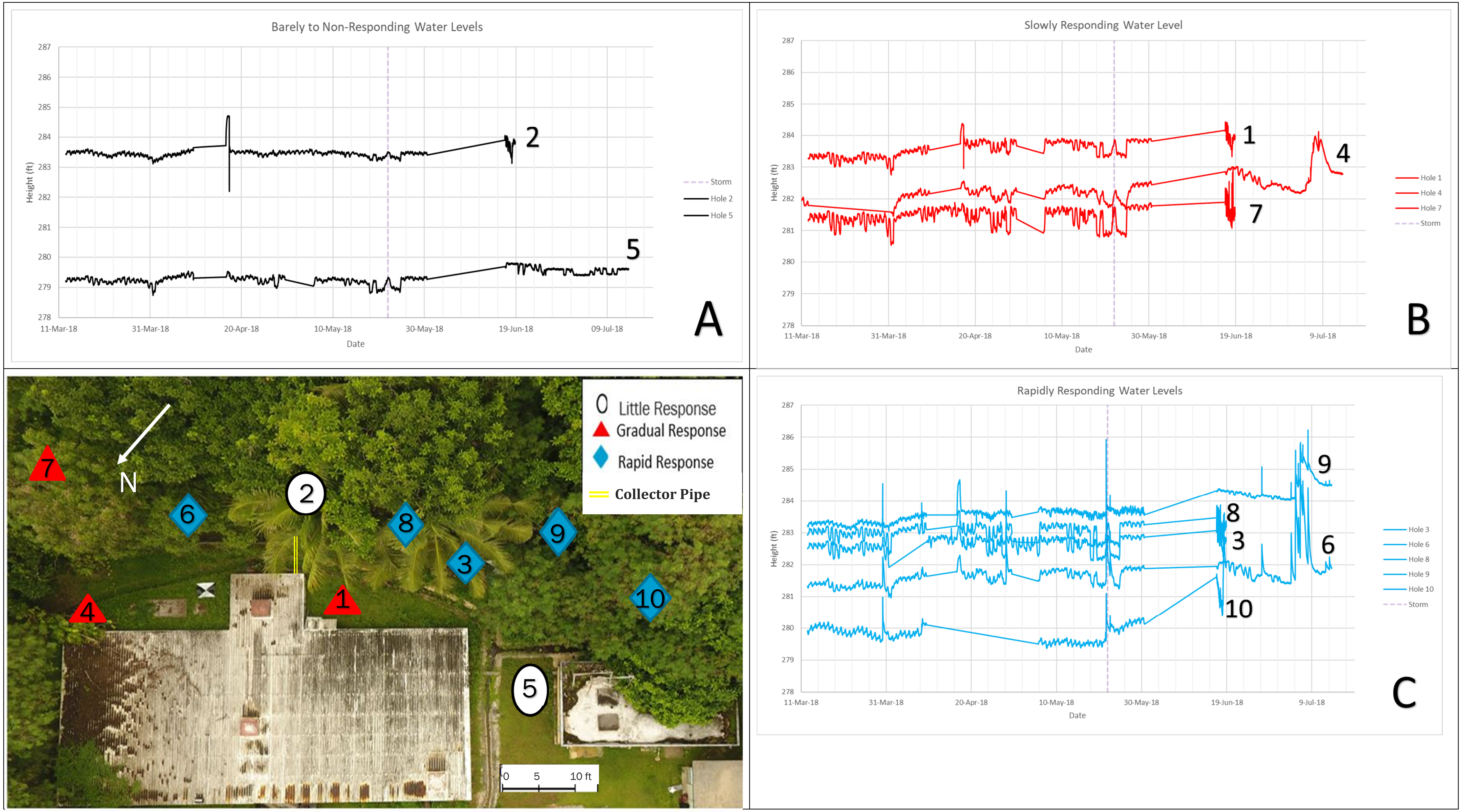


Figure 3.10. Locations of Boreholes 1-10 and the responses of the water level in each to the rainfall on the 21st May, 2018 .

Section 4: New Spring Rita Spring Facility Design Concept

This section describes the essential components for a design to capture the maximum volume of spring discharge arriving at the site. We recommend phased construction, in which implementation of each phase is informed by exploratory excavation at its beginning as well as by information gained from the previous phase.

4.1 Phase 1: Cutoff Wall and French Drain Collector

To intercept all of the water arriving from the distributed karst conduit system (Section 3.1) we propose installing a cutoff wall spanning the entire width of the site (Figure 4.1) with its footing anchored in the Talisay aquiclude (Table I, column 7), and a French drain set at the base of the cutoff wall (Figures 4.2 and 4.3) designed to accommodate up to 1220 gpm. To maximize the hydraulic effectiveness of the aquifers conduit system estimated to be between 20,000 to 36,000 ft/day (Figure 3.14) the French drain should be located so that it abuts as many of the conduits discovered as possible, The thickness and span of the water-bearing zone and the depth to the aquiclude should first be discovered and documented by exploratory trenching along the 115-ft span of the wall. Exploratory trenching for the cutoff wall should start in the southwest corner, by Borehole 10 (Figure 4.1) and proceed northeast, so that the current SRS facility can continue to collect spring water for as long as possible during construction. Based on the drilling results and hydrogeologic data (Section 3), the cutoff wall should extend from the surface down to approximately 14 ft, so as to be set into the aquiclude. See drawings D1 to D3.

Figure 4.1. Proposed location and dimensions of cutoff wall.

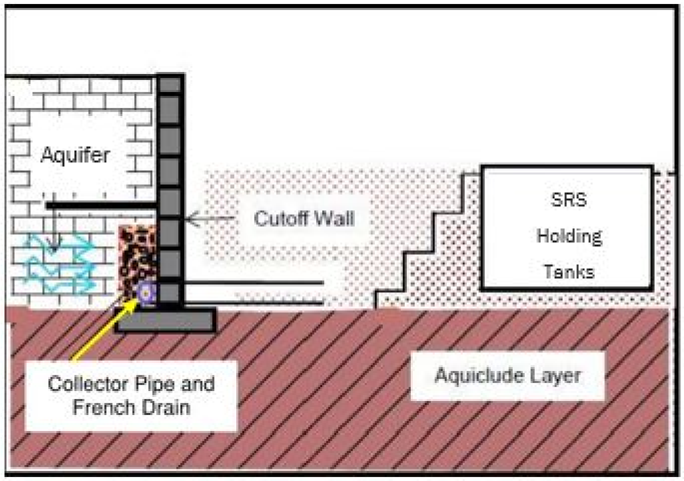


Figure 4.2. Improvement Phase 1: Cutoff wall and French drain

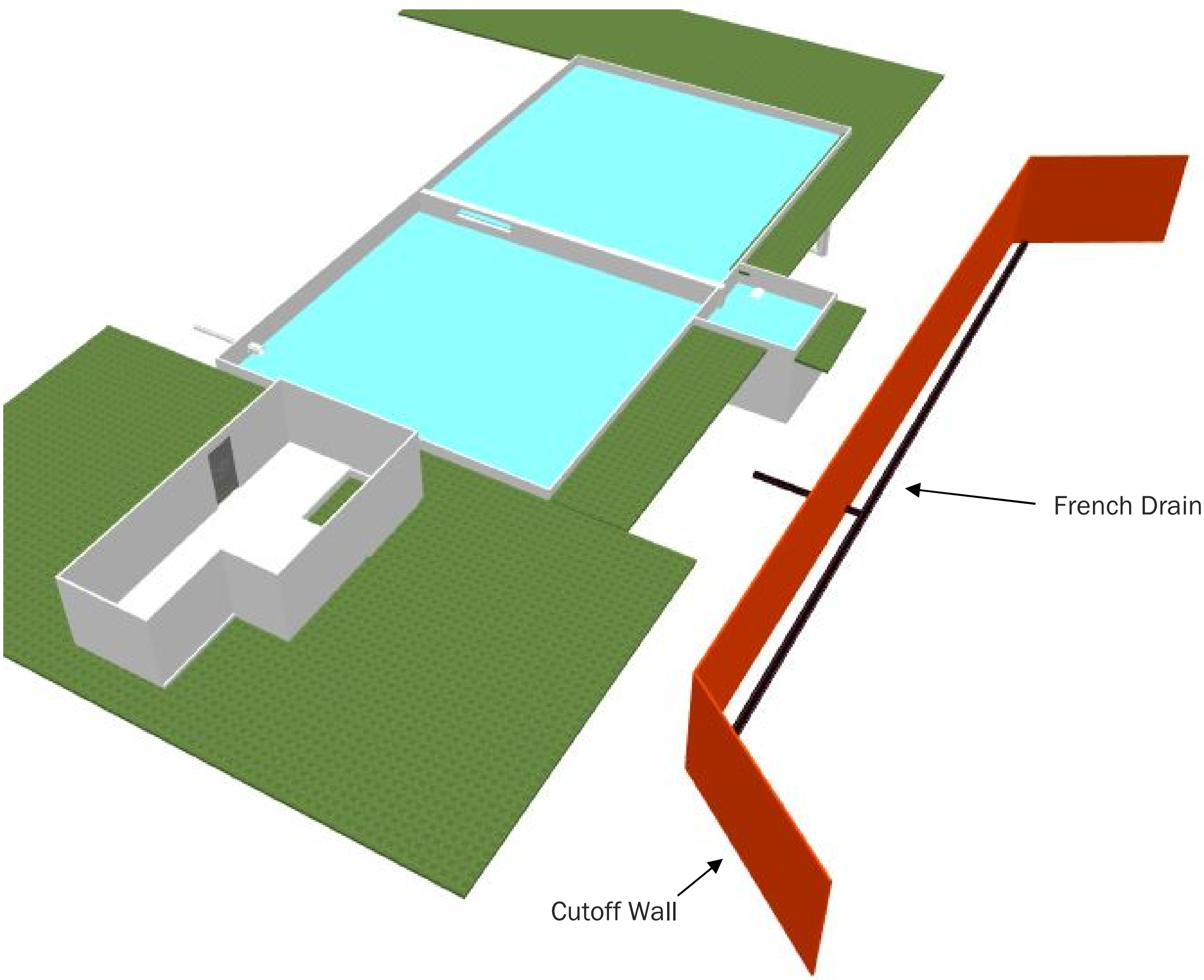


Figure 4.3. 3D model of Cutoff wall and French drain

4.1.1 Specifications: (see drawing labeled D1 to D3).

1) The collector piping for the French drain should consist of a perforated large-gauge pipe running parallel to the base of the cutoff wall and in opposite directions out to each end of the war from a Y- or T-fitting on the spring-box input pipe.

2) The piping should be placed no higher than about 6 inches above the base of the cutoff wall so as to allow all the spring water impounded by the cutoff wall to drain by gravity into the spring box (Figure 4.2).

3) The collector piping of the French drain must be surrounded by 6 inches of washed, coarse, rounded, uniform-grade gravel, to prevent soil and debris from fouling the pore space of the aggregate or the holes in the piping.

4) Clean-outs should be placed at each end of the collection piping to allow the system to be purged periodically to prevent fouling by accumulation of fine-grained sediment.

5) A serviceable flow meter should be installed and maintained on the pipe to the spring box so that the flow can be reliably monitored and recorded. The data collected by the collector pipe flow meter should be studied for at least one wet/dry cycle to determine whether it would be economically viable to proceed with a third phase, of lowering the holding tanks (Appendix K).

6) To prevent surface runoff from entering the new collection system, a diversion ditch should be dug upslope from the cutoff wall to divert surface water around the new collection system and into the existing SRS surface channel system.

7) To prevent water from percolating down through the soil into the collector piping, a ledge tied into the cutoff wall should be constructed above the collector piping.

4.2 Phase 2: The Spring Box

The water collected by the French drain will enter a re-engineered spring box (SB), set deep enough to preclude back-pressure on the spring-box entry pipe (Figures 4.4 and 4.5).

The expected flow captured by the new SRS collection system is predicted to range from 250 gpm to 1220 gpm, with a mean of 735 gpm (see Section 2). At an inflow rate of 1220 gpm, the SB which is 2,445 ft^3 would overflow in only 15 minutes.

Due to the significant difference between the expected maximum and minimum inflow rates, two pumps should be utilized to pump the water from the SB up to the existing SRS from which it will enter the holding tanks. By utilizing two pumps capable of pumping up to 750 gpm each, the system will have a built-in redundancy to deal with single-pump failures and will be more economical to run during periods of low spring discharge.

To deal with a double-pump failure or the pumps getting overwhelmed during periods of extremely high discharge, the access hatch to the SB should be fitted with overflow hatches to allow the spring water to flow into surface channels, that can take the flow around the site and into the existing creek spillway at the northwest of the site (Figure 1.6).

Automatic diversion valves controlled by a turbidity sensor should be fitted to the pipes taking the water from the SB up to the existing SRS to prevent turbid water from entering the GWA system. When there is a large volume of rainfall, the groundwater table rises, and pressure in the aquifer forces water through fractures and or conduits in the limestone that are rarely used and may be filled with sediment. This historically has caused turbidity spikes in the SRS system.

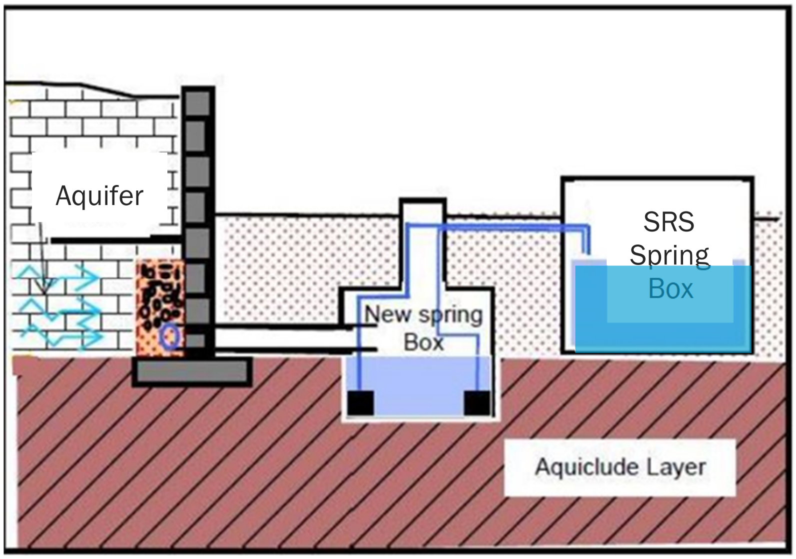


Figure 4.4. Improvement Phase 2: Lowered Spring Box

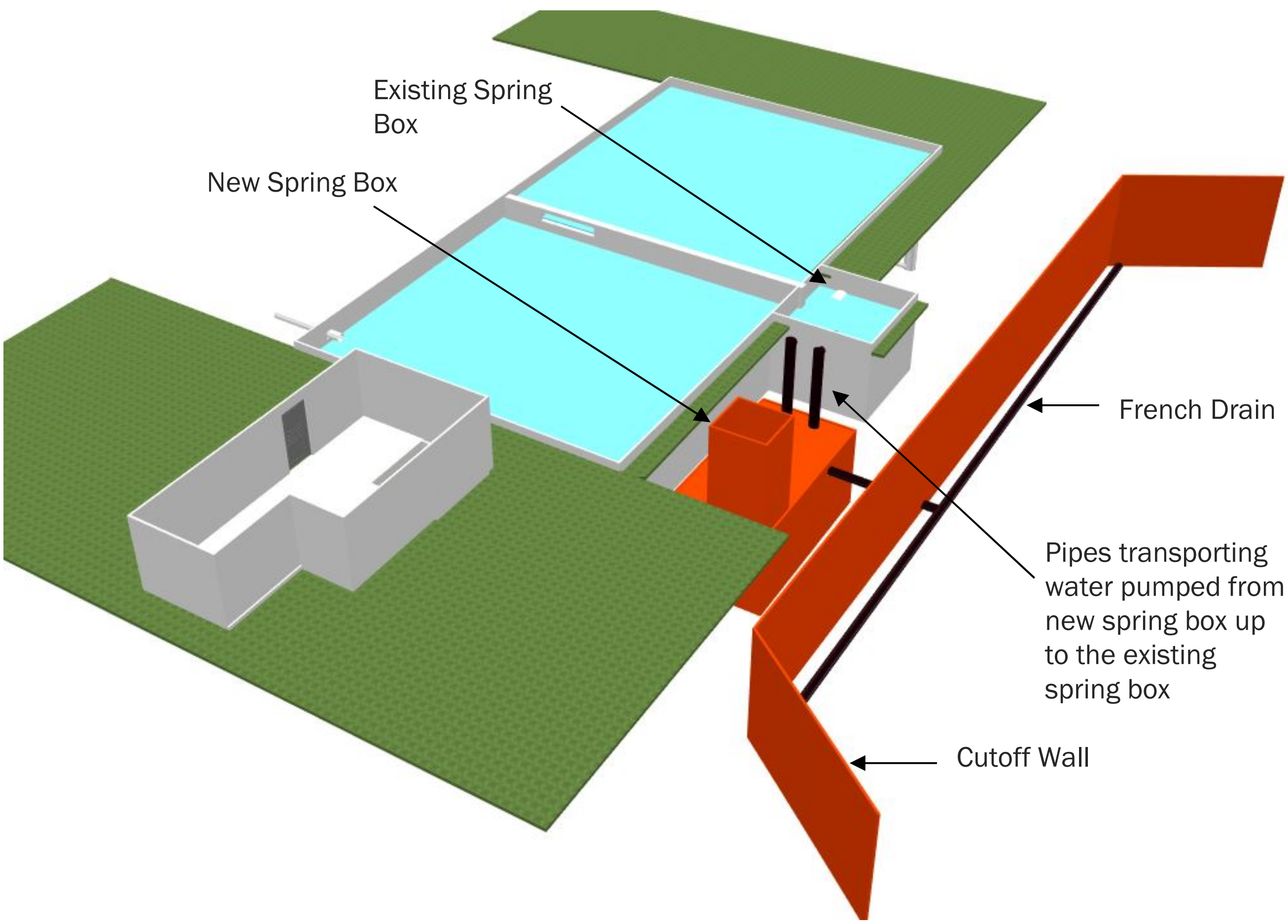
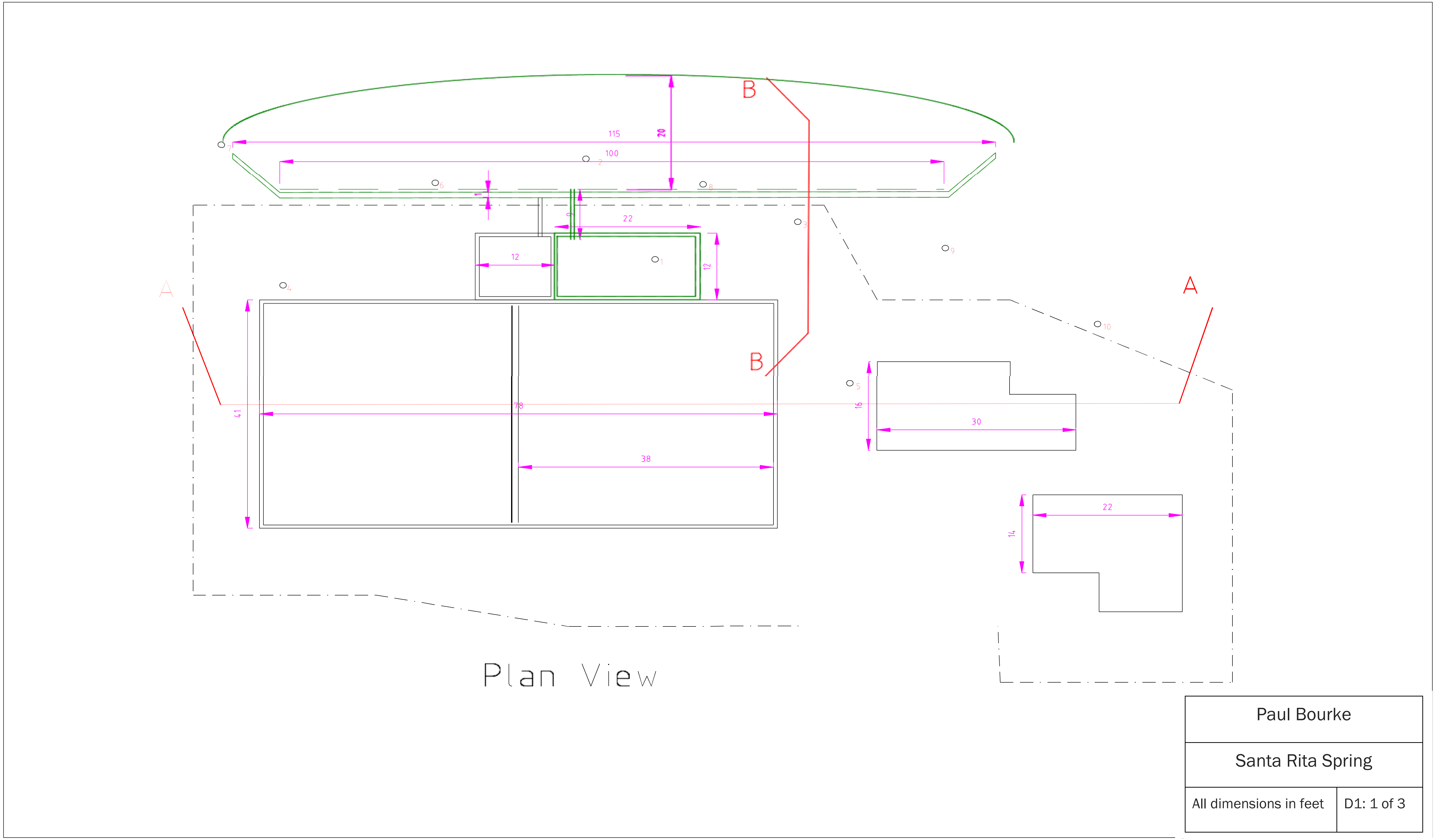


Figure 4.5. 3D Model of the New Spring Box


115
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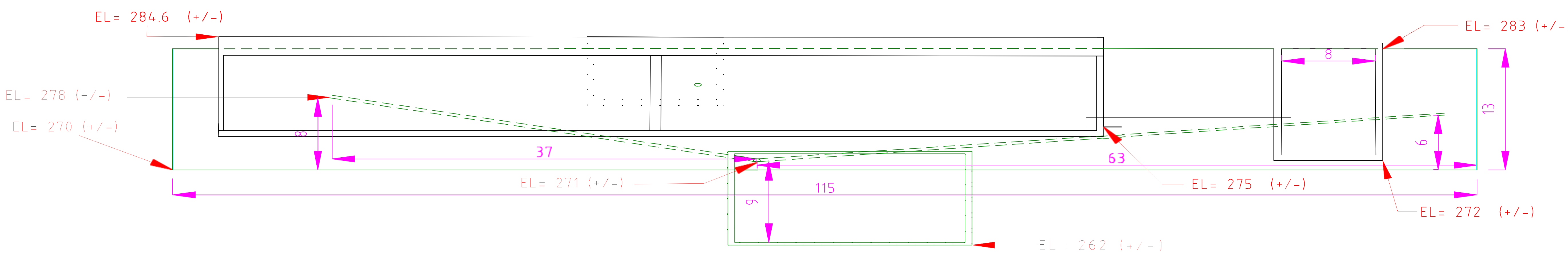
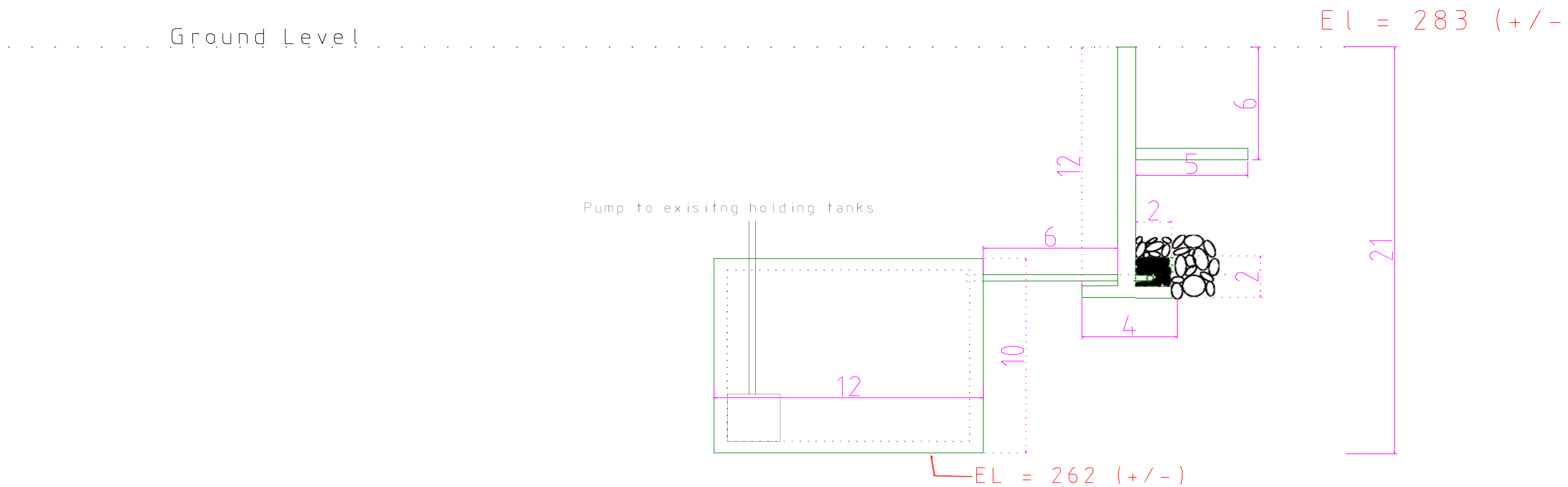
Plan View
Paul Bourke
Santa Rita Spring
All dimensions in feet
D1: 1 of 3



Section A-A

Paul Bourke
Santa Rita Spring

All dimensions in feet	D1: 2 of 3



Paul Bourke	
Santa Rita Spring	
All dimensions in feet	D1: 3 of 3

Section 5: New Design Concept Summary

Based on the findings of this investigation, we propose the following elements and parameters for design of a facility that will capture all of the water being delivered to the site by the natural system.

The recommended design will:

1) Utilize a cutoff wall intercepting the water-bearing conduits at the contact between the overlying limestone aquifer and the underlying clayey aquiclude, the foundation for which will be set at least 1.5 ft. into the aquiclude layer (Section 3.2.2: Figure 3.5 a, b, c and d).
2) The French drain must be capable of transmitting discharge of up to 1220 gpm from the base of the cutoff wall into the spring box. (Section 2.4.2: Figure 2.11).
3) Utilize a dual pumping system to pump the spring water from the new spring box up to the existing facility (Section 4.2: Figure.4.5). The dual system will:
    a. Provide redundancy should one of the pumps fail.
    b. Each pump should be capable of pumping up to 750 gpm to deal with the mean expected discharge of 735 gpm.
    c. Allow the water to be pumped economically (*i.e.*, with a single pump) when spring discharge is low (e.g. during the dry season).
    d. Accommodate high spring discharge by using both pumps in tandem.
4) Have overflow hatches built into the sides of the access hatch to the new spring box. This will allow water to escape from the spring box to surface channels if the pumping system fails or is overwhelmed by peak, i.e., storm-driven spring discharge (Section 4.2).
5) Have clean-outs attached to the ends of the collector piping to facilitate cleaning and purging the French drain (Section 4.1.1).
6) Automatic diversion valves should be fitted to the pipes connecting the SB and the existing SRS and controlled by a turbidity sensor to prevent turbid water entering the GWA system (Section 4.2).
7) Collect the spring water from a protected underground source to preserve its classification as groundwater. Specifically,
    a. The French drain collector pipes will be located at the base of the cutoff wall, surrounded by a minimum of six inches of washed gravel, and wrapped in a geotextile filter fabric to prevent soil clogging the pipe.
    b. Surface water percolation into the French drain will be prevented by the placement of a horizontal concrete ledge attached to the cutoff wall above the collector piping.
    c. Surface water runoff will be prevented from entering the French drain by a surface water diversion channel placed up-slope of the cutoff wall.
8) Once the cutoff wall is in place, the hydraulic pressure forcing the outside water into the compartments will be relieved (Section 1.1). The leaks in the floors of Compartment 1 and 2 will therefore need to be sealed to ensure that water pumped into the existing compartments does not leak out.
9) Exploratory trenching for the cutoff wall should start in the southwest corner by borehole 10 (Figure 4.1) and be dug northeasterly so that the current SRS facility can continue to collect spring water for as long as possible during construction.

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Section 6: Suggested Areas for Development

There are springs and water seeps emerging all around the Alifan Limestone cap that covers the western mountains of Southern Guam.

6.1 Seepage at Our Lady of Guadalupe Church

Father Krzysztof Szsafarski, pastor of the Our Lady of Guadalupe Church, granted permission to install a rain gauge on the roof of the church. While installing the rain gauge, Fr. Krzysztof mentioned that the church was having subsidence issues due to water flowing under the foundation. In addition, the owners of the house directly upslope of the church reported water flowing around their property, especially after heavy rainfall. Based on this local information and proximity to the SRS site, further investigation is warranted. If the water flowing from this area could be intercepted economically, it might not only alleviate the church's subsidence problem but also provide additional spring water that could be utilized by GWA. We recommend exploring for this water source in this adjacent area to assess whether there is potential for development which could augment the SRS supply.

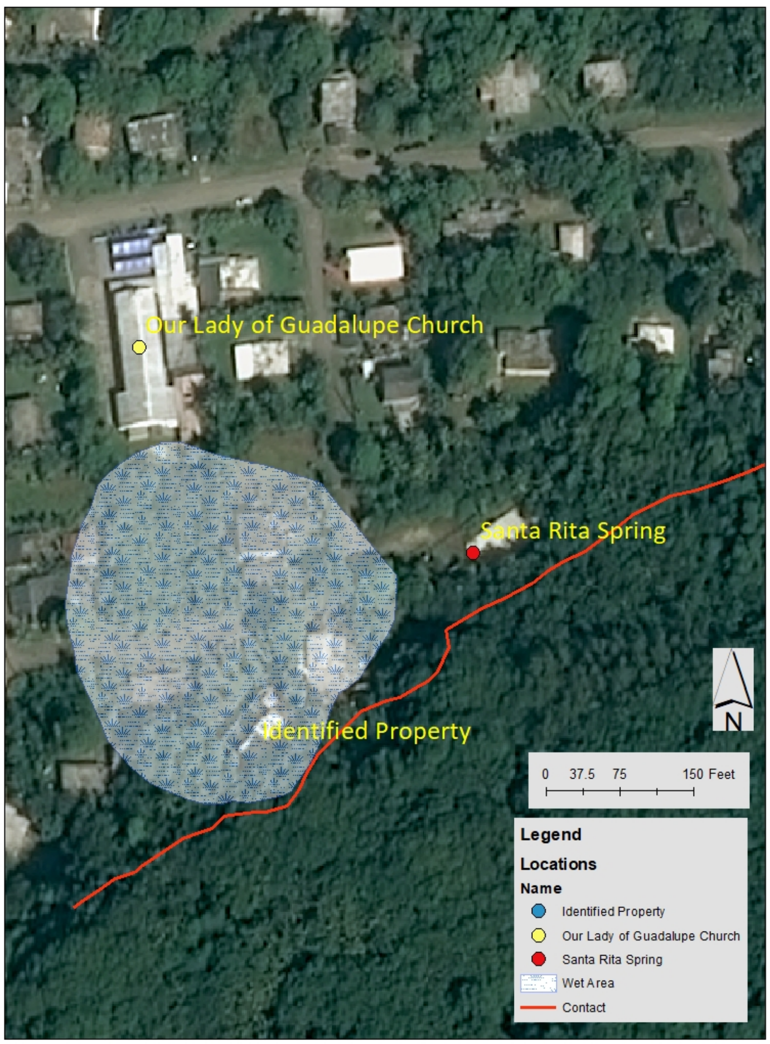

Figure 6.1. Location of additional groundwater source behind the church.

6.2 Possibility of natural reservoirs under the Alifan Limestone cap

The GIS analysis of the electromagnetic survey carried out by the USGS in 1985 revealed two prospective closed depressions in the volcanic basement topography (Figure 6.2). These depressions could form significant reservoirs. The cross-sections A-A' and B-B' in Figure 6.2 reveal the size and depth of the depression in the volcanic basement topography between the Bona Spring and the Santa Rita Spring. A new and more focused electromagnetic study of these areas would need to be carried out to determine the true scope and scale of these depressions.

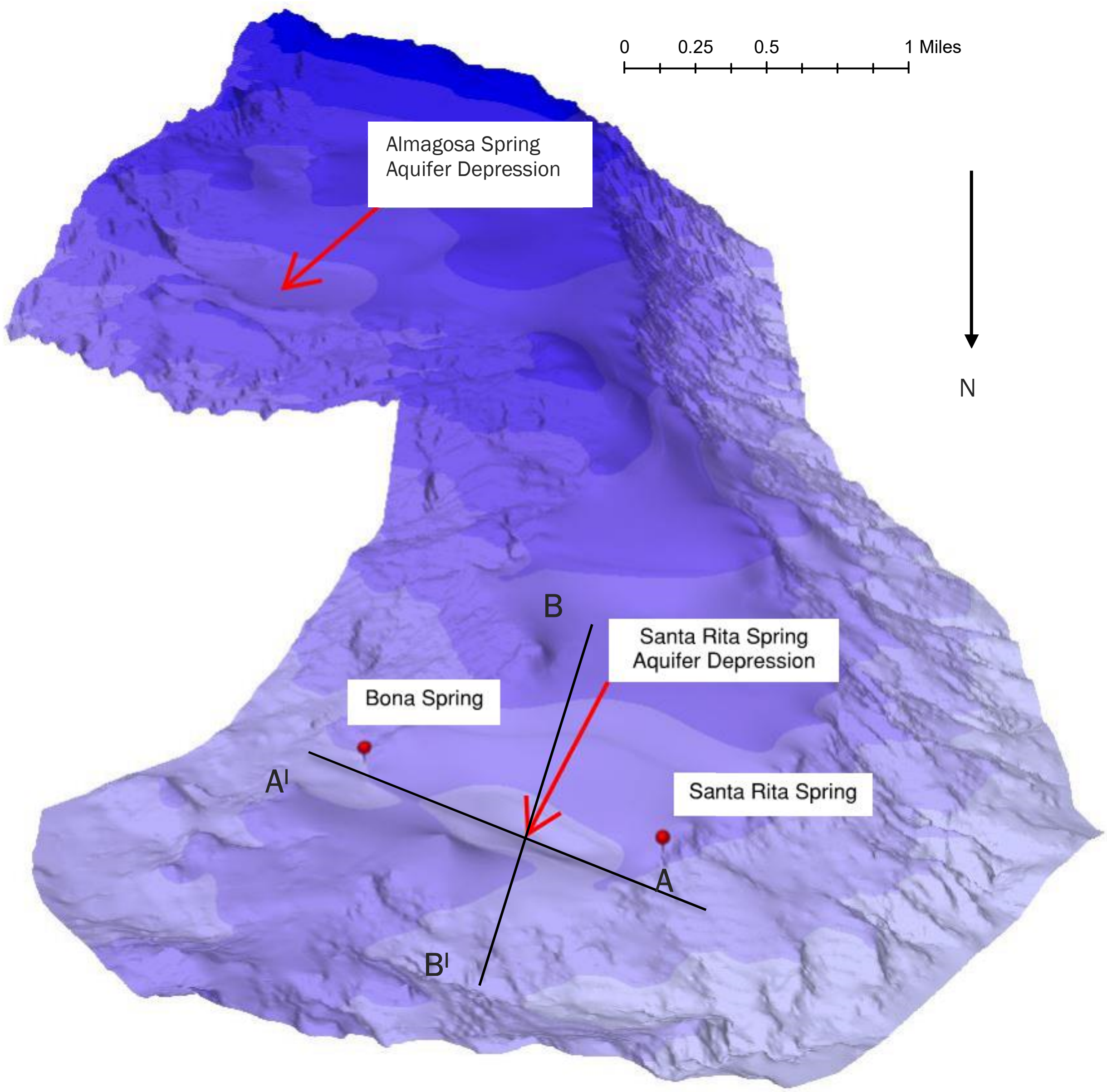

Figure 6.2. 3D model of the underlying volcanic basement topography with the two possible areas of depression indicated

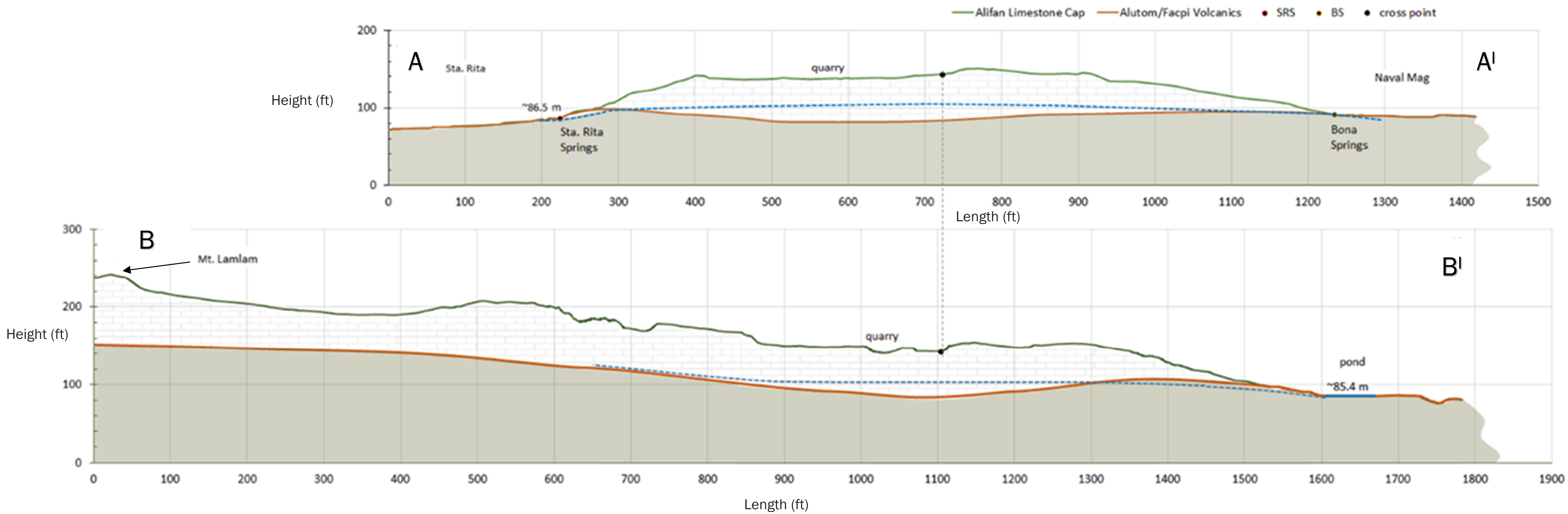

Figure 6.3. Cross section of the Alifan cap running north to south from SRS to Mt Lamlam (B—B^I) and east west from the Bona spring to SRS (A—A^I) showing the water table elevation and the estimated size of the inferred reservoir depression in the volcanic Alutom formation

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Appendix A: Santa Rita Project Proposal

Proposal

Hydrogeologic Survey of Santa Rita Spring: Determination of Its Natural Capacity and Potential Development Options

1. Background. The Santa Rita Spring is a natural freshwater spring that rises from a hillslope above the village of Santa Rita. In 1929, Navy engineers installed a concrete impoundment and reservoir to capture and contain the spring-water discharge. Spring water captured by the structure currently supplies an estimated 0.07 to 0.58 MGD (50 to 400 gpm) to the GWA system servicing Santa Rita area customers. During recent years, however, it has become apparent that there is substantial spring-water discharge near and around the impoundment. This could include water that was never captured by the impoundment, or new spring flow that has emerged since the impoundment was installed, or flow that was originally captured by the impoundment, but which has since re-routed itself above or around the impoundment—or some combination of the three. The total amount of such discharge is currently not known, but besides representing undeveloped potential capacity, water piping around the structure presents a threat the integrity of the impoundment.

   Besides receiving local natural spring discharge, the reservoir at the site currently also receives an additional 0.94 MGD (650 gpm) from the Navy water system. Navy water, however, will costs GWA 8.64 cents per 1000 gal, 1.18 times as much as the GWA rate charged to its customers. GWA's wholesale cost to produce Santa Rita Spring water is about 2.5 cents per 1000 gal; thus the rate paid to the Navy is more than three times GWA's production cost. f the Santa Rita Spring facility could be economically re-engineered to capture sufficient additional spring water so as to relieve GWA from having to purchase additional water from the Navy, GWA could realize substantial savings. GWA engineers and managers are therefore interested in determining 1) whether, and how much, additional spring discharge could be captured at the Santa Rita Spring site; and 2) what kinds of engineering options would be feasible for expanding capacity and increasing the production from the spring.

2. Objectives. To answer these questions, the objectives of the project would include determining the following:

   a) Watershed characteristics. Delineate the hydrologic boundaries, vegetation, land use, and other conditions that might affect the quantity and quality of recharge;

   b) Water budget. Evaluate the spring's water budget (recharge, storage, discharge);

   c) Spring hydrogeology. Investigate the geologic conditions (soil cover, bedrock, and flow paths) that control the spatial distribution, amounts, and timing of spring discharge at and around the site;

   d) Spring hydrology. Quantify the total spring flow (volume per unit time) at the site, including its responsiveness to seasonal recharge cycles, and to ordinary rain showers and heavy storms;

   e) Natural water quality controls. Characterize the baseline quality (mineral and sediment content) of the spring water, to include how water quality might be affected by seasonal recharge cycles, ordinary and heavy storms, and by changes in watershed conditions or management practices; and

   f) Recommendations. Recommend options for improving the efficiency of the impoundment and capturing flow that currently escapes it.

2. Scope. The proposed project would have the following scope.

a) Personnel: The project will be led by WERI Senior Hydrogeologist, Dr. John Jenson, assisted by WERI Groundwater Hydrologist, Dr. Nathan Habana. Together, they will also supervise a graduate research assistant who will assist with field and laboratory work and build a professional master's thesis around the project in UOG's Graduate Environmental Science Program. Dr. Jenson will lead the fieldwork and overall project. Dr. Habana will lead the GIS and related geospatial and hydrographic analyses, while also contributing to the fieldwork. WERI's meteorologist, Dr. Mark Lander, will assist and advise in the field and laboratories on rainfall data collection and analyses of rainfall, recharge, and spring-flow data.

b) Facilities and equipment. Fieldwork will be conducted on site, using hand-held instruments, tools, and equipment (including hammer-driven piezometers). Field techniques for this project will be limited to what can be done without drilling or excavating with heavy equipment. Water quality analyses will be conducted in WERI's Water Quality Laboratory. Geospatial analysis will be conducted in WERI's Hydrology Computing Laboratory.

c) Timeframe. This will be a two-year project, sufficient to capture a full water year (wet season-dry season cycle) and accomplish the required preparatory fieldwork and related laboratory analyses.

d) Education and training. The project will educate and train a young professional with a general understanding of local groundwater hydrology and specific knowledge of Santa Rita Spring hydrogeology, whose new-found expertise will be available to GWA and the rest of the local water resource management community.

3. Tasks, timelines, and methods. Specific tasks include the following, some of which will be sequential, and some concurrent:

1) Literature search: We will begin by locating, compiling, and archiving relevant historical scientific, engineering, and management records. The task will begin immediately, but will continue throughout the project. The bulk of this effort will be concentrated in the first six months of the project.

2) Watershed inventory: The next major component of the project will be a comprehensive GIS analysis incorporating existing geospatial data (e.g., LiDAR and aerial photos), with ground-truth from a concurrent field investigation (Task 3, below) of the watershed. Objectives of the watershed inventory will include identifying the hydrological boundaries of the watershed and watershed hydrologic properties that affect storm water capture, infiltration, and runoff, including vegetation, urbanization, and land use. This task will begin immediately, so as to provide essential data for water-budget evaluation (Task 4, below) and interpretation of spring-flow hydrographs (Task 5, below). The bulk of this work will occupy the first year, but maps and geospatial data sets will be updated and refined throughout the project.

3) Hydrogeologic field investigation: The hydrogeologic field study will consist of two parts, which will be conducted concurrently. The first will be a study of the area immediately around the spring to precisely locate its discharge points and identify the potential capacity and development prospects for each. It is anticipated that this will require installation of some instrumentation, such as piezometers to measure the distribution of hydraulic head in and around the spring site. Over the same time span, we will also traverse the entire watershed to identify geologic conditions that control natural infiltration, storage, and transmission of groundwater in the watershed. These investigations will begin early in the project, and run throughout it, concurrently with water-budget evaluation (Task 4, below) and interpretation of spring-flow hydrographs (Task 5, below).

4) Water budget evaluation: The fourth component of the project will be the evaluation of the water budget for the catchment and aquifer that feeds the spring, to include upper and lower estimates of aquifer recharge, runoff, storage, and the likely pathways and total potential volume of groundwater flow to the

spring. This will require installation, maintenance, data collection, and analysis of data from at least one rain gage installed in the watershed for at least one year. It is anticipated that the rain gauge will be installed and tested during the first six months of the project, so as to be in place, collecting reliable data during at least one full wet season-dry season cycle inside the two-year duration of the project.

5) Spring-flow analysis: Spring-flow analysis will have two parts. The first will be a hydrographic evaluation of the flow from the spring to determine how the quantity and timing of flow relates to seasonal changes in rainfall and to episodic changes, such as local thunderstorms or tropical storms. This will require installation, maintenance of a weir and logger or flow-meter by which to monitor springflow and its relationship to the timing and amounts of rainfall in the catchment. It is anticipated that, along with the rain gauge, these instruments will be installed and tested during the first six months of the project, so as to be in place, collecting reliable data during at least one full wet season-dry season cycle inside the two-year duration of the project. Throughout the project, we will also collect water samples to determine how water quality relates to season and episodic changes in spring flow. The sampling program with thus consist of regular (e.g., weekly) sampling, as well as intensive (e.g., daily) sampling following major storm events. Samples will be analyzed for chemical clues regarding water contact and residence times in soil and bedrock, and whether the bedrock aquifer is volcanic or limestone. We will thus use hand-held instruments and kits, as well as instruments at the WERI Water Quality Laboratory, to measure basic natural water parameters including electrical conductivity, total dissolved solids, pH, alkalinity, and turbidity.

6) Development alternatives: From the outcomes of the above tasks, we will identify and explain feasible alternatives for capturing, impounding, and utilizing spring discharge, so as to maximize the production from the spring. This task will culminate during the final six months of the project.

7) Design recommendations: For each of the options identified in Task 6, above, we will describe their attributes and limitations for development and operation of the spring. Accordingly, we will provide recommendations and considerations for the successful design and implementation of each. These will be prepared at the end of the project.

4. Schedule. The following is the anticipated schedule of the project:

    1) Jan-May 2016: Recruit and hire student intern/research assistant. Begin literature search (Task 1), GIS and field study (Tasks 2 and 3), and install rain gage in catchment (Task 4).
    2) Jan-May 2016: Install weir/flow-meter in spring to begin collecting spring-flow data (Task 5).
    3) Jun-Aug 2016: Conduct intensive site investigation to identify the specific concentrations and pathways of water flow into and out of the spring site. Install instrumentation to characterize and quantify spring water discharge. (Tasks 3-5)
    4) Sep-Dec 2016: Compile and integrate findings to develop the "big picture" of catchment and aquifer capacity and "plumbing". Begin study of alternatives for design and optimal operation of spring.
    5) Jan-May 2017: Complete one annual cycle of rainfall and concurrent springflow measurements. Integrate full annual water cycle data with historical statistical data to predict spring performance in response to long-term end-member conditions, i.e., heaviest storms and most severe and extended droughts that might be expected (based on the historical record).
    6) Jun-Dec 2017: Completion of the following final products, i.e.," deliverables." from the project:

5. Deliverables. Products are anticipated at the completion of each phase of the project are as follows:

Phase 1: Literature search, set-up, and preliminary investigations (end of sixth month):

- Brief written progress report and verbal presentation to GWA engineering staff on work to date, knowledge gained and problems encountered to date, and actions anticipated during next six months.

Phase 2: Watershed inventory, watershed and site instrumentation, initial field investigations (end of first year):

- Brief written progress report and verbal presentation to GWA engineering staff on work to date, knowledge gained and problems encountered to date, and actions anticipated during next six months.

Phase 3: Completion of water-year study: initial water budget, hydrographic and chemical results (middle of second year):

- Brief written progress report and verbal presentation to GWA engineering staff on work to date, knowledge gained and problems encountered to date, and actions anticipated during next six months.

Phase 4: Completion of water-year study: water budget, hydrographic and chemical studies (middle of second year):

a) WERI technical report that documents the findings, with a chapter on each of the projects basic objectives. The anticipated technical content of each is outlined below:

   Chapter 1 - Watershed: Maps, photos, and tables delineating the watershed boundaries and describing the watershed terrain, surface, and geology.

   Chapter 2 - Water Budget: Diagrams, tables, spreadsheets, and graphs illustrating and explaining the amounts and relationships between rainfall, evapotranspiration, runoff, percolation, storage, recharge, transmission, and discharge, and the characteristics of the watershed surface, soil layers, and bedrock (which will be described in Chapter 1) that affect them.

   Chapter 3 - Spring Hydrogeology: Photos, diagrams, and maps illustrating and explaining the internal "plumbing" of the spring, i.e., how water is captured, stored, transmitted, and discharged from the aquifer that supplies the groundwater to the spring. Specifics aspects to be addressed include the nature and thickness of the soil layer, the types and distributions of the bedrock in the aquifer, whether volcanic rock or limestone, and the characteristics of the bedrock that control spring hydrology (Chapter 4, below).

   Chapter 4 - Spring Hydrology: Photos, diagrams, tables, spreadsheets, and graphs illustrating and explaining how spring flow is related to long-term, seasonal rainfall, and to short-term, episodic rainfall. The spring hydrology will provide the basis for evaluating the minimum, average, and maximum capacities of the spring, and the consequent design parameters for impoundment storage capacity and production management.

   Chapter 5 - Natural Variables Controlling Water Quality: Photos, diagrams, tables, spreadsheets, and graphs illustrating and explaining how natural water quality parameters, such turbidity, hardness, and pH relate to spring hydrology. This will provide a basis for knowing what routes the water takes to the spring under different conditions and under what conditions water quality might be degraded, and in what ways.

   Chapter 6 - Recommendations: Recommendations will include diagrams, flow charts, and tables explaining the estimated capacities that might expected from different development options, along with the advantages and disadvantages of each. These will provide the basis for informed engineering decisions on how to best capture, store, and manage the production of drinking water from the spring.

b) Formal verbal presentation of the technical report to GWA senior management and technical staff, presenting and summarizing the findings documented in the technical report.

c) Completion of a master's degree in Environmental Science, geoscience-engineering (hydrology) by the student employed on the project.

6. Budget

The following budget provides for a two-year full-time WERI/RCUOG research assistantship for a WERI-based graduate student, supervised at WERI by Dr. Jenson and Dr. Habana. The proposal thus requests 6 weeks annual salary each for Dr. Jenson and Dr. Habana, who will not only supervise the student's thesis research but will contribute their own expertise to the execution of the project. In addition, the proposal requests 2 weeks annual salary for Dr. Mark Lander, who will assist in the deployment and maintenance of the rain gages and the interpretation and application of rainfall data to the water budget analyses.

The proposal also provides for supplies and equipment to support GIS laboratory analyses and field instrumentation, specifically the installation of piezometers and loggers to measure groundwater levels in an around the spring site, and flow meters to monitor spring flow. No funds are requested for travel or consultant services. UOG overhead costs, calculated at 59% of total salary, comprise 28% of the total budget.

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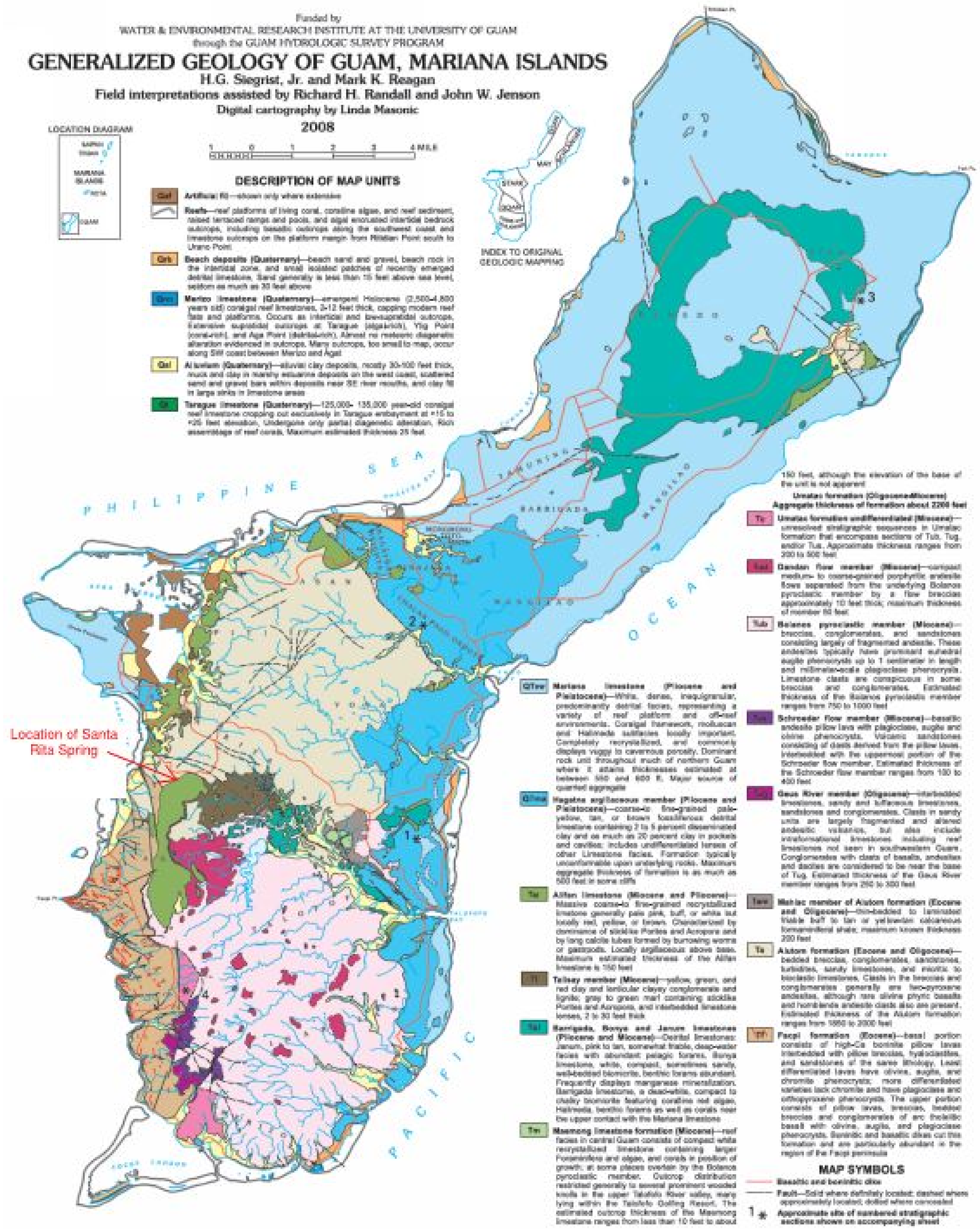
Appendix B: General Geology and Stratigraphy of Guam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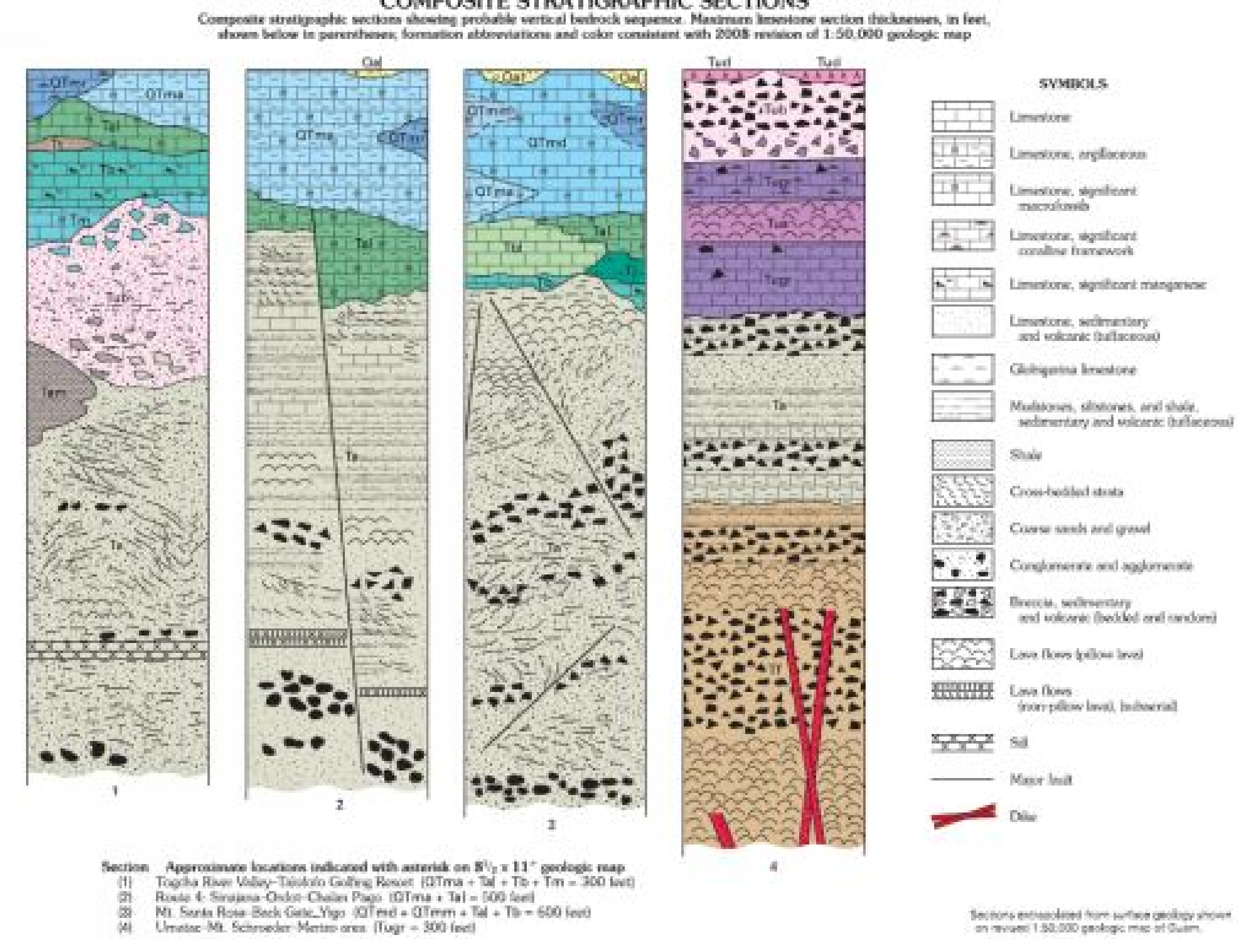
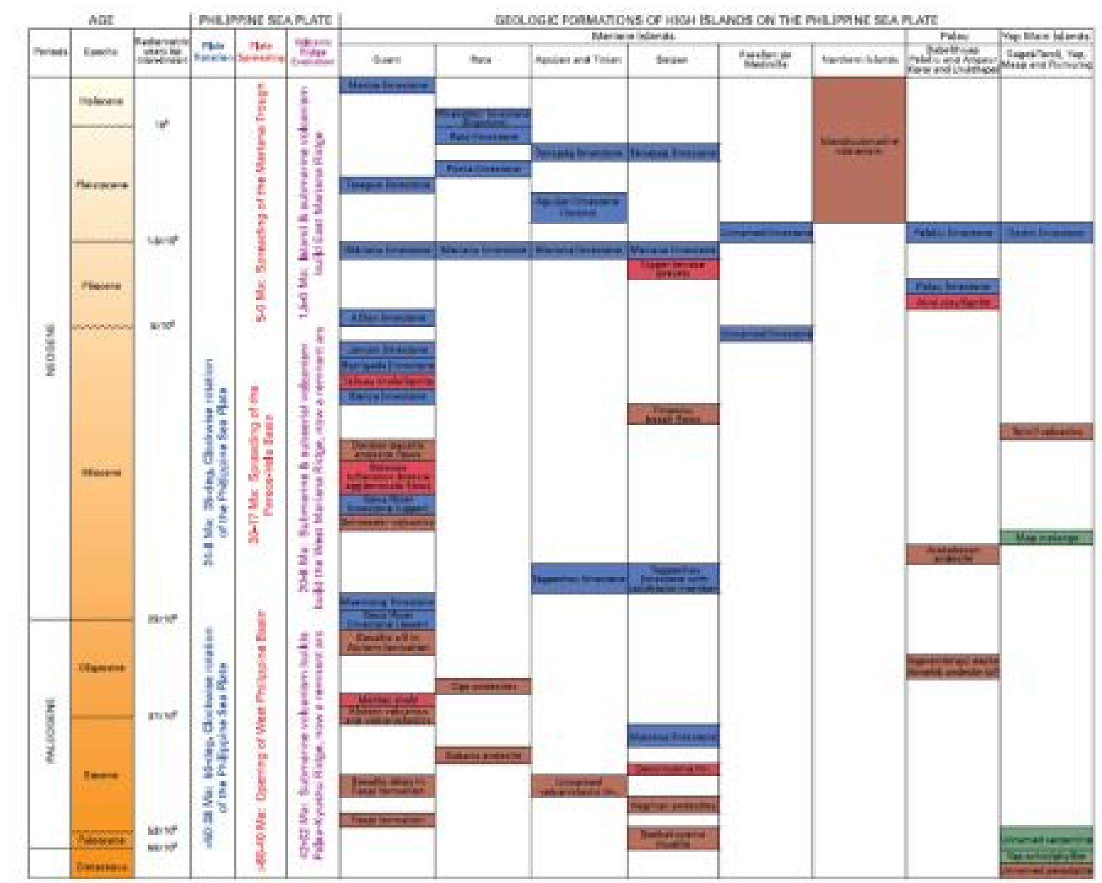
H.G. Siegrist, Jr. and Mark K. Reagan
Field interpretations assisted by Richard H. Randall and John W. Jenson
Digital cartography by Linda Masonic
2008
LOCATION DIAGRAM
DESCRIPTION OF MAP UNITS
INDEX TO ORIGINAL GEOLOGIC MAPPING
PHILIPPINE SEA
PACIFIC OCEAN
Location of Santa Rita Spring
MAP SYMBOLS


COMPOSITE STRATIGRAPHIC SECTIONS
Composite stratigraphic sections showing probable vertical bedrock sequence. Maximum limestone section thicknesses, in feet, shown below in parentheses; formation abbreviations and color consistent with 2008 revision of 1:50,000 geologic map
SYMBOLS
Limestone
Limestone, argillaceous
Limestone, significant macroliths
Limestone, significant coralline framework
Limestone, significant manganese
Limestone, sedimentary and volcanic (tuffaceous)
Globigerina limestone
Mudstones, siltstones, and shale, sedimentary and volcanic (tuffaceous)
Shale
Cross-bedded strata
Coarse sands and gravel
Conglomerate and agglomerate
Breccia, sedimentary and volcanic (bedded and random)
Lava flows (pillow lava)
Lava flows (non-pillow lava), (subaerial)
Sill
Major fault
Dike
Section Approximate locations indicated with asterisk on 8½ x 11" geologic map
(1) Togcha River Valley-Talofofo Golfing Resort (QTma + Tal + Tb + Tm = 300 feet)
(2) Route 4: Sinajana-Ordot-Chalan Pago (QTma + Tal = 500 feet)
(3) Mt. Santa Rosa-Back Gate_Yigo (QTmd + QTmm + Tal + Tb = 600 feet)
(4) Umatac-Mt. Schroeder-Merizo area (Tugr = 300 feet)
Sections extrapolated from surface geology shown on revised 1:50,000 geologic map of Guam.


AGE
PHILIPPINE SEA PLATE
GEOLOGIC FORMATIONS OF HIGH ISLANDS ON THE PHILIPPINE SEA PLATE
NEOGENE
PALEOGENE

Appendix C: Weir Flow Data

TIME	FLOW (gpm)	Date			Rainfall (in)			in/day
1/25/2017 11:45	183.582581	1/25/17 11:00	11:00:10 AM	0	0	1/25/2017	1/26/2017 0:00	0.39
1/25/2017 12:00		1/25/17 12:00	12:00:10 PM	0	0	1/25/2017	1/27/2017 0:00	0.06
1/25/2017 12:15	175.829819	1/25/17 13:00	1:00:10 PM	0	0	1/25/2017	1/28/2017 0:00	0.21
1/25/2017 12:30	245.900375	1/25/17 14:00	2:00:10 PM	0	0	1/25/2017	1/29/2017 0:00	0.04
1/25/2017 12:45	242.554108	1/25/17 15:00	3:00:10 PM	0	0	1/25/2017	1/30/2017 0:00	0.15
1/25/2017 13:00	241.497162	1/25/17 16:00	4:00:10 PM	0	0	1/25/2017	1/31/2017 0:00	0.04
1/25/2017 13:15	247.471771	1/25/17 17:00	5:00:10 PM	0	0	1/25/2017	2/1/2017 0:00	0.3
1/25/2017 13:30	232.327408	1/25/17 18:00	6:00:10 PM	0	0	1/25/2017	2/2/2017 0:00	0.38
1/25/2017 13:45	226.9673	1/25/17 19:00	7:00:10 PM	0	0	1/25/2017	2/3/2017 0:00	0.19
1/25/2017 14:00	227.834717	1/25/17 20:00	8:00:10 PM	0	0	1/25/2017	2/4/2017 0:00	0.1
1/25/2017 14:15	226.228317	1/25/17 21:00	9:00:10 PM	0	0	1/25/2017	2/5/2017 0:00	0.26
1/25/2017 14:30	230.02066	1/25/17 22:00	10:00:10 PM	0	0	1/25/2017	2/6/2017 0:00	0
1/25/2017 14:45	229.445847	1/25/17 23:00	11:00:10 PM	0	0	1/25/2017	2/7/2017 0:00	0.06
1/25/2017 15:00	230.095139	1/26/17 0:00	12:00:10 AM	0	0.39	1/26/2017	2/8/2017 0:00	0.05
1/25/2017 15:15	237.682953	1/26/17 1:00	1:00:10 AM	0	0.39	1/26/2017	2/9/2017 0:00	0
1/25/2017 15:30	230.095078	1/26/17 2:00	2:00:10 AM	0	0.39	1/26/2017	2/10/2017 0:00	0
1/25/2017 15:45	229.353134	1/26/17 3:00	3:00:10 AM	0	0.39	1/26/2017	2/11/2017 0:00	0.15
1/25/2017 16:00	230.095078	1/26/17 4:00	4:00:10 AM	0	0.39	1/26/2017	2/12/2017 0:00	0.08
1/25/2017 16:15	230.838196	1/26/17 5:00	5:00:10 AM	0	0.39	1/26/2017	2/13/2017 0:00	0.24
1/25/2017 16:30	231.954849	1/26/17 6:00	6:00:10 AM	0	0.39	1/26/2017	2/14/2017 0:00	0.02
1/25/2017 16:45	233.073288	1/26/17 7:00	7:00:10 AM	0	0.39	1/26/2017	2/15/2017 0:00	0.2
1/25/2017 17:00	235.541412	1/26/17 8:00	8:00:10 AM	0	0.39	1/26/2017	2/16/2017 0:00	0.04
1/25/2017 17:15	231.113556	1/26/17 9:00	9:00:10 AM	0	0.39	1/26/2017	2/17/2017 0:00	0

Continues for 14775 rows

Appendix D: Rain Gauge Data Comparison

SRS1					SRS 2						SRS1					SRS2			
Date		tips	Total		Date		tips	Total			Date		tips	Total		Date		tips	Total
9/16/2016	37.66	0	13.5		9/16/2016	0.01	0	14.45			12/19/2016	19.91	0	10.79		12/19/2016	0.01	0	12.52
9/17/2016	37.67	0.01			9/16/2016	0.02	0.01				12/19/2016	19.92	0.01			12/19/2016	0.02	0.01	
9/17/2016	37.68	0.01			9/16/2016	0.03	0.01				12/19/2016	19.93	0.01			12/19/2016	0.03	0.01	
9/17/2016	37.69	0.01			9/16/2016	0.04	0.01				12/19/2016	19.94	0.01			12/19/2016	0.04	0.01	
9/17/2016	37.7	0.01			9/16/2016	0.05	0.01				12/19/2016	19.95	0.01			12/19/2016	0.05	0.01	
9/17/2016	37.71	0.01			9/16/2016	0.06	0.01		Percentage difference		12/19/2016	19.96	0.01			12/19/2016	0.06	0.01	
9/17/2016	37.72	0.01			9/16/2016	0.07	0.01		-7%		12/19/2016	19.97	0.01			12/19/2016	0.07	0.01	
9/17/2016	37.73	0.01			9/16/2016	0.08	0.01				12/19/2016	19.98	0.01			12/19/2016	0.08	0.01	
9/17/2016	37.74	0.01			9/16/2016	0.09	0.01				12/19/2016	19.99	0.01			12/19/2016	0.09	0.01	
9/17/2016	37.75	0.01			9/16/2016	0.1	0.01				12/19/2016	20	0.01			12/19/2016	0.1	0.01	
9/18/2016	37.76	0.01			9/16/2016	0.11	0.01				12/19/2016	20.01	0.01			12/19/2016	0.11	0.01	
9/18/2016	37.77	0.01			9/16/2016	0.12	0.01				12/19/2016	20.02	0.01			12/19/2016	0.12	0.01	
9/18/2016	37.78	0.01			9/16/2016	0.13	0.01				12/19/2016	20.03	0.01		=	12/19/2016	0.13	0.01	
9/18/2016	37.79	0.01			9/16/2016	0.14	0.01				12/19/2016	20.04	0.01			12/19/2016	0.14	0.01	
9/18/2016	37.8	0.01			9/16/2016	0.15	0.01		Average Difference		12/19/2016	20.05	0.01			12/19/2016	0.15	0.01	
9/18/2016	37.81	0.01			9/16/2016	0.16	0.01		7		12/19/2016	20.06	0.01			12/19/2016	0.16	0.01	
9/18/2016	37.82	0.01			9/16/2016	0.17	0.01		14		12/19/2016	20.07	0.01			12/19/2016	0.17	0.01	
9/19/2016	37.83	0.01			9/16/2016	0.18	0.01		2		12/19/2016	20.08	0.01			12/19/2016	0.18	0.01	
9/19/2016	37.84	0.01			9/16/2016	0.19	0.01		**7.67**	**%**	12/19/2016	20.09	0.01			12/19/2016	0.19	0.01	
9/19/2016	37.85	0.01			9/16/2016	0.2	0.01				12/19/2016	20.1	0.01			12/19/2016	0.2	0.01	
9/19/2016	37.86	0.01			9/16/2016	0.21	0.01				12/19/2016	20.11	0.01			12/19/2016	0.21	0.01	
9/19/2016	37.87	0.01			9/16/2016	0.22	0.01				12/19/2016	20.12	0.01			12/19/2016	0.22	0.01	
9/19/2016	37.88	0.01			9/16/2016	0.23	0.01				12/19/2016	20.13	0.01			12/19/2016	0.23	0.01	
9/19/2016	37.89	0.01			9/16/2016	0.24	0.01				12/19/2016	20.14	0.01			12/19/2016	0.24	0.01	
9/19/2016	37.9	0.01			9/16/2016	0.25	0.01				12/19/2016	20.15	0.01			12/19/2016	0.25	0.01	
9/19/2016	37.91	0.01			9/17/2016	0.26	0.01				12/19/2016	20.16	0.01			12/19/2016	0.26	0.01	
9/19/2016	37.92	0.01			9/17/2016	0.27	0.01				12/19/2016	20.17	0.01			12/19/2016	0.27	0.01	
9/19/2016	37.93	0.01			9/17/2016	0.28	0.01				12/19/2016	20.18	0.01			12/19/2016	0.28	0.01	

Appendix E: Hydrograph Calculations

	Date		
Peak Q	4/26/2017	220	gpm
Peak Rain	4/24/2017	2.97	in

Rainfall	Area				
in	mi²	in²	in³	gallons	40% recharge
2.97	0.6178	2480151675	7366050474.75	3.19E+07	1.28E+07

Storm Water (40%)	1.28E+07	gallons
Captured Discharge	7.43E+06	gallons
Percentage	58%	

Base Flow	gpm	gpd	Time 39 Days	Volume
4/23/2017	150	21600	33	712800
6/4/2017	150		33	

Storm Discharge			Storm Discharge	
4/25/2017 20:45	124.700958	1870.51437	7.43E+06	
4/25/2017 21:00	161.68985	2425.34775		
4/25/2017 21:15	187.590408	2813.85612		
4/25/2017 21:30	189.806229	2847.093435		
4/25/2017 21:45	171.975693	2579.635395		
4/25/2017 22:00	178.108215	2671.623225	42847	158.321335
4/25/2017 22:15	191.310471	2869.657065	42847.01042	159.002014
4/25/2017 22:30	183.957565	2759.363475	42847.02083	169.594528
4/25/2017 22:45	177.403122	2661.04683	42847.03125	167.457794
4/25/2017 23:00	176.699615	2650.494225	42847.04167	165.330093
4/25/2017 23:15	181.055206	2715.82809	42847.05208	159.002136
4/25/2017 23:30	180.701324	2710.51986	42847.0625	136.519379
4/25/2017 23:45	183.086487	2746.297305	42847.07292	131.233521
4/26/2017 0:00	183.246521	2748.697815	42847.08333	145.889938
4/26/2017 0:15	168.788528	2531.82792	42847.09375	147.929733
4/26/2017 0:30	181.763809	2726.457135	42847.10417	143.859238
4/26/2017 0:45	173.182693	2597.740395	42847.11458	146.555786
4/26/2017 1:00	173.778122	2606.67183	42847.125	161.341614
4/26/2017 1:15	194.263885	2913.958275	42847.13542	161.393143
4/26/2017 1:30	179.52121	2692.81815	42847.14583	167.920731
4/26/2017 1:45	206.294144	3094.41216	42847.15625	157.270508
4/26/2017 2:00	239.065887	3585.988305	42847.16667	159.293106
4/26/2017 2:15	246.2966	3694.449	42847.17708	157.423477
4/26/2017 2:30	239.372559	3590.588385	42847.1875	159.63475
4/26/2017 2:45	253.98848	3809.8272	42847.19792	157.47467
4/26/2017 3:00	227.913864	3418.70796	42847.20833	144.771072
4/26/2017 3:15	237.43689	3561.55335	42847.21875	159.293381
4/26/2017 3:30	209.006531	3135.097965	42847.22917	145.18689

Data continues for 2902 data points see link

Appendix F: Type Locale Investigation: Talisay Member

FIELD NOTES 1703A

A Field Investigation of a Search for the Type Locality of the Talisay Member of the Alifan Limestone Formation

Date: April, 23, 2018

Geographic Location: U. S. Naval Magazine Base (see 1703A-1 for locality)

Written by: Richard Randall

INTRODUCTION

Dr. John Jenson from the University of Guam asked me if I would be interested in accompanying him to investigate the type locality of the Talisay member of the Alifan limestone formation. Not to let an opportunity of such slip by I gladly accepted, as although I had investigated the Talisay member a number of times I had never really done so at the type locality that is located on the U. S. Naval Magazine property, which is difficult to gain access to.

On the April 23, 2018 I agreed to meet Dr. Jensen at The U. S. Naval Station visitor processing center located just outside the main gate entrance where together with his graduate assistant we met Ms. Maria Lewis who would be our official sponsor who assisted us in acquiring a one-day pass. We also learned that transportation to and within the Naval Magazine would be provided and that Ms Lewis would drive us to the various locations within the magazine that we wanted to investigate. This was quite fortunate for us as a maze of winding intersecting roadways within the magazine can be somewhat confusing.

INVESTIGATION AT STOP 1

Stop 1 is located 200 meters north of the Talisay River at the backside of Building NM465 on the west side of Parson Road that was thought by Dr. Jensen and his assistant to be the type section location Talisay member.

According to Tracey *et al.*,1964 their type section for the Talisay member was assigned one-half mile southeast of the entrance to the Depot, in an excavation behind a loading ramp of the Naval Ammunition Depot where they collected Specimen Fj-5 whose location is shown on their Sample Locality Map of Guam ((Plate 2) [about 250 meters north of the Talisay River]. At this location the Talisay member is faulted against the Alutom formation by a small fault within the outcrop, and the Alutom probably underlies Talisay a few feet beneath the cut [this small fault at the south end of an elongate section of the Alutom formation is mapped on the Tracey *et al.*(1964) Geology map]. At the base of the cut weathered gravel of limestone and volcanic pebbles is overlain by about 5 feet of clayball [basically a round chunk of clay] conglomerate, in turn overlain by 10 feet of dark gray marly [pertaining to, or resembling marl] clay that contains abundant finger-sized fragments of coral, mostly *Porites* and *Acropora,* and mollusc shells. Most of the shells are broken and the coral leached and rotten. Above the marly clay of the Talisay member are 12 feet of thin-bedded argillaceous molluscan limestone and about 10 feet of reddish-brown fine-grained hard limestone typical of the lower part of the Alifan limestone in this area. The above bracketed sections are my comments.

General Overall Setting as Shown on Reference Map Figure 1703A-1: The building rests on the flat level floor of a wedge-shaped cut into the lower southeast slope of a prominent north-south trending oval shaped hill slightly more than 340 feet in elevation at the top that is mostly covered by an outlier of Alifan limestone deposits. Within the general area of this hill a number of other Alifan outliers occur with one of similar size immediately to the north, three smaller ones to the south and a small one to the east. Also within the general area of Building NM465 are three inliers of Alutom volcanic deposits with two located to the south and a narrow elongate one located on the northeast slope of the same hill that Building NM465 is located on that is bordered by younger Alifan deposits on its southwestern side and Talisay deposits on its northeast side. The south end of the inlier is truncated by a small northeast-southwest aligned fault with the downthrown side to the southwest. The intervening surface between all the above inliers and outliers is mapped by Tracey *et al.,*1964 as Talisay deposits.

Description of the deposits behind Building NM465: At the backside of Building NM465 the excavation cut has exposed approximately 15 feet of the original hillside slope. Following is a general physiographic description of the site and location of collected rock samples.

I first made a cursory inspection at the site to locate the Alutom deposits on which type section of the Talisay was faulted against but was unable locate such an exposure.

The basal 5 to 6 feet of the cut consists of a tree, brush and weed covered region that irregularly slopes upward to a 10-foot local vertical fresh exposure of a light yellowish tan, faintly bedded rock. Upon removing the vegetation cover of the lower slope, it was shallowly excavated at a series of holes that revealed a weathered gravel of limestone and volcanic pebbles intermixed with a pale yellowish tan plastic clay where water saturated and a grainy plastic consistency where less wet, which was similar to basal material described at the Talisay type location. Since I saw Dr. Jensen collect some of the pebbly clay I did not personally collect a sample.

Next I investigated the 10 foot local vertical fresh exposure of a light yellowish tan faintly bedded rock located immediately above the lower basal slope, which was definitely not the 5 foot layer of clayball conglomerate described at the Talisay type location. The freshness of the rock surface and presence of penetrating tree roots indicates that it is a local exposed face where a section has most likely been spalled away by root pressure. This exposure is an argillaceous rudstone limestone, typical of the lowermost deposits of the Alifan limestone formation. Scattered throughout the exposure were pieces of coral stems and mollusc valves. Rock Sample 1703A-1 was collected in the middle part of the exposure.

Above the freshly exposed vertical section the steep to vertical slope continues upward to a narrow 10 to 12 foot wide terrace at about the height of the roof comb of Building NM465 (estimated at about 30 ft.) which was highest region investigated. The backwall of the terrace sloped steeply upward into a densely forested region. Random sampling of the terrace revealed an argillaceous rudstone limestone similar to that at the lower exposure, but with slightly less clay content, presence of white coralline mottling, and scattered pockets of fossil soil. Several unfilled soil pipes were observing on the terrace surface. Three rock samples were collected from the terrace surface; 1703A-2 from the outer terrace margin, 1703A-3 from the middle surface of the terrace, and 1703A-4 from a section of a fossil soil pocket at the outer terrace margin.

Sampling of the terrace backwall slope revealed a somewhat different argillaceous rudstone in that it distinctly contained less clay and more abundant fossil coral stems. Three rock samples were collected from the terrace backwall slope: 1703A-5 slightly above the terrace floor, 1703A-6 about 6 feet above the terrace floor, and 1703A-7 about 10 feet above the terrace floor. Both the height of the narrow terrace floor and steep to vertical section below it attenuates gently downward to the northwest, possibly in response to downthrown side of the above-mentioned fault.

A short excursion was made about 100 feet north of the building road cut where a sample of Alifan limestone (Sample No. 1703A-8) was collected that protruded up through a veneer of sheetwash deposits. The sample was collected from about the same elevation as sample 1703A-1 and is of the same lithology, composition, and color.

A short excursion on the east side of Parson Road was made on a gently eastward dipping slope covered with patches of tall grass and scattered trees, The surface consists of loose sheetwash sand and gravel with occasional scattered cobbles. One-half of one of the cobbles was collected (1703A-9) close to the roadway that revealed a pure white detrital limestone with scattered coral stems and mollusc molds that is quite different from the argillaceous material in the vicinity of Building NM465. No in-place outcrops were noted, so the origin of the scattered cobbles were of questionable origin. possibly of exotic origin from nearby base course roadway material brought in from another location.

Description of the Collected Samples

The following sample descriptions are based upon field and 10x to 20x microscopic examination.

Sample 1703A-1 consists of an argillaceous, detrital, fossilliferous, yellowish tan rudstone limestone that is moderately well indurated. It breaks with an irregular chalky fracture surface that at places displays occasional irregularly spaced lenses and horizontal thin marly somewhat friable brown clay rich pockets and layers up to 5 mm thick. Fossils within the overall unit and sample contains occasional unoriented, separated, entire or broken bivalve shells and broken round coral stem pieces.

Sample 1703A- 2 consists of an argillaceous, detrital, well indurated, fossilliferous, rudstone limestone, that breaks with an irregular surface fracture. Overall the color is a somewhat mottled buff and off white gray with scattered crystalline white patches and pockets of brown granular clay. The mottled off white, buff to light brown appearance is the result of white crystalline rounded gravel to pebble-sized and round stem-like carbonate pieces (probably of coral origin) intermixed with abundant rounded and broken gravel to pebble-sized limestone and volcanic material weathered to a tan to brown clay. The gravel and pebble-sized carbonate and weathered volcanic clasts are mostly in framework contact with the void spaces between them in-filled with mostly fine grained material cemented with calcite.

Sample 1703A-3 consists of an argillaceous, detrital, mottled, fossilliferous, rudstone limestone similar to 1703A-2, but differs in having a section of a reddish brown soil pocket at one end and at the other end has a thin layer, less than a half inch in thickness, of lithified gray sand-sized grains.

Sample 1703-4 consists of a section of a pocket of calcite cemented reddish brown fossil soil. The exposed surface is weathered into a lumpy irregular surface, characteristic of the fresh fractured surface.

Samples 1703A-5, 1703A-6 and 1703A-7 all three samples consists of an argillaceous, detrital, mottled, fossilliferous, rudstone limestone similar to 1703A-2, but differs in having distinctly less clay content and more abundant broken coral stems. One end of Sample 1703A-5 shows a cross section of a coral stem replaced with crystalline calcite.

Sample 1703A-8 is of the same lithology, composition, and color as Sample 1703A-1.

Sample 1703A-9 consists of a, detrital, white colored, fossilliferous, limestone that is well indurated and breaks with an irregular surface fracture. The sample lacks contaminated material of volcanic origin and thus is different from the argillaceous material collected from the vicinity of Building NM465.

Interpretation of Region Behind Building NM465 in Respect to it Being the Type Section of the Talisay Geologic Unit

My interpretation of what we found behind the backside of Building NM465 on the west side of Parson Road was quite different from the above type description. Foremost of which was the absence of an Alutom section against which the Talisay deposits were faulted against. Secondly the up-section sequence of the described geologic units behind Building NM465 is significantly different from that described at the type section.

Google Earth view shows a building 665 feet north of and on the same side of Parson Road as Building NM465, that is a much more likely location of the Talisay type section. This building is also one-half mile from the main gate of the magazine and is at a dowthrown side of a short fault section of an Alutom inlier.

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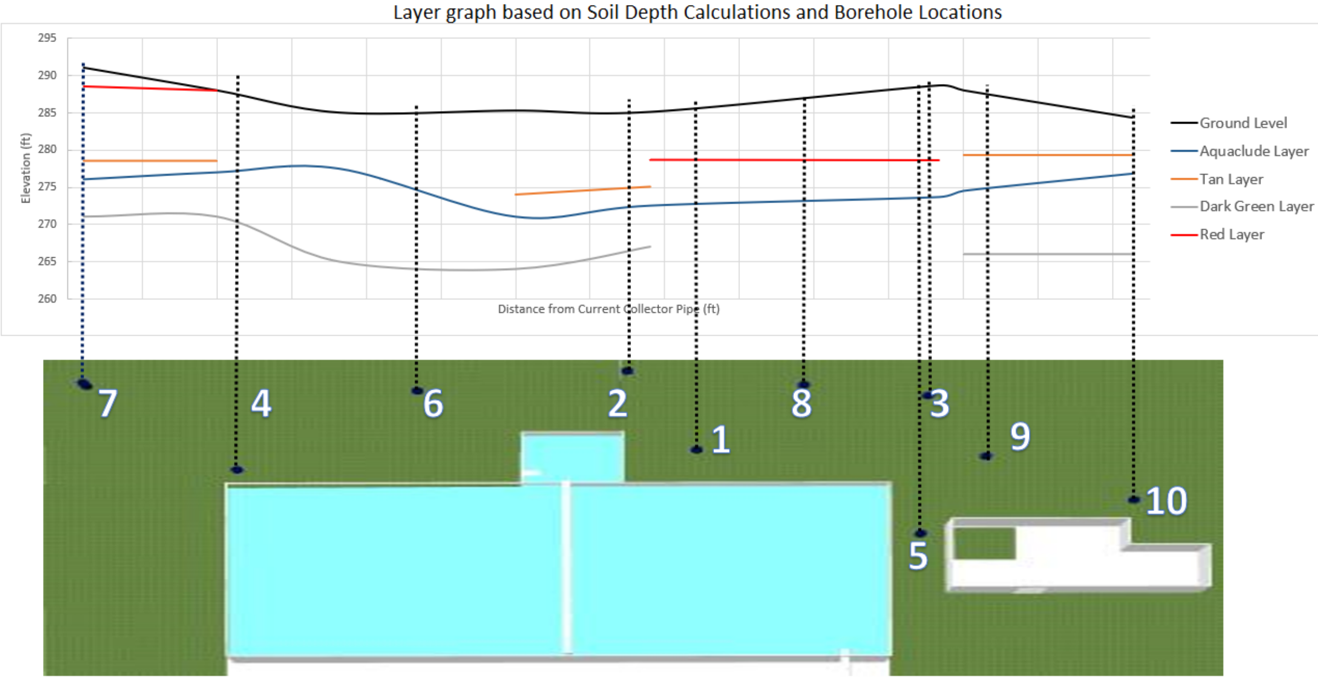
Appendix G: Drilling Logs

Borehole Stratigraphy																				
Depth (ft)	Soil	Elevation 7	Soil	Elevation 6	Soil	Elevation 1	Soil	Elevation 8	Soil	Elevation 9	Soil	Elevation 4	Soil	Elevation 2	Soil	Elevation 3	Soil	Elevation 5	Soil	Elevation 10
0.0		291.1		285.0		284.0		285.1		288.7		283.4		284.0		284.7		283.5		284.3
2.5	RED	288.6	TAN	282.5	TAN	281.5	TAN	282.6	RED	286.2	TAN	280.9		281.5	TAN	282.2	RED	281.0	TAN	281.8
5.0	Tan	286.1	TAN	280.0	TAN	279.0	TAN	280.1	RED	283.7	TAN	278.4		279.0	TAN	279.7	RED	278.5	TAN	279.3
7.5	Tan	283.6	LIGHT G	277.5	TAN	276.5	DARK G	277.6	RED	281.2	Dark G	275.9		276.5	TAN	277.2	RED	276.0	LIGHT G	276.8
10.0	Tan	281.1	LIGHT G	275.0	TAN	274.0	TAN	275.1	RED	278.7	Dark G	273.4		274.0	LIGHT G	274.7	TAN	273.5	LIGHT G	274.3
12.5	Tan	278.6	LIGHT G	272.5	TAN	271.5	LIGHT G	272.6	BLACK	276.2	LIGHT G	270.9		271.5	LIGHT G	272.2	TAN	271.0	LIGHT G	271.8
15.0	Dark G	276.1	DARK G	270.0	LIGHT G	269.0	LIGHT G	270.1	LIGHTG	273.7	LIGHT G	268.4		269.0	LIGHT G	269.7	TAN	268.5	LIGHT G	269.3
17.5	Dark G	273.6	DARK G	267.5	LIGHT G	266.5	DARK G	267.6	LIGHTG	271.2	LIGHT G	265.9		266.5	LIGHT G	267.2	TAN	266.0		266.8
20.0	Dark G	271.1	DARK G	265.0	DARK G	264.0	DARK G	265.1	LIGHTG	268.7	Dark G	263.4		264.0	LIGHT G	264.7	Dark G	263.5	Dark G	264.3
22.5	Light G	268.6	LIGHT G	262.5		261.5	DARK G	262.6	LIGHTG	266.2	Dark G	260.9		261.5	LIGHT G	262.2	Dark G	261.0	Dark G	261.8
25.0	Light G	266.1	LIGHT G	260.0		259.0	DARK G	260.1	LIGHTG	263.7	Dark G	258.4		259.0		259.7	Dark G	258.5	Dark G	259.3
27.5	Dark G	263.6		257.5		256.5	DARK G	257.6	DARK G	261.2	Dark G	255.9		256.5		257.2	Dark G	256.0	Dark G	256.8
30.0		261.1		255.0		254.0		255.1		258.7		253.4		254.0		254.7		253.5		254.3

Layer graph based on Soil Depth Calculations and Borehole Locations



Depth	Borehole 1		Borehole 2		Borehole 3		Borehole 4		Borehole 5		Borehole 6		Borehole 7		Borehole 8		Borehole 9		Borehole 10	
(ft)	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color	Lithology	Munsell Color
2.5			Clay and Coarse Angular clast 0.25 to 0.5cm	5YR6/3 (l light reddish brown)	1-2cm Día	Y2.52/3 Soil color	brown clay w/ coarse particulate	25Y6/6	Terracotta clay fine sediment limestone clasts sub angular to sub rounded 2mm <>1cm	2.5Y 4/4 REDISH BROWN	Limestone mud and fine volcanic rock Size 3mm to 10mm	2.5Y6/4	Fine with occasional coarse clasts 5% or less Coarse clasts	5YR6/3 (l light reddish brown)	clayey silt	25Y6/4 light yellowish brown			brown clay	25Y6/6
5	Bi Model Angular Clasts 1/2 1 to 10mm 1/2 5 to 10mm 0.5 to 1	5Y8/1- yellowish grey 1/4 of sample 5GY7/2 grayish yellow green	Hard Angular 1-2cm Surrounded	10YR8/4 (very pale brown)	Greyish Green		brown clay w/ coarse particulate	25Y6/6	2/3 red clay 1/3 white fine grain matrix 15 - 20% Clast angular to Sub rounded Color dominated by red/brown matrix	2.5Y 4/4 REDISH BROWN	Generally same as above but larger 3.5 inch Soft Yellowish fine grain silty texture	2.5Y5/3	Medium to coarse fragments of limestone 20 to 25 % clasts	10YR8/4 (very pale brown)	Occasional Clast angular 1cm	5Y5/4 olive	red silty clay	2.5Y 4/4 REDISH BROWN	Same as above	Same as above
7.5			Large clast of Lime 5 TO 10 CM	10YR7/4 (very pale brown)	Angular Clast 1/3 sample Limestone clast 1/3 sample Saprolite 1/3 sample	N2 Dark 5Y8/1 Yellowish gray 5G5/6 Moderate Green (wet sample)	limey mud mixed with greenish brown clay, 2-4 mm fragments, silty textured limestone mud is a fizzy clay	10GY3/2	3cm -1mm fragments fill 5%red 2% green 93%white	7.5YR9.5/1 White 10Y4/2 dark greyish olive	Silty texture carbonate to another gray non carbonate mud	10GY5/2 (GREYISH GREEN)	same as above	10YR7/4 (very pale brown)	Medium angular clast less than 3mm	5G4/1 Dark greenish grey	black fragments red silty clay	2.5Y 4/4 REDISH BROWN	no bigger than a penny fragment	Same as above
10	Clay and Coarse Angular clast 0.25 to 0.5cm	5Y8/4 N2 greyish black	Same as above	Same as above	Angular Clast 1/3 sample Limestone clast 1/3		limestone fragments in gray green silty clay	10GY3/2	30%black20%green 48% white 2% red None carbonate	10Y5/4 light olive green 5Y2.5/2 black	mud 50 % Greenish 50% y e l l o w i s h	10GY4/4 (dark yellowish green)	same as above	same as above	Fine to course 50% 2mm to 3 cm Abundant limestone	5Y6/3 Pale Olive	same above	same above	Blueish tourquise	5GY5/2 Greyish green
12.5						10GY3/2 Dusky yellowish green	.5 cm limestone fragments mixed gray nonfizzy clay with buff tan fizzy clay	10GY3/2	60% dark (black max 5mm green/ blueish) 40% WHITE 5% angular 5mm to 1 cm fill	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	95% Greenish non carbonate silt 5% Light gray carbonate	10gy6/4 (moderate yellowish green)	10 to 15% fine to medium coarse clast	10YR5/4 (Yellowish brown)	sand <5 mm less fine 2% to Course gravel 20 mm 90% limestone TAL member angular	2.5Y6/4 Light greenish brown 2.5Y8/2 Pale Yellow 2.5Y7/1 Light grey	black gray green clay	5GY4/2 Dark grayish green	Blue grey with chunks of tan clay	2.5Y6/4 Light greenish brown 2.5Y8/2 Pale Yellow 2.5Y7/1 Light grey
15	Hard Angular 1-2cm Surrounded	5GY7/2 grayish yellow green 10GY6/4 Moderate yellowish green			Clasts = soft greenish gray 1-2mm max tabular 2x5x10 mm	10GY3/2 Dusky yellowish green	primarally gray clay, <5% buff or white	10GY3/2	90% blue 5 % white 5% red 2 shades of blue dark round and harder	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	Greenish Grey Non carbonate silt	10GY3/2 (dusky yellowish green)	same as above	same as above	Fine sand size particles Occasional limestone fragments Marley angular medium to coarse	5GY5/2 Greyish green	same above	same above	same above	same above
17.5					Clasts = soft greenish gray 1-2mm max tabular 2x5x10 mm	10GY3/2 Dusky yellowish green	Competent blue gray clay, like a mudstone in 1 cm fragments, occasional limestone fragments	10GY3/2	93% blue 5% white 2% red darker blue more competent lighter mud silty	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	same as above	10GY3/2 (dusky yellowish green)	same as above	same as above	Marley 20 - 25% Abundant fine grain size clasts	5GY4/2 Dark grayish green	same above	same above	Blue grey with black clay	5G4/2 Greyish Green
20	Clay like Matrix Dark Saprolite	10GY3/2 Dusky yellowish green N2 1-2mm Dark			Clasts = soft greenish gray 1-2mm max tabular 2x5x10 mm	10GY3/2 Dusky yellowish green	1-1.5 competent blue gray clay, very dry when disaggregated	10GY3/2 + Darker	less than 1% white medium to coarse matrix 30% fine grained greenish mud derived from greenish clast 70%	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	Darker color silt firmer	no sample bag	same as above	same as above	Rest of sample same as above	5GY/4/2 Dark greyish green 2.5Y6/4 Light yellow brown	same above	same above	less black mostly blue grey	10GY5/2 (GREYISH GREEN)
22.5									20% white may have hit color 20% black 2% red rest green of clast fraction 30%matrix fine grained greenish	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	Greenish gray silt Small amount of yellowish Red terracotta angular clasts 1cm	5BG5/2 (greyish blue green)	shows 2 tone of light and dark	same as above			same above	same above	light blue grey clay	5BG5/2 (greyish blue green)
25									clast bimodal blue and soft finer grain and sticker silt/clay fraction medium sand size particles 30% matrix clast fraction 5%white/5%black/2 %red Rest green blue	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White	same as above SAMPLE DRIER	10GY5/2 (GREYISH GREEN)		same as above	Very stiff plastic material like bentonite Marine clay responds to acid	5G4/2 Greyish Green	dark green and black	5GY4/2 Dark greyish green	grey clay bits of blue and tan	5GY4/2 Dark grayish green
27.5									same as above	10Y5/4 light olive green 5Y2.5/2 black 7.5YR9.5/1 White					Medium sand with greenish matrix 90% dark clasts of soft disaggrate	5GY4/2 Dark Greyish	same above	same above	same above	same above
30	Clay like Matrix Dark Saprolite	10GY3/2 Dusky yellowish green N2 1-2mm Dark															buff tan	10YR8/4 (very pale brown)	same above	same above
32.5																	same above	same above	same above	same above
35																	grey	5GY4/2 Dark greyish green	PVC 2" 33 ft casing	
37.5																	same above	same above		
40																	grey green	5GY4/2 Dark greyish green		
42.5																	same above	same above		
45																	same above	same above		
47.5																	42.5 ft cased			
50																				

Appendix H: Atmospheric Pressure

#	Date Time, GMT+	kPa	Atmospher	Actual Change (kPa)	Depth (ft)	Depth (m)	Logger Elevation (ft)	Water Elevation (ft)
1	3/12/2018 14:00	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
2	3/12/2018 14:05	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
3	3/12/2018 14:10	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
4	3/12/2018 14:15	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
5	3/12/2018 14:20	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
6	3/12/2018 14:25	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
7	3/12/2018 14:30	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
8	3/12/2018 14:35	105.47	101.325	4.145	1.3867222	0.422674	282.05	283.4367
9	3/12/2018 14:40	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
10	3/12/2018 14:45	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
11	3/12/2018 14:50	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
12	3/12/2018 14:55	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
13	3/12/2018 15:00	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
14	3/12/2018 15:05	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
15	3/12/2018 15:10	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
16	3/12/2018 15:15	105.453	101.325	4.128	1.3810348	0.42094	282.05	283.431
17	3/12/2018 15:20	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
18	3/12/2018 15:25	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
19	3/12/2018 15:30	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
20	3/12/2018 15:35	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
21	3/12/2018 15:40	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
22	3/12/2018 15:45	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
23	3/12/2018 15:50	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
24	3/12/2018 15:55	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
25	3/12/2018 16:00	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
26	3/12/2018 16:05	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
27	3/12/2018 16:10	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
28	3/12/2018 16:15	105.419	101.325	4.094	1.36966	0.417473	282.05	283.4197
29	3/12/2018 16:20	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
30	3/12/2018 16:25	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
31	3/12/2018 16:30	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
32	3/12/2018 16:35	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253
33	3/12/2018 16:40	105.436	101.325	4.111	1.3753474	0.419207	282.05	283.4253

Appendix I: Hydraulic Testing at the Santa Rita Spring Site

For conventional wells, pump or slug tests are used to evaluate the transmissivity of the water-bearing zone. Conducting conventual pump or slug test on the boreholes would have tested the transmissivity of the granular materials around each well. We thus designed a test focused on the transmissivity of the materials between the boreholes, using the spring's collector pipe as the pump for the test.

I.1 Test Procedures and Results

1) Level loggers were placed in boreholes 1, 2, 3, 4, 6, 7, 8, 9, and 10 (Figure 3.10) and were set to record every minute.
2) On 16 April 2018 at 1355, a bung was placed in the spring collector pipe, blocking the flow into the spring box (Figure).
3) On 16 April 2018 at 1400, the water in the spring box was pumped out. Once all the water was pumped out of the spring box, two level loggers were placed on the bottom of the spring box and set to record every minute.
4) The bung remained in place for 18 hours until 0758 on 17 April 2018. While the bung was in place, the water level rose at the site until there was water standing on the surface around the spring box.
5) When the bung was removed:
    a. The volume rate of the water flowing into the spring box was measured using the dimension of the spring box and the level logger data.
    b. The level loggers placed in each borehole recorded the simultaneous behavior of the water table in each.
6) The data were then interpreted to yield the transmissivity of the water-bearing zone feeding the spring.

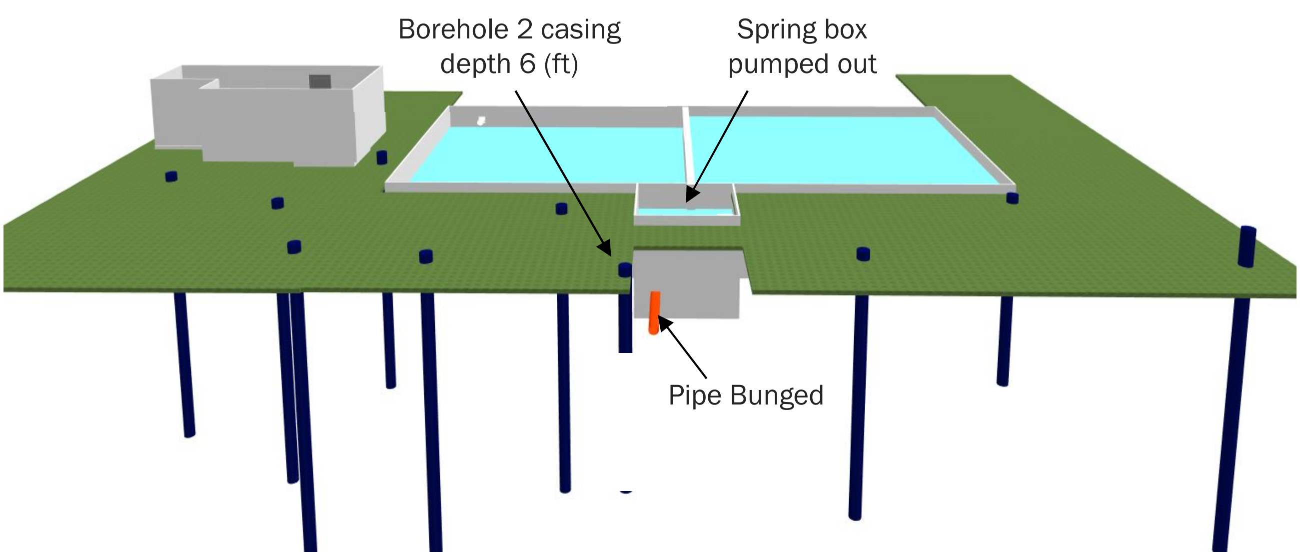


Figure I.1. 3D model of the hydraulic test configuration.

Figure I.2 below, is a graph of the level-logger pressure data (converted to head (ft)) from the SRS spring box, captured after the bung was removed from the 8-inch-diameter collector pipe. The water level in the tank went from 0 up to a maximum height of 6 feet in 29 minutes. The water entered the tank at a rate of 169 gpm. This flow rate was used as the pumping rate, Q.

Borehole 2 was drilled nine feet up the slope from the end of the current SRS spring collector pipe. During the drilling, it was observed that Borehole 2 was hydraulically linked directly to the spring collector pipe. When the water from the mud pump was pumped down the hollow drilling stems to lubricate the cutting head the water did not come back up the drilling collar but instead went into the spring box. Because of this, Borehole 2 is considered a well pumped at 169 gpm for the test. The reaction of all the other boreholes (Figure I.3) were calculated against the water table reaction around Borehole 2.

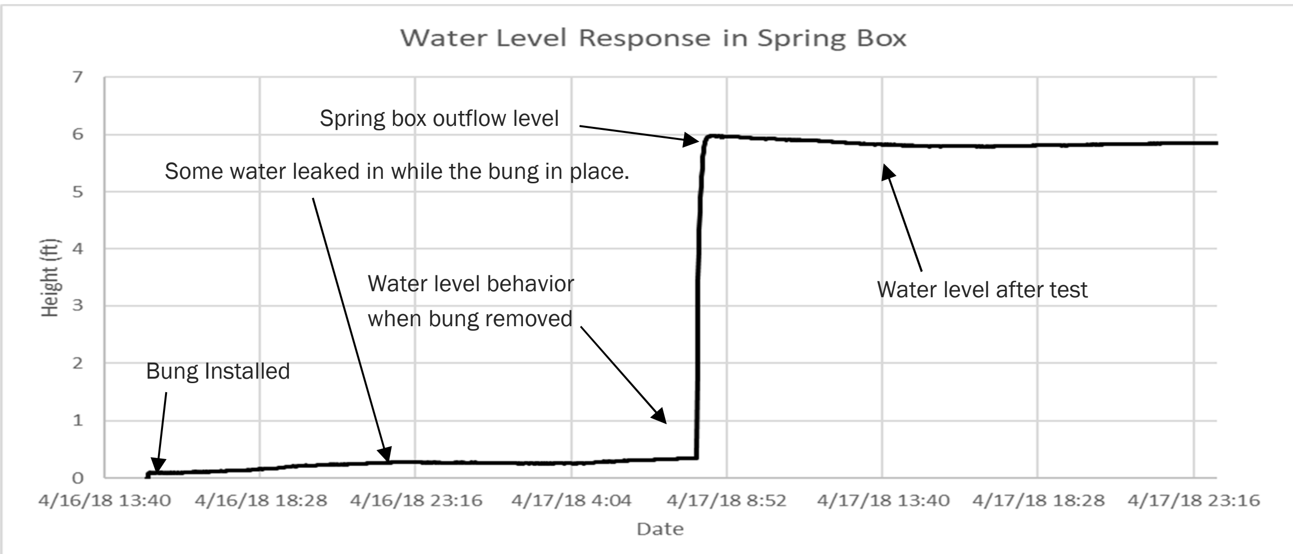


Figure I.2. Level logger data collected from the spring box during the hydraulic test.

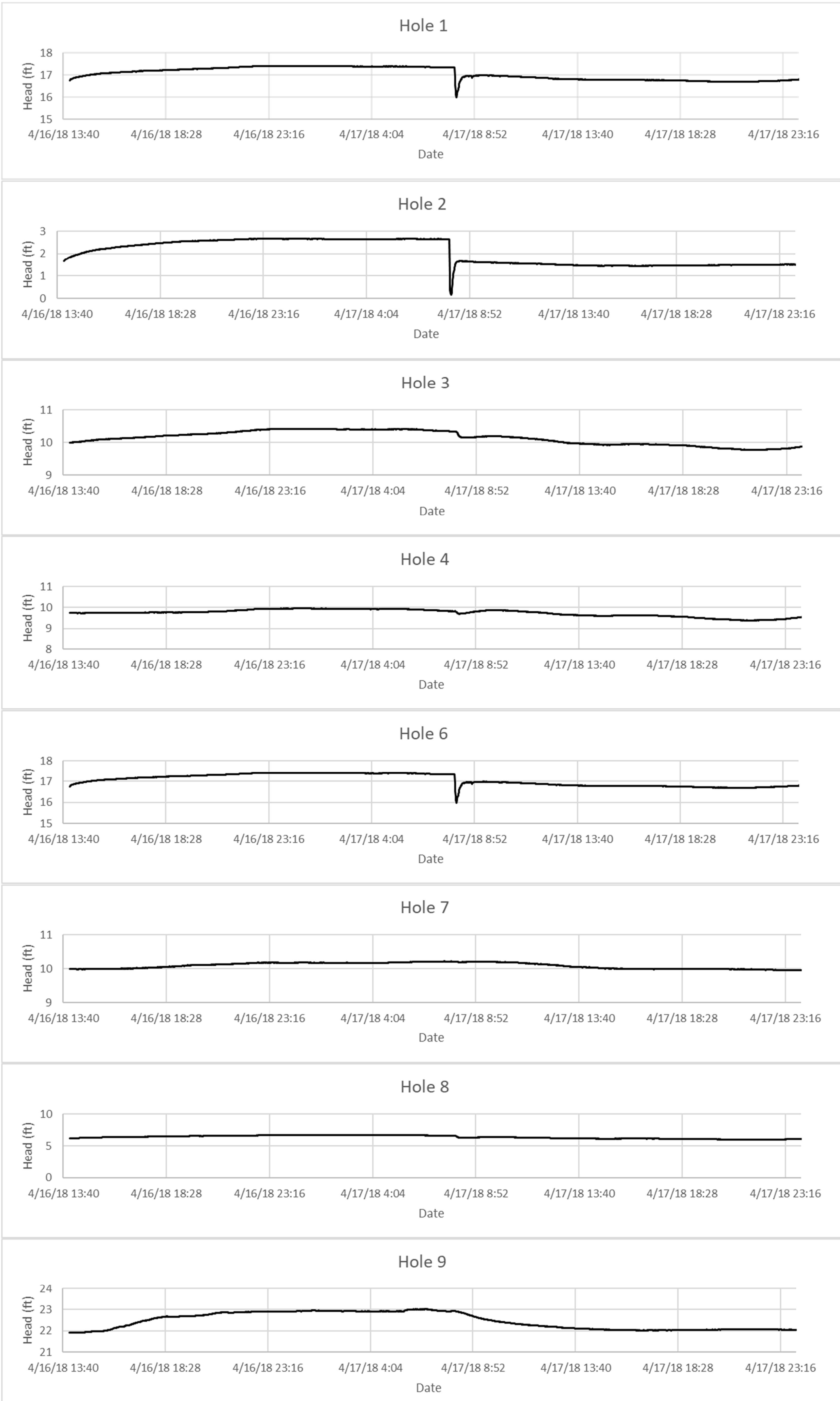


Figure I.3.. Borehole water level response to hydraulics test

Borehole 1 was the first to respond (Figure I.3). The water at Borehole 1 dropped by 1.36 feet within 6 minutes (Figure). The boreholes south of borehole 2, (i.e., Boreholes 8, 3, and 9) responded faster than the boreholes located to the north of Borehole 2 (i.e., Boreholes 4, 6, and 7). Borehole 10 was not instrumented for the test as its level logger was used to record the water rise in the spring box. The reaction of each borehole is summarized in Table I-1 below.

Table I-1. Response of the water table in each borehole

Borehole	Maximum Height (ft)	Minimum Height (ft)	Change in Height (ft)	Distance, r, to pumping well (ft)	Depth, b, to Aquiclude (ft)
1	284.33	282.97	1.36	20.9	12.5
3	283.14	282.58	0.56	43.3	7.5
4	281.71	281.27	0.44	43.3	7.5
6	282.30	281.70	0.60	23.4	12.5
7	282.57	282.30	0.27	56.8	12.5
8	284.02	283.41	0.61	18.1	15
9	284.59	283.69	0.90	65.4	15
				Average thickness, $\overline{b}$	12

The transmissivity of an aquifer is the amount of water that can be transmitted horizontally through a unit width by the full-saturated thickness of the aquifer under a hydraulic gradient of one (Fetter, 1980). The following assumptions were made to estimate the transmissivity of the aquifer material from time-drawdown data:

1) The pumping well is screened only in the aquifer being tested.
2) All the observation wells are screened only in the aquifer being tested.
3) The pumping well and the observation wells are screened throughout the entire thickness of the aquifer.

All these conditions were met at the SRS site, thus Thiem's equation (Fetter, 1980) can be used:

$$T = \frac{Q}{2\pi(h2-h1)} \ln\left(\frac{r2}{r1}\right) \quad \text{Equation 2}$$

Where,
T= Aquifer transmissivity (ft^2/day)
Q= Pump Rate (ft^3/day)
h_1 = head at distance r_1 from the pumping well (ft)
h_2 = head distance r_2 from the pumping well (ft)

Using the values for Q; h_1, h_2, r_1, and r_2; see Table I- or Appendix I.

Q = 169gpm = 3.25 x 10^4 ft^3/day

We may solve for T: $T = 2435\ ft^2/day$

Table I-2. Theim's Equation Calculations

Borehole	h	r	Wells	h_2-h_1	2π	$2\pi(h_2-h_1)$	Q	$q/2\pi(h_2-h_1)$	r_2/r_1	ln(r2/r1)	T	Units
1	282.97	20.9	3 and 6	0.88	6.2832	5.529216	32535	5884.19769	1.85	0.615417	3621.233	ft^2/day
3	282.58	43.3	8 and 6	1.71	6.2832	10.744272	32535	3028.12513	0.773504	-0.25682	777.6955	ft^2/day
4	281.27	43.3	9 and 6	1.99	6.2832	12.503568	32535	2602.05727	2.794872	1.027786	2674.359	ft^2/day
6	281.70	23.4	9 and 7	8.6	6.2832	54.03552	32535	602.103949	1.151408	0.140986	84.88819	ft^2/day
7	282.30	56.8	3 and 7	0.28	6.2832	1.759296	32535	18493.1927	0.762324	-0.27138	5018.751	ft^2/day
8	283.41	18.1								Total	12176.93	ft^2/day
9	283.69	65.4							**Average T**		**2435**	**ft^2/day**

The conductivity of the aquifer material is obtained by dividing the T by mean aquifer thickness, $\overline{b}$. Once we identified the aquiclude in the lab at WERI (section 3.2.5), we were then able to determine the depth of the aquifer layer by examining the drill logs. The average depth to the aquiclude layer was calculated to 12 ft (Table 3-4).

$$K = \frac{T}{b}$$ **Equation 3**

Where,

K=Conductivity

T= Transmissivity = 2435 ft^2/day

b= Thickness of the aquifer = 12ft

We may solve for K: $K = 203\ ft/day = 7.16 \times 10^{-2}\ cm/s$

This value represents the local hydraulic conductivity and includes the fill material. We expect the hydraulic conductivity of the aquifer's conduit system to be at least two orders of magnitude greater. Typically, the regional hydraulic conductivity of limestone aquifers can be as great as 36,000 ft/day (Freeze and Cherry, 1979).

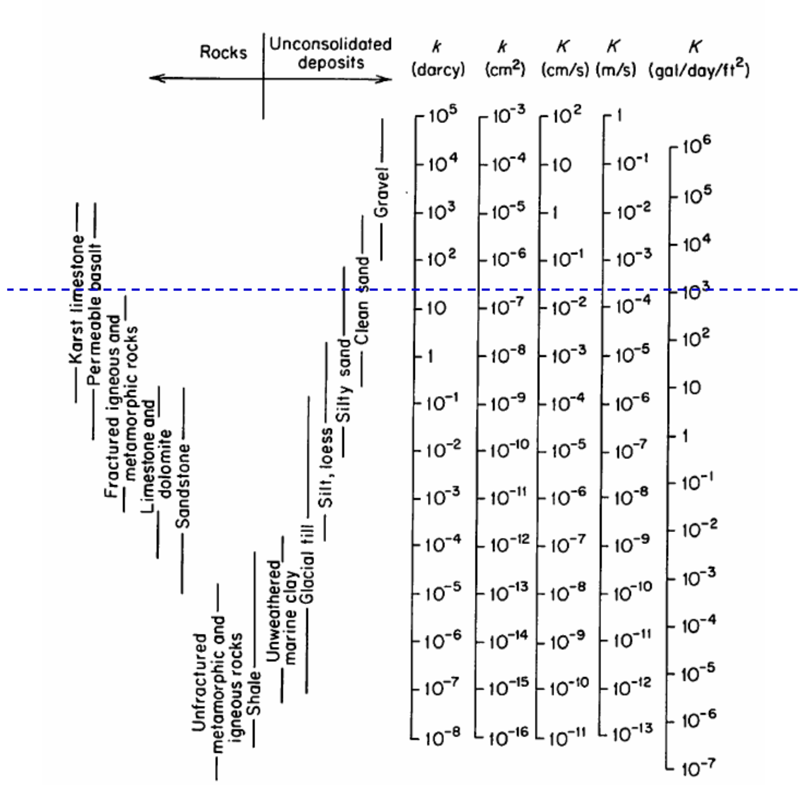


Figure I.4. Range of Values of Hydraulic Conductivity and Permeability *from Groundwater* by Freeze and Cherry,1979.

I.2 Thiem's and Conductivity Calculations

	h	r	Wells	h2-h1	2π	2π(h2-h1)	Q	q/2π(h2-h1)	r2/r1	ln(r2/r1)	T	Units
1	282.97	20.9	3 and 6	0.88	6.2832	5.529216	32535	5884.19769	1.85	0.615417	3621.233	ft²/day
3	282.58	43.3	8 and 6	1.71	6.2832	10.744272	32535	3028.12513	0.773504	-0.25682	777.6955	ft²/day
4	281.27	43.3	9 and 6	1.99	6.2832	12.503568	32535	2602.05727	2.794872	1.027786	2674.359	ft²/day
6	281.70	23.4	9 and 7	8.6	6.2832	54.03552	32535	602.103949	1.151408	0.140986	84.88819	ft²/day
7	282.30	56.8	3 and 7	0.28	6.2832	1.759296	32535	18493.1927	0.762324	-0.27138	5018.751	ft²/day
8	283.41	18.1								Total	12176.93	ft²/day
9	283.69	65.4							Average T		**3044.232**	**ft²/day**

K= T/b	254	ft/day
	8.96E-02	cm/s

I.3 Standpipe Data

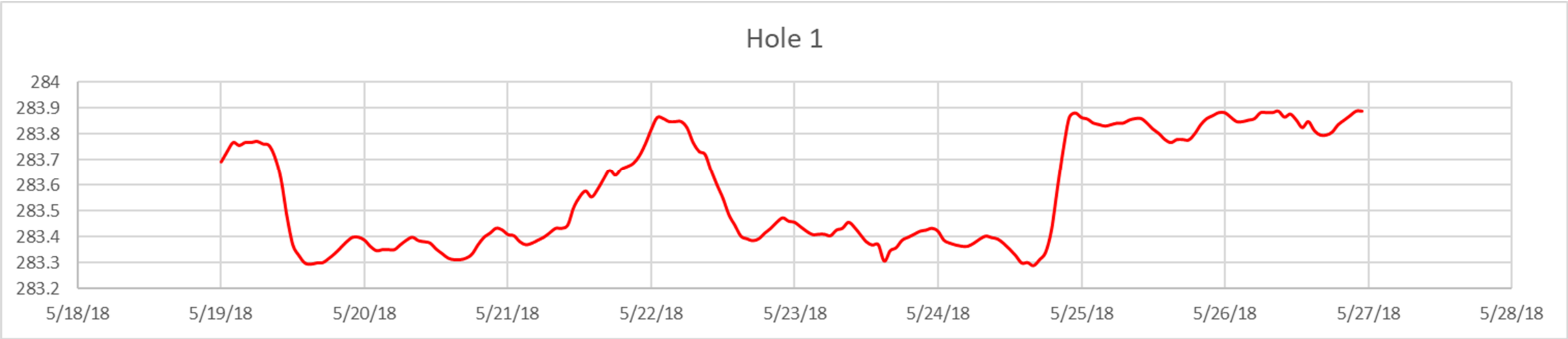


Figure I.5. Water level response borehole 1

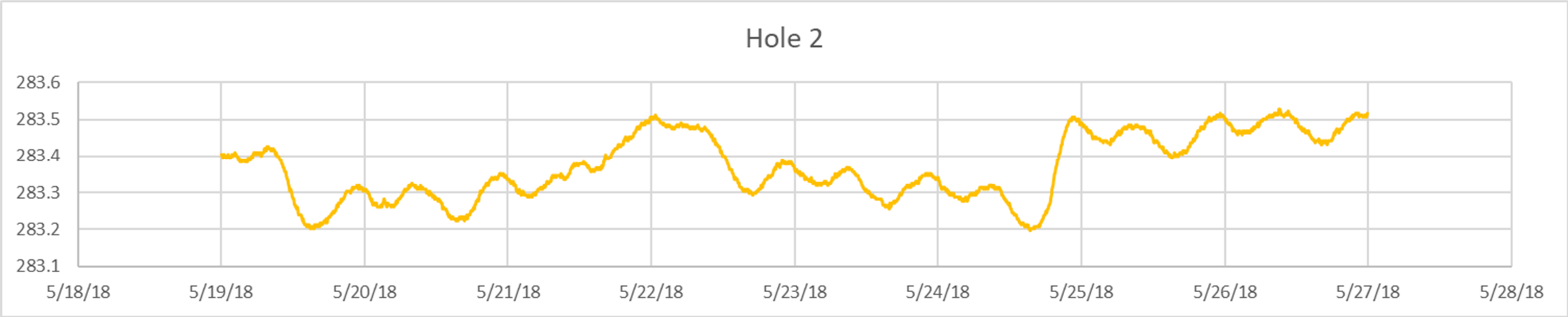


Figure I.6. Water level response borehole 2

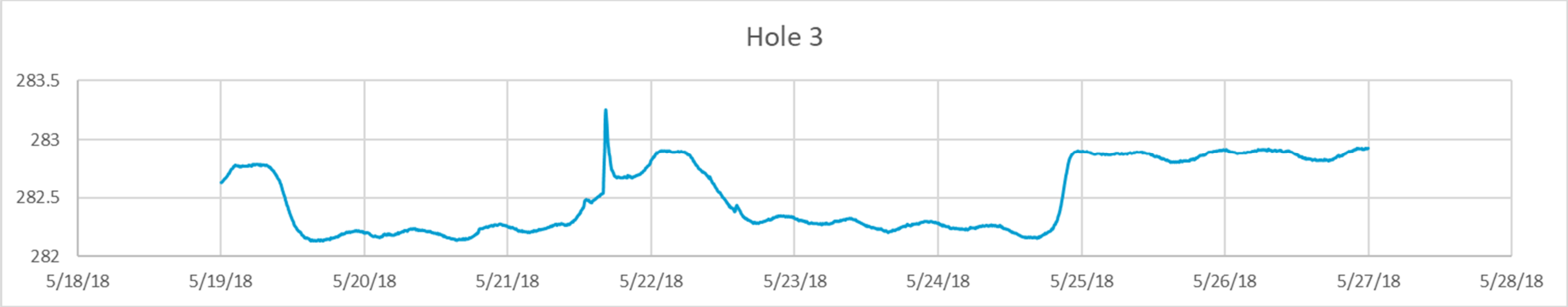


Figure I.7. Water level response borehole 3

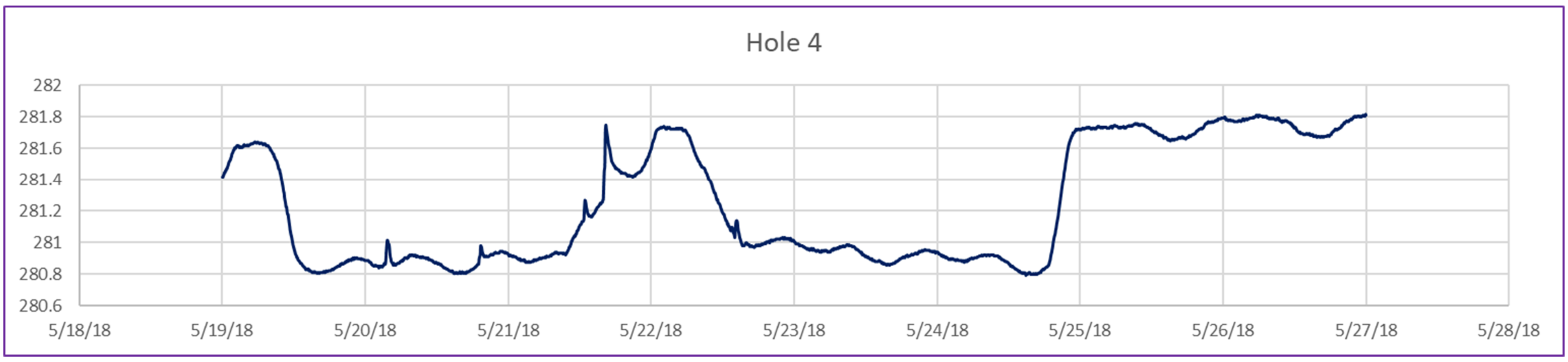


Figure I.8. Water level response borehole 4

Figure I.9. Water level response borehole 5

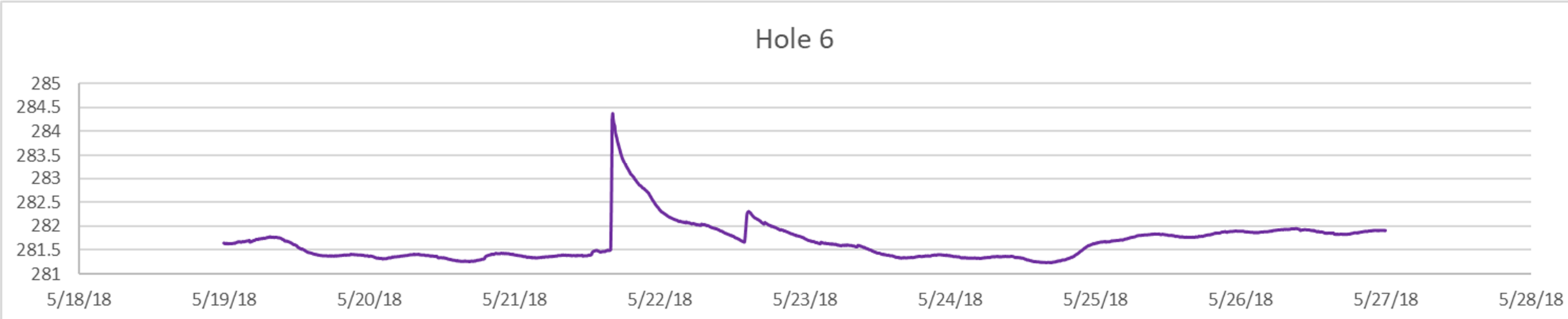


Figure I.10. Water level response borehole 6

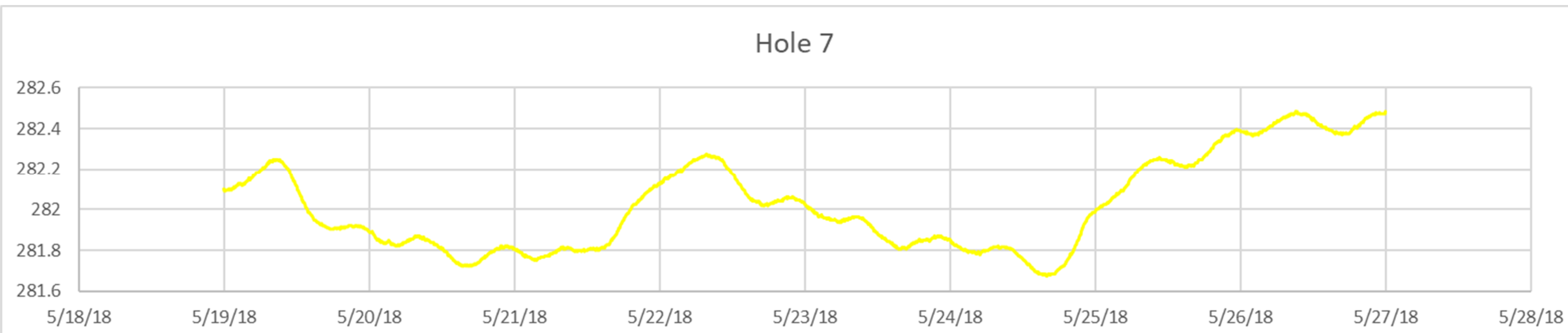


Figure I.11. Water level response borehole 7

Figure I.12. Water level response borehole 8

Figure I.13. Water level response borehole 9

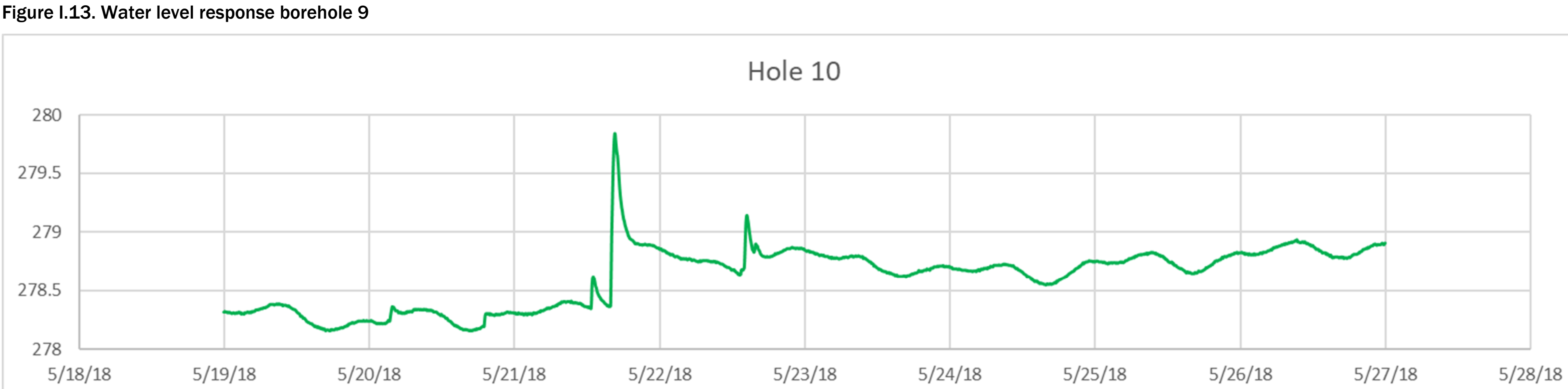


Figure I.14. Water level response borehole 10

Appendix J: Dr. Leroy F. Heitz Review

FINAL COMMENTS ON

Mr. Paul Bourke's
Thesis Project titled:

"A Hydrogeologic Survey of Santa Rita
Spring Guam, engineering and design
recommendations for rehabilitation"

Following are my comments concerning various aspects of the project:

1. In general, the project design, execution and write up were all very well done.
2. I am not providing any comments on the Geology investigations other than they seemed to be well thought out and very thorough.
3. In some cases, it might be clearer and easier for a reviewer to check your calculations if you provide the equations and units used (in proper engineering format) to get the values shown in tables or in sentence format.
    a. Two example areas where you may want to consider providing equations are:
        i. 2.4.1 bottom of page 15
        ii. 2.4.2 on pages 16 and 17
    b. Just a suggestion. I find it easier to follow a calculation if it is in equation form rather than just putting values in a table or written out in sentences.
4. Figures ES1 and 1.6: In the text describing the existing project, it is implied that the upstream perforated pipe is perpendicular to the slope. All the drawings show it as horizonal. Might want to be a little clearer about that.
5. Since Section 2.4.1 is key to the estimated yield and hydraulic design of the proposed system improvements, I checked the numbers.
    a. Using Table 2.4 values:
        i. W.S. area .62 mi^2
        ii. Rainfall inches 86 inches in wet season only no recharge in dry season.
        iii. Evaporation rate = 40% reasonable
        iv. Recharge 86 in * (1-.40) = 51.6 inches during wet season
        v. Recharge volume (during wet season) =
        (51.6 inches /12in/ft) *.62 mi^2*5280ft/mi*5280 ft/mi) = 7.432 *10^7 ft^3 in wet season
        vi. Average annual flow to discharge recharge =
        7.432*10^7 ft^3/365 day/year 7.48 gal/ft^3= 1.523 MGD
        vii. Average annual Flow to discharge recharge =
        1.532 MGD */24 hr/day/60 min/hr*1000000 gal/mg =1057 gpm
        viii. ALL CHECKS OK WITH TABLE
    b. At the bottom of the table the term "notional estimate" shows up. I am not sure where that term comes from or what it means. In engineering design using hydrology numbers, everyone knows that all the numbers are "ESTIMATES".

c. Is there adequate storage in the aquifer to supply the minimum dry season design flow of 250 gpm for 6 months of the year on average. That requirement would be:
    i. (250 gpm *182 days *24 hr/day*60 min/hr) / 1000000 gallons/mg = 65.5 mg
    ii. From our discussions you stated that you estimate that there are 71 mg of storage available. Therefore, the aquifer storage is adequate. You might want to include this calculation in your report somewhere.

6. Table 4.1: There is a need to identify units and coordinate system of the location values provided for the bore holes. It looks like UTM-ft?? Need to also identify what geographic system was used (WGS 84, NAD 83 MA11 etc.). Also, elevation should be identified as msl / (geoidal) or ellipsoidal just to avoid any GPS confusion.
7. Section 4.1.1: I assume you are not trying to provide a design for the French Drain components.
    a. I made a quick calculation that is shown on slide 11of the provided PowerPoint presentation. I computed a value of 7292 gpm for flow through the French Drain aggregate with no back pressure on the aquifer. It appears that the French drain aggregate can easily deliver the required design maximum flow of 1050 gpm. You should check my computations and might consider providing these computations in your report
    b. The designer will have to pick an appropriate underdrain pipe with proper pipe diameter, hole size and hole spacing. Size distribution of cover aggregate will also have to be considered. The designer must also consider the desired flow and head conditions between the French Drain and the delivery point.
    c. Another issue that could arise: Is there enough sediment and debris in the aquifer water to possibly plug the suggested filter cloth around the aggregate? If so, how will that problem be remedied?
    d. The Slow Sand Filter Design Manual has good information on the required design process for an underdrain system water filter. As I mentioned previously, a slow sand filter is just a giant sized slow acting French drain. The publication I sent to you, "The Hydraulic Performance of Perforated Pipe Under-Drains Surrounded by Loose Aggregate" by Patrick Murphy from Clemson University, is also a good reference on the hydraulics of perforated pipe under drains. It has an excellent biography of source material. You may want to pass that information on to GWA.

I think it important for GWA to know what your best estmate is as to how much increase in water production they can expect from carrying out your proposed project improvements. If you do not feel comfortable with providing one value, then possibly providing a range of values would be appropriate. They will be spending public monies to make the improvement and will want to be sure that the improvements have a positive benefit to cost ratio.

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Appendix K: Optimal Santa Rita Spring Design Recommendation

Lowering the Holding Tanks

(See drawings labeled D3)

This option involves the construction of new holding tanks with a base elevation of 259 ft.,13 ft deeper than the current holding tank base elevation (Figure H.1). This design option allows water to be stored on site without placing back pressure on the spring flow coming into the system. The decision to excavate and construct new holding tanks can be made after the performance of the new spring water collection system has been proven by the data collected with the construction of design phases 1 and 2. The capacity and dimensions of the new holding tanks should be chosen to meet the needs of the current and future system demands.

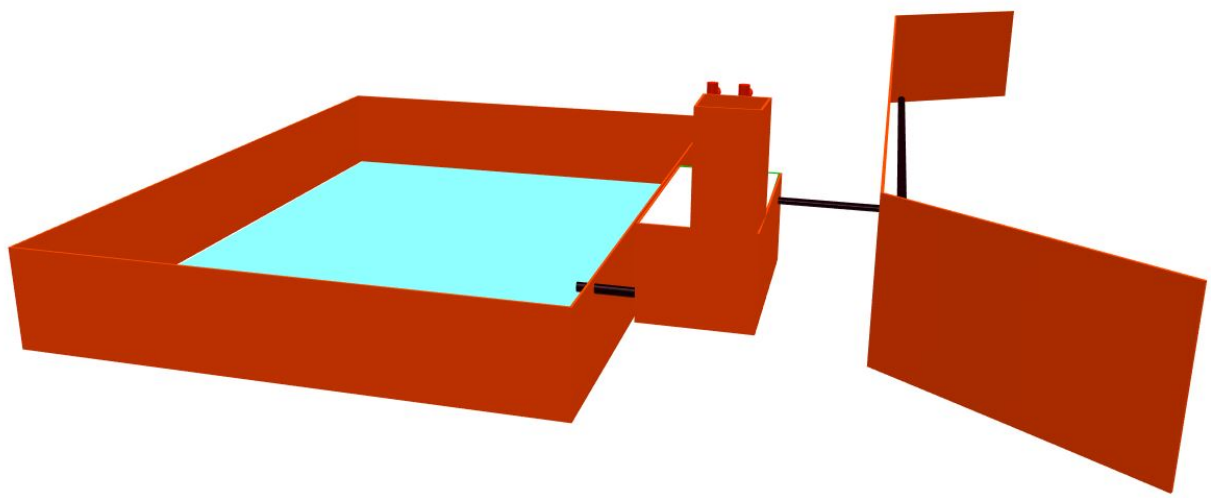
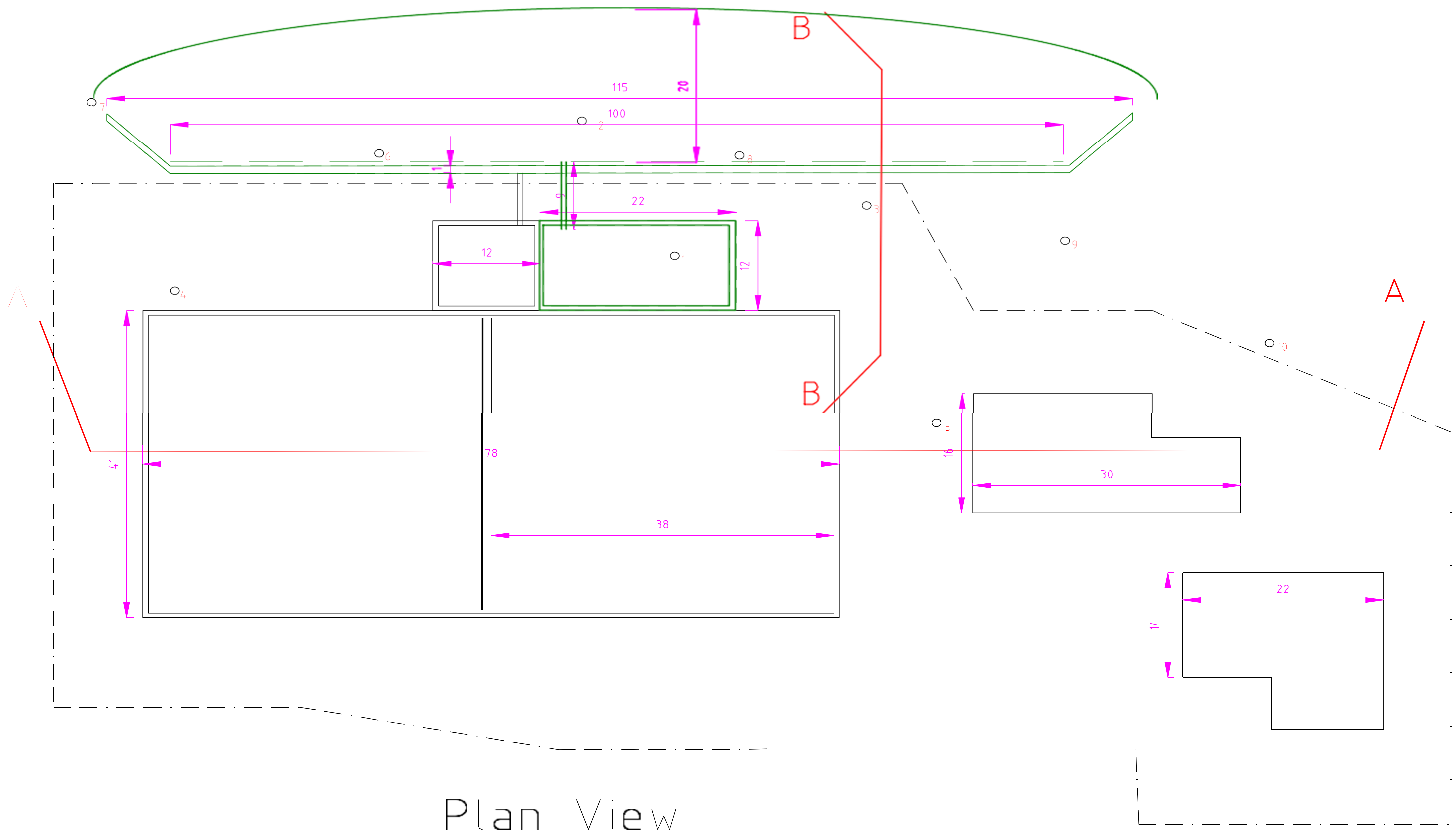
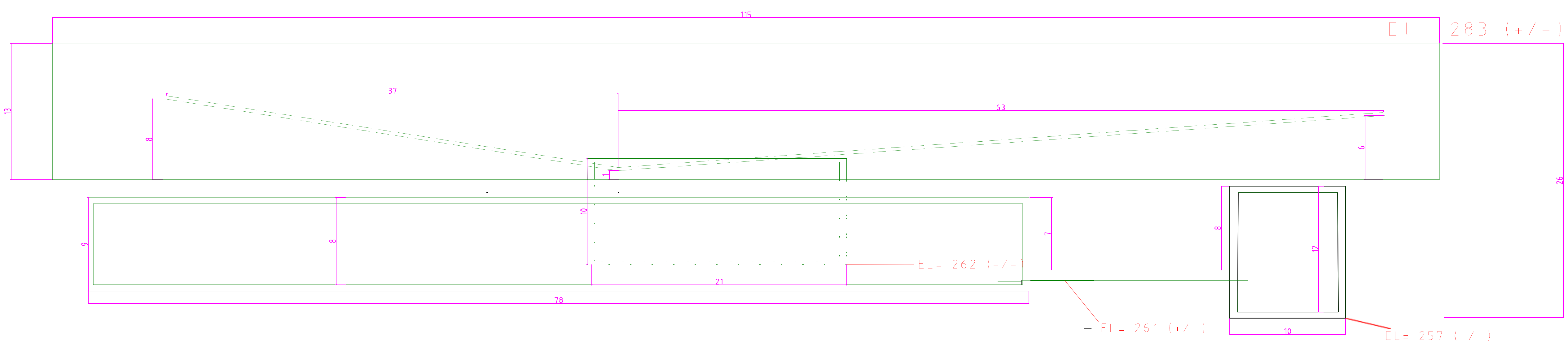


Figure I.1. 3D model of New Holding Tank



Plan View

Paul Bourke	
Santa Rita ring	
All dimensions in feet	D3: 1 of 3

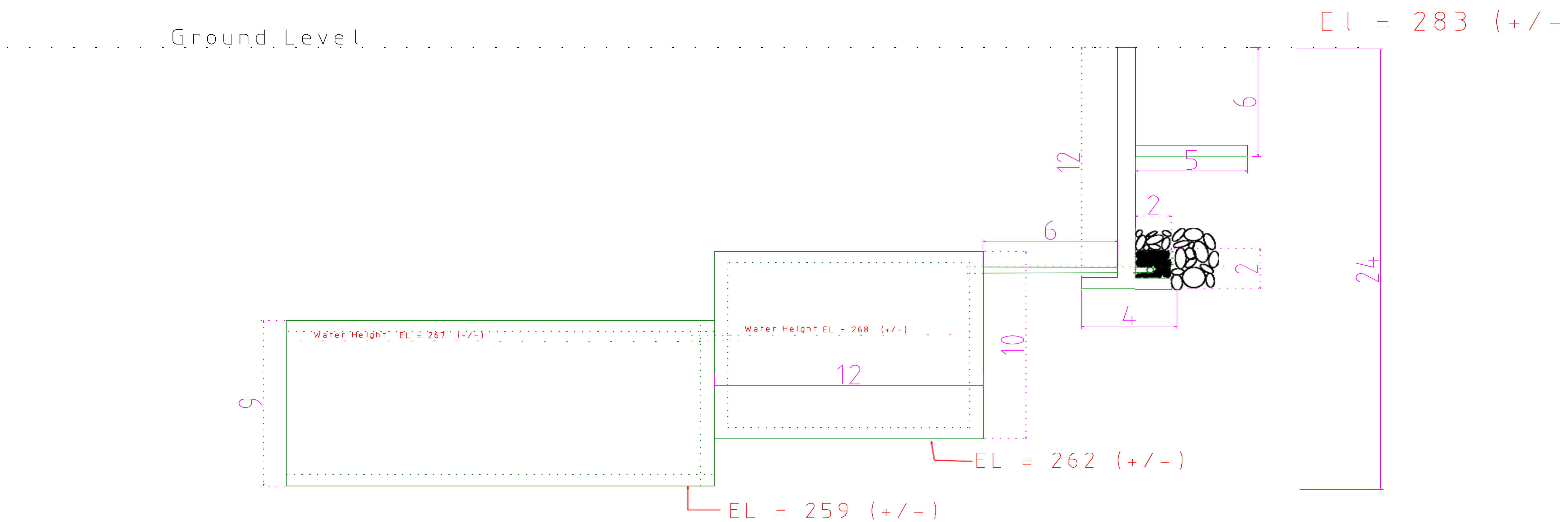


Section A-A

Paul Bourke

Santa Rita Spring

Dimensions in feet	D3: 2 of 3



Section B-B

Paul Bourke

Santa Rita Spring

Dimensions in feet | D3: 3 of 3

Appendix L: Alternate Santa Rita Spring Design Option

The Pump House Option

(See drawing labeled D2)

We also considered using the existing SRS booster pump house wet well instead of building a new spring box (Figure I.1). Despite the fact that this option eliminates the extra excavation and construction costs associated with the other proposed option, we ultimately decided not to recommend this option for the following reasons:

1) The slope and depth of the cutoff wall collector piping would have to change from a collector pipe discharge elevation of 272 ft to an elevation of 275ft. This elevation change would place the collector pipes above the bottom of the aquiclude allowing some water to remain unused.
2) The captured spring water would need to be pumped to the Santa Rita 2 million-gallon storage tank, utilizing the current booster pumps and piping system almost constantly. The current wet well is 8 ft by 8 ft and the collection piping will enter at an elevation 272 ft, which is 2 ft above the base of the well. At 730 gpm this would provide less than two minutes of storage before the water level in the wet well would reach the elevation of the spring collection piping and start to back-pressure the system.
3) The rapid changes in the turbidity level of spring water, especially after big storms. When there is a large volume of rainfall, the groundwater table rises and pressure in the aquifer forces water through fractures and or conduits in the limestone that are rarely used and thus have collected sediment. This historically has caused turbidity spikes in the SRS system. An automatic shut-off or diversion valve controlled by a turbidity sensor would need to be fitted to the collector pipe to prevent turbid water entering the GWA system. The turbid water could be diverted into the existing overflow swales until the turbidity returned to acceptable levels. But should this system fail then there would be nothing to stop extremely turbid water entering the GWA supply system.

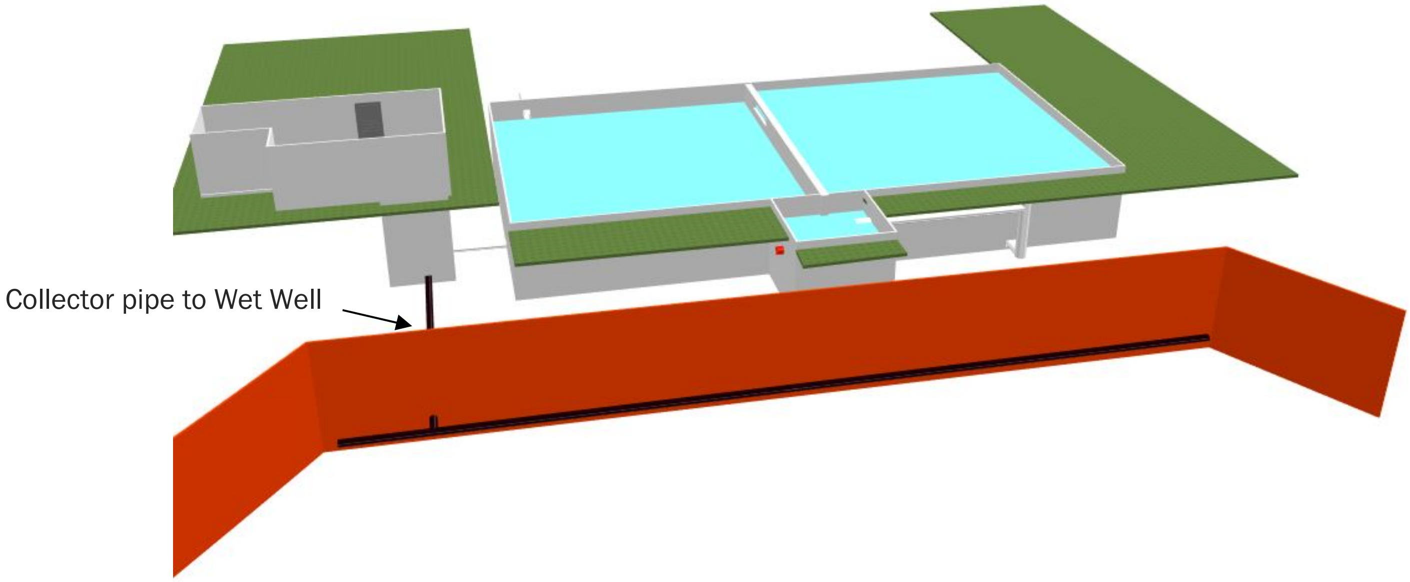
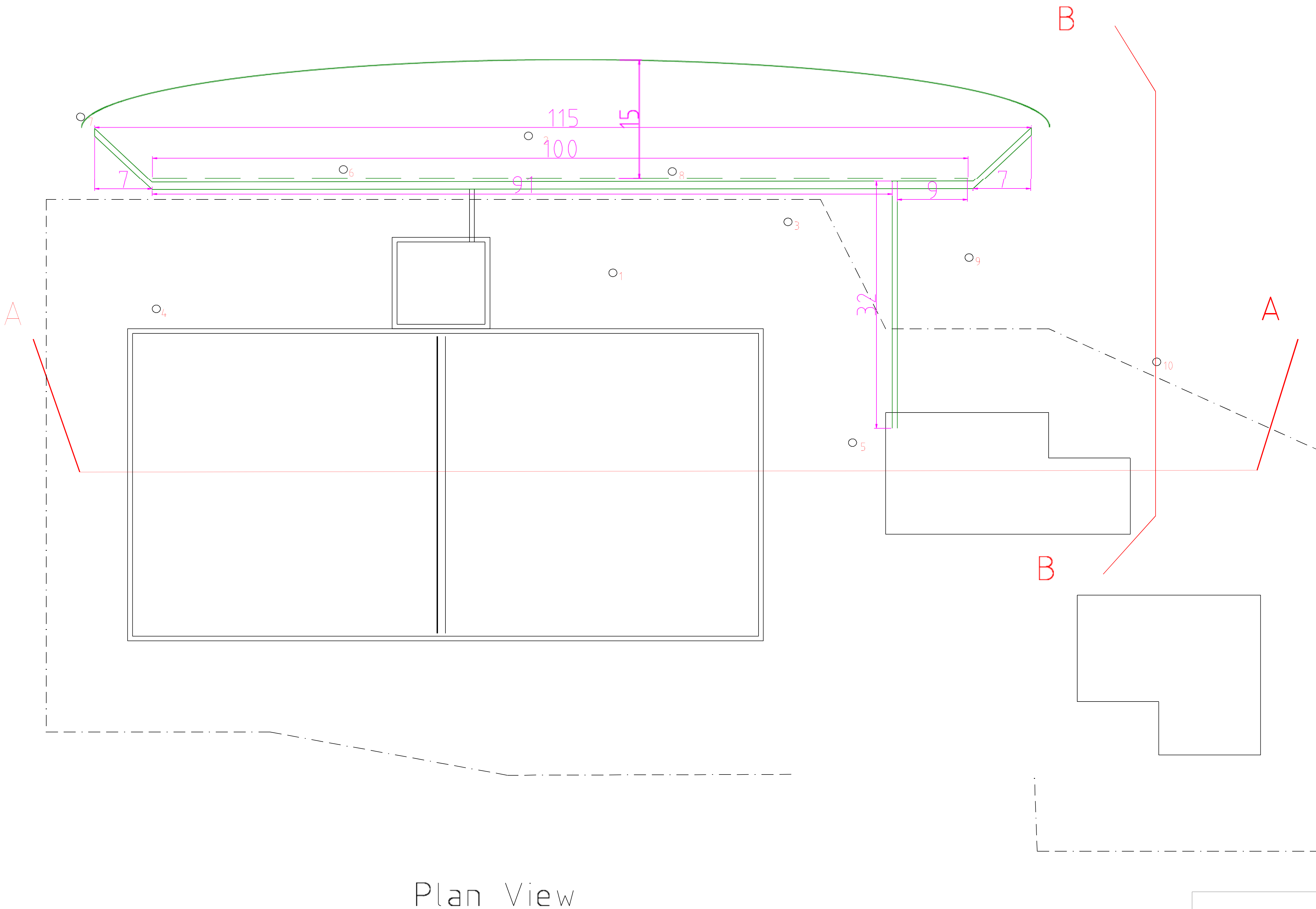


Figure J.1.. Spring discharge captured by the French drain is piped directly into Santa Rita Spring wet well



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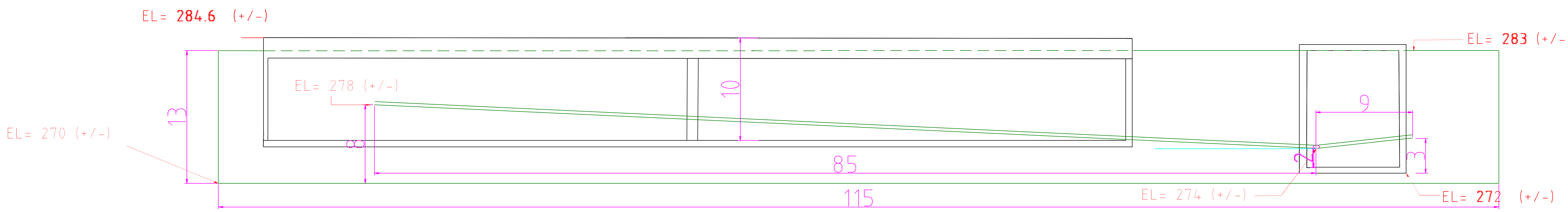
Santa Rita Spring

Dimension in feet	D2: 1 of 3



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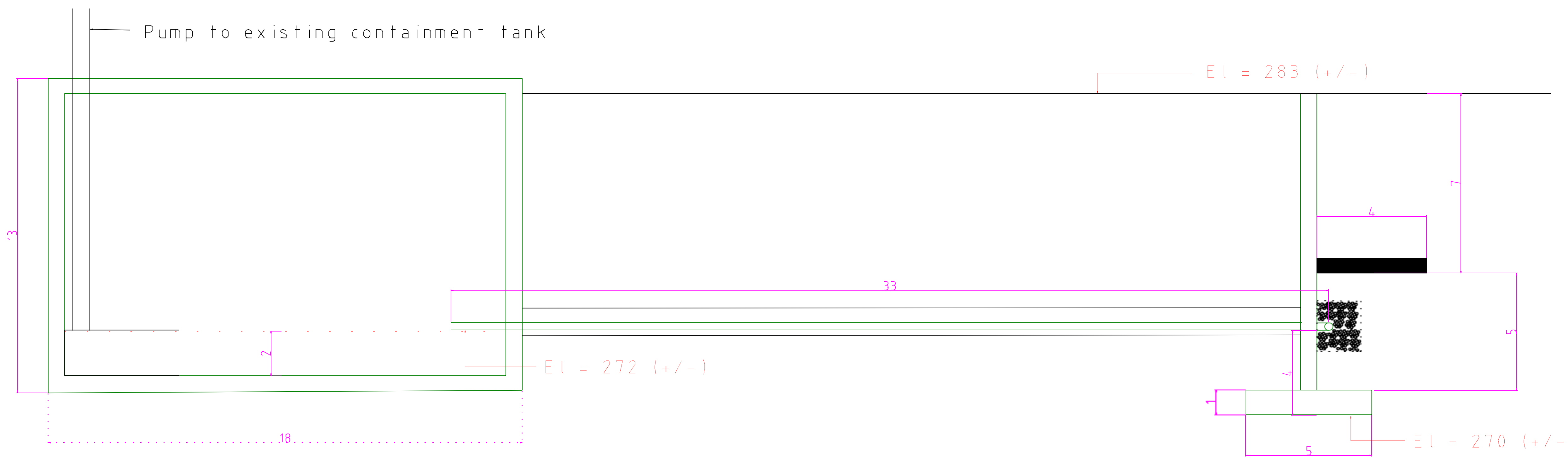
Santa Rita Spring

Dimension in feet	D2: 2 of 3



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Santa Rita Spring

Dimension in feet	D2: 3 of 3