Surface Hydrology of the Northern Guam Lens Aquifer

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

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Abstract

A concerning major pathway for contaminant transport into limestone aquifers is through major surface infiltration areas such as dolines. The Northern Guam Lens Aquifer (NGLA), a major source of the island's utility water, has a surface plateau formed from uplifted and tilted geologic formations of limestone bedrock. This aquifer has a deep vadose zone (80-120 m) that may filter much of the rain infiltration and percolation, however, during intense rainfall when infiltration rate is exceeded, surface runoff occurs. The porous karst terrain on the plateau has connected surface depressions that may fill and overflow into a focal low point during intense rainfall. Runoff may easily transport cumulative and secondary sources of contaminants into its low areas. Some of these surface depressions have turned out to be sinkholes (collapsed and solution dolines) and fractures that are entry conduits, draining large volumes of potentially contaminated runoff into the freshwater source. This is a major concern with activities within these basins. If these activities are not carefully constructed and operated, anthropogenic contaminants may be transported to the water source and drawn up from nearby production well drawdown zones or in down gradient production wells.

Guam Environmental Protection Agency is keen on regulating development over hydrologically significant sinkholes, fractures, and surface depressions that require hydrogeological assessment and site inspection. However, initial assessment via existing maps of closed contour depressions used to determine potential sinkholes were derived from old topography and has proven to have major inaccuracies and limitations. The development of a new map using the latest lidar based digital elevations (1 m raster resolution) and GIS hydrologic spatial analysis updates the island's stormwater management over the aquifer.

The surface hydrologic map products from this project applies modern technologies and high-definition data to advance our ways of determining aquifer protection. An online web map application, WERI Web MApps: Surface Hydrology of the NGLA, is now available on the Guam Hydrologic Survey website for use by Guam EPA, Guam Waterworks Authority, US Military, and island developers and planning agencies and contractors. These fundamental hydrologic maps of the NGLA are integral to the reassessment of groundwater protection zones. The surface hydrology of the NGLA is a frontline and online map product reference for determining strategic development plans over our precious water source.

Keywords: Northern Guam Lens Aquifer, surface hydrology, plateau basin, watershed, fill, runoff, WERI Web MApps

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Acronyms

amsl – above mean sea level

CTD – Conductance, Temperature, and Depth

CVA – Consolidated Vertical Accuracy

DEM – Digital Elevation Model

ESRI – Environmental Systems Research Institute

FVA – Fundamental Vertical Accuracy

GBSP – Guam Bureau of Statistics and Plans

GDLM – Guam Department of Land Management

GEPA – Guam Environmental Protection Agency

GIS – Geographic Information Systems

GWA – Guam Waterworks Authority

LiDAR – Light Detection and Ranging

MCL – Maximum Contaminant Level

MGD – Million Gallons per Day

mya – Million years ago

NGLA – Northern Guam Lens Aquifer

RCUOG – Research Corporation University of Guam

RMSE – Root Mean Square Error

SEIS – Supplemental Environmental Impact Statement

SVA – Supplemental Vertical Accuracies

USEPA – United States Environmental Protection Agency

USGS – United States Geological Survey

WERI – Water and Environmental Research Institute of the Western Pacific

Chapter 1

INTRODUCTION

This study, titled Surface Hydrology of the Northern Guam Lens Aquifer (NGLA), emerged from several investigations carried out over recent years concerning development near suspect sinkholes or closed depressions located over the NGLA. Guam Environmental Protection Agency is keen and serious about identifying areas of potential contaminant and sediment loading and enforcing regulations on development activities around major surface depressions and fractures, especially ones with identified sinkholes, considered to be major recharge conduits to Guam's fresh groundwater sources. The investigations utilized various GIS techniques, and applied fundamental hydrologic spatial analysis to the aquifer terrain. These GIS techniques determined specific hydrologic terminology (defined in Chapter 2), and a composite map of plateau basins, watersheds, fill areas, and runoff paths. These features revealed the runoff network of a drainage system of various areas located on the karst plateau. It was then determined that the same analysis should be applied for the entire NGLA in order to enhance geo-hydrologic mapping and to help developers decide strategies for storm drainage management. It was also decided that it would be desirable to train Guam interagency partners to use these hydrologic products in an all-out effort to improve Guam's water resources protection.

1.1 The Northern Guam Lens Aquifer

The Island of Guam is a territory of the United States in the Western Pacific and is located approximately 1,560 mi southeast of Narita, Japan, and 1,600 mi east of Manila, Philippines. As of 2022, the population of the island was over 171,000[1]. The NGLA (Figure 1.1) is a physiographic region that includes the entire land area north of the Pågu-Adilok Fault. Guam's land area is approximately 210 sq mi. The NGLA is approximately 102 sq mi, 49% of Guam's total land area. The NGLA is an uplifted limestone plateau that has undergone karstification and forms a freshwater lens. The karstified plateau surface is highly porous and may deliver stormwater to the lens. The economic extraction and distribution of this groundwater resource is one important key to the prosperous development that has occurred on the island. This development includes residential areas where thousands of people are living over the NGLA.

1.2 Statement of Water Resource Concern

The Northern Guam Lens Aquifer is the island's major source of fresh utility water. Because of the readily available water supply, much of the island's population, development, and other activities are situated above the NGLA. As growth and development continue above this unconfined aquifer, the potential for anthropogenic contamination of the water resource increases. One of the major concerns is surface runoff that may easily bring together particles and soluble toxic byproducts that accumulate into surface depressions and sinkholes. These particles and byproducts can then flow into various conduits and fractures and eventually be transported into the freshwater zone and later may be drawn up by production wells

[1] https://www.worldometers.info/world-population/guam-population/

Figure 1.1. Northern Guam study area and location.

downgradient (see figure 1.2). Recent WERI-RCUOG hydrogeologic and hydrologic contract assessment reports for the development of military facilities included useful site maps and hydrologic terminology for karst plateaus such as the plateau basin (defined in Chapter 2). The plateau basin contains tributary watersheds that cascade stormwaters to a focal watershed. These watersheds often may have a conduit path to the groundwater known as a sinkhole. Guam EPA uses an old and sometimes inaccurate closed contour depression map extracted from contour topography maps to initially flag any development that poses a threat to the water source. This map is limited by inaccuracies compared to the hydrologic analysis of LiDAR based Digital Elevation Models (DEM). The closed contour depression map also does not have an organized surface hydrology of the plateau, which could help builders develop and strategize proper drainage systems. The closed contours are considered suspect sinkholes. Presently, field inspections by geologists verify hydrologically significant sinkholes. However, the map GEPA is using for regulatory purposes is from crude contour depressions, and their personnel should be

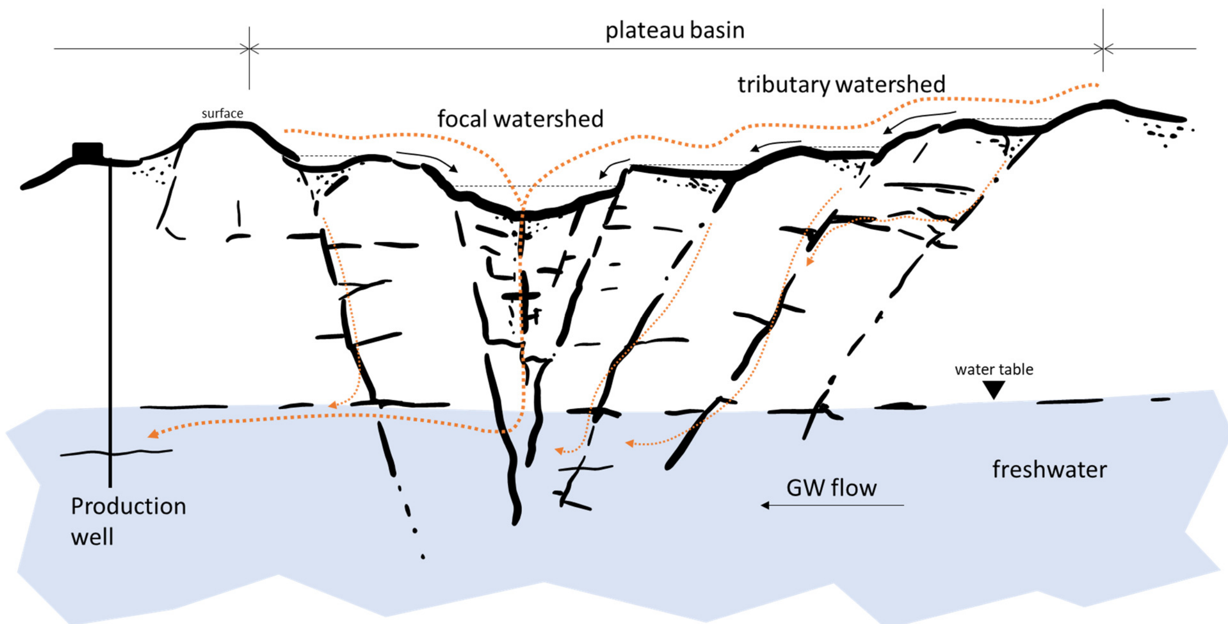

Figure 1.2. Plateau basin surface to groundwater transport schematics.

trained in using these updated surface hydrology map products. The new high-resolution digital elevation based hydrologic maps developed from this project vastly improves surface analysis capabilities thus improving groundwater protection strategies. These analyses are useful and valuable for managing stormwater movement, identifying possible sinkholes, and strategically planning for major development over the aquifer.

1.3 Goal, Purposes, and Specific Objectives

The goal is the production of a fundamental surface hydrology map of the Northern Guam Lens Aquifer plateau. The purpose of a surface hydrologic map, as it also reveals potentially vulnerable areas for production wells, is ultimately for assessing and determining development strategies towards water source protection. Specific objectives of the study were to:

1. apply hydrologic spatial analysis to the latest digital elevation model
2. organize the hydrologic features and rasters to produce useful surface hydrology maps
3. make the hydrologic maps available as a web map application
4. provide workshop(s) for online access to maps and recommended use, most specifically for Guam's regulating agencies (GEPA, GWA, and GDLM) and contract developers.

The map products were developed with Environmental Systems Research Institute (ESRI) ArcMap and ArcGIS Pro. The resulting map products are made available via ESRI's ArcGIS Online as WERI Web MApps and made available at the Guam Hydrologic Survey website. Another purpose for the use of these hydrologic map products is to provide everyone an awareness and attention to the details of the terrain, not to limit every development plan over the aquifer, but to achieve responsible plans, construction, and facilities, and proper designs, emissions control, disposal, confinement, and mitigations that keep the utility water source clean.

1.4 Scope, Limitations, Delimitations, Assumptions, and Disclaimer

Scope: This project is a surface hydrologic analysis of the Northern Guam Lens Aquifer. The products are useful fundamental surface hydrologic maps and associated GIS files for determining areas that may require attention concerning hydrologically significant sinkholes that pose a possible contaminant transfer threat to Guam's major groundwater resource.

Limitations: The base data for all the analyses is the 2012 LiDAR derived bare-earth DEM of Guam. However, this DEM has areas where no elevation data is available, or "holes." Chapter 2 discusses the nature of the data, and Chapter 3 has a method applied for filling missing data. With these limitations, a disclaimer for its intent of use is provided below.

Delimitations: Select limits were determined for the hydrologic analysis. Chapter 2, hydrology section, defines the hydrologic terminology used here. Watershed analyses are delineated around a fill area (closed surface depressions) greater than 300 sqm. The 300 sqm minimum value was selected in order to maintain a manageable number of fill area polygons in the GIS analysis. The plateau basins are further divided manually, such that the focal watershed, a terminal watershed in the plateau basin that has a deep fill area, has a maximum fill depth greater than 20 feet, which may never fill and overflow. Plateau basins do not reach the coast. Fill areas are suspect sinkholes until verified in the field.

Assumptions: Because of the unique geology and geometry of the Northern Guam Plateau, certain assumptions were applied to the rainfall-runoff-contaminant transfer relationships that apply to the area. These include:

1. The most significant effects of development activities over the NGLA will occur as a results of high intensity long duration typhoon related rainfall. These storms can result in as much as 2 feet of rainfall occurring in a single day. It is also well known that typhoons or intense storms occur in Guam.
2. The high volume of typhoon related rainfall will fall on relatively saturated ground surface conditions causing high rainfall-runoff coefficients. This means that a high percentage of the rainfall will move through rainwater drainage ways toward the natural surface detention collection areas.
3. It is likely that, during extremely high rainfall, water will overflow from higher to lower rainwater detention areas with possible movement of contaminants beyond the original rainwater collection area watersheds.
4. Some of the depressions that serve as rainwater collection areas may or may not contain geologic sinks that tend to provide for high volume flow rates and fast flows from the detention area to the NGLA.
5. Contaminants that have been deposited on or near the ground surface will most likely make their way to the detention collections areas where eventually they will be carried through the relatively porous Karst geology to the NGLA.

Disclaimer: This scientific study was designed to develop GIS spatial analysis techniques and subsequent maps for defining water flow topology on the relatively flat karst terrain overlying the NGLA. The basic aim of the project was to update the old USGS topography based closed contour depressions (as possible sink hole locations) provided by previous studies. On-ground surveys carried out during the study have shown that this study provided much improved location data over previous mapping. Even though this is the best hydrologic analysis available at this time, the data and maps should be used with caution and as a guide for determining where detailed on ground investigations are required.

1.5 Benefits

The hydrologic maps developed in this study updates the methods of assessment and reevaluates and fine tunes methods of protecting the aquifer. This in turn give GEPA and GWA the map reference to promote cooperative protective development of the area overlying the NGLA. The workshops and training that are proposed assures that the data is most reliable, useful, and available to both regulating agencies and those proposing development over the aquifer. The bottom line is that the NGLA will be protected both now and in the future for all the people of Guam.

Chapter 2

BACKGROUND AND REFERENCE LITERATURES

The development of this project titled, Surface Hydrology of the NGLA, emerged from the planned construction of the US Marines facilities, complex, and training site in Northern Guam. WERI-RCUOG (Research Corporation UOG) was consulted to investigate site suspect sinkholes, which included hydrologic analysis of the terrain. Using a high-definition Digital Elevation Model (DEM) and GIS hydrologic analysis, the investigation went beyond sinkhole determination/verification and analyzed the surface hydrology at proposed development sites. The surface hydrology analysis proved to be integral in developing an understanding of the terrain, hydrologic processes, and drainage network, in and around the areas of interest. Results of the analysis helped the contractors strategize facility design, determine mitigation, and become aware of aquifer protection and vulnerabilities. Soon after completion of this project, WERI decided that the same hydrologic analyses should be applied to the entire NGLA, so contractors may configure the best designs over the aquifer. This chapter covers the background and literature of aquifer characteristics and properties pertaining to the plateau terrain, aquifer protection and regulations on development over the aquifer, GIS data source and quality, and an overview of the hydrologic terrain analyses methods that were applied to meet the specific objectives of this report.

2.1 Geology, Hydrology, and Hydrogeology of the NGLA

The NGLA's limestone plateau consists of effective stormwater drainage terrain. The terrain is a result of millions of years of karstification processes and speleogenetic collapse that has developed an enhanced surface and subterranean drainage system. The aquifer is very receptive to stormwaters that either runoff or cause ponding. Flooding is ephemeral with exemptions at less pervious areas such as in the argillaceous limestone formation where streams occur or at fines-deposit filled and layered depressions. Unlike typical mountain valley watersheds with surface flows of streams and rivers that flow overland all the way out to the sea, the NGLA plateau has many large basins of watersheds that may overflow stormwaters that converge into a deep closed surface depression—sinkhole. Sinkholes may have subterrain conduits that reach the freshwater source. The following subsections cover the geology, hydrology, and hydrogeology of the NGLA in greater detail.

2.1.1 Geology

The NGLA is a result of 16 M years of limestone unconformity on an uplifting volcanic basement. Periodic deposition of limestone, mainly Barrigada and Mariana, formed on a volcanic formation, Alutom (Tracey et al. 1964). Mariana Limestone, 3-2 mya, formed on and around the Barrigada Limestone (16-3 mya). These features comprise the two major limestone formations of the NGLA bedrock. The major basement uplift (~2 mya) resulted in a fractured, faulted, and tilted limestone plateau (200-500 ft amsl). The faults and fractures became the major subterranean drainage and possibly a major route of underground flow, where large dolines form. Another source of surface depression is speleogenetic collapses from subterranean cavities. These faults and fractures form solution dolines, cockpit karst terrain, and polygonal karst landscapes, possibly from freshwater lens interfaces of horizontal caverns, including cavities of former freshwater lens positions. Although karst geology is highly complex, most interestingly discovered from GIS terrain and hydrologic analysis is the organization of cascading overflow runoff paths or a watershed throughflow system in the NGLA's *plateau basin.* This system delivers stormwaters to a focal watershed, a deep *fill area* doline (see Figure 1.2).

The NGLA has undergone karstification and speleogenesis, since carbonate bedrock is partially soluble, undergoes weathering, erosion, deposition, and dissolution, resulting in voids and weakening of surrounding structure. Some of these subterrain voids collapse, and surface depressions or subsidence occur. Limestone dissolution forms cavities and weakens the rock structure, and the overburden stress eventually causes collapsing resulting in a sinkhole (Bonacci 2015). Thus, sinkhole evolution is a subterrain process borne of water movement through dominant pores, enhancing size through dissolution, and weakening of pore side walls. Karst triple porosity enhances heterogeneity and anisotropy, or either way, promotes the dissolution and deposition process, weakening and strengthening the limestone bedrock for surface collapse to occur.

Limestone dissolution, speleogenesis, is known to occur at the freshwater lens interfaces, between unsaturated-saturated (water table) and saturated freshwater-saltwater, also referred to as the transition zone (Dougher et al. 2019). The lifted plateau reveals former sea level and lens position, evident throughout the karst perimeter, breached as flank margin caves. Subterranean cavities are also evident in borehole data.

Dissolution also occurs at fractures, limestone formation contacts, and in voids between basement and bedrock. Voids enlarge at conduits, fractures, and contact gaps, where infiltrated water flows quickly. At contacts, the weaker dissolvable material may transfer or be displaced, increasing flow, and enlarging into a cavity. Some of these collapsed voids result in sinkholes, often expressed in surface depressions, with conduits and fractures that reach from the groundwater to the surface depression.

The types of sinkholes found on the NGLA are solutional dolines, collapsed dolines, uvalas, poljes, banana holes, and cenotes. Map terrain analysis on the plateau reveal that large dolines are found along faults and fractures, however, map and field investigation also observed that many sizes of dolines are common. Many parts of the plateau are characteristic of doline and cockpit karst evolution in progress (Williams 1985), which may explain much of the surface hydrology flow patterns on the plateau. Hydrologic analysis of surface watersheds and runoff paths over the NGLA reveals a polygonal karst landscape (Ford and Williams 2007). Accordingly, polygonal terrain is a result of surface collapse into underlying caves. This uplifted aquifer, based on sea notches on the plateau edge along the coast, had undergone sea level stands, along with former freshwater lens position interface speleogenesis. Some of the shallow surface cavities may be due to cavities from former lens position. Polygonal karst has a very well developed and efficient drainage system (Ford and Williams 2007, Williams 1985), thus draining over the NGLA is mostly fairly quick even during major storms.

GIS hydrologic terrain analyses of the NGLA greatly reveal the faults, fractures, strikes, and lineaments, thus enhancing visibility of dip-slip faults and graben and horst. As mentioned above, large dolines form along major faults and fractures. Major faults have large depressions and tend to have parasitic faults and fractures that have smaller closed surface depressions

(Jenson et al. 2020). Some of the depressions along these resulting faults have been found to have swallow holes. Large depressions in focal watersheds often have soil accumulation at its low point and deep ones may never overflow to the next watershed.

Large dolines are visible with satellite imagery (even with the canopy); however, the vegetation cover limits visibility of a lot of the important finer details concerning hydrology. Taborosi et al. (2006) extracted closed contour depressions from a contour map of Guam. GEPA uses this closed contour depression map to flag for suspect sinkholes. From 2015–2020, Habana applied hydrologic analysis to LiDAR based DEM (bare-earth) on the NGLA to reveal the surface hydrology of a basin of watersheds, fill areas, and runoff paths. These included boundary flowthrough drainage networks in several construction project sites (Jenson et al. 2018-2020). These analyses were used to analyze development and activities impact to the water source.

2.1.2 Hydrology and terminology

Karst plateau terrain hydrology differs from typical mountain valley streams, watersheds, and basins. The runoff paths can have spatially varied permeability, which makes the terrain difficult to assess (Bonacci 2015). The surface hydrology of the NGLA is a result of karst processes that have been carved by stormwater that developed a drainage system of paths in the karst plateau.

The NGLA plateau terrain is an exceptional rain catchment system for aquifer recharge. This system has been mapped in several consultant reports. In 2019, the Mokfok Plateau Basin and tributary watershed drainage system was mapped in a hydrologic assessment report (Jenson et al. 2020) for the development of US Marines urban combat training facility in the MARBO area. Other reports include sinkhole and hydrologic assessments that including maps of surface hydrologic analysis for the US Marines facilities, Camp Blaz, and Firing Range (Jenson et al. 2015-2020). The surface hydrology studies over these local sites provided valuable strategic information that is useful for determining aquifer protective measures including design modifications and mitigation measures.

The following hydrologic terminology updates and refines earlier terminology used in the investigation reports mentioned above. The following hydrologic terminologies are based on specific ESRI spatial analysis hydrology tools and some distinct terms for the special hydrologic analysis and unique hydrology in Guam's karst plateau. These terminologies and definitions are part of the GIS hydrologic analysis features of interest that were derived from the DEM. The delimitations and assumptions described above were used as boundary conditions in the applied methods.

Fill area (fillable area): The areal extent of a *closed surface depression*, also referred to as *closed contour depression*, in a watershed that receives runoff during high intensity rainfall and often collects water. Figures 2.1 and 2.2 illustrates fill areas. Fillable area also refers to a *fill* analysis of a DEM, which is the result of the filled DEM minus the original terrain DEM, and can be converted into a polygon. This method results in the best mapping of the areal extent of a surface depression. The fill analysis is a program that assumes the closed depression does not drain and would fill to its overflow point, thus the areal extent of the depression is limited to the overflow point elevation. This point is where a fill area touches a watershed boundary. If the fill area should receive any more rainwater, it would then overflow to the next watershed. These fill areas

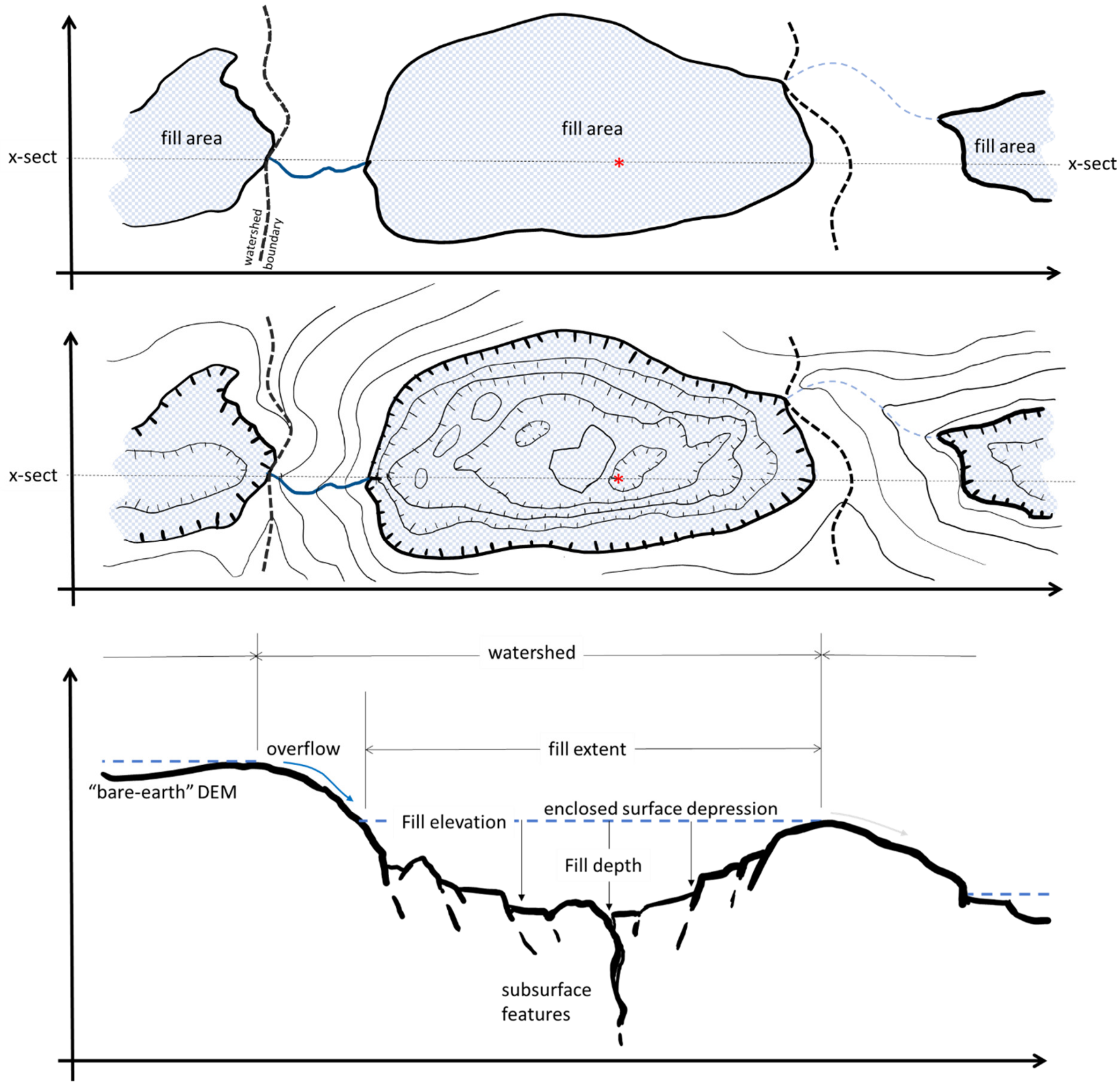

Figure 2.1 Fill area and watershed, cross-section schematic.

are often considered *suspect sinkholes*, and the surface depression may be a result of a sinkhole. The suspect sinkhole is only confirmed a sinkhole by field inspection and analysis. Field surveys have found that deep and large fill areas are often sinkholes. Many fill areas may not fill to their overflow point in the watershed, especially deep ones, which may determine the focal watershed (see definition of focal watershed below).

Fill area depth (fillable area depth): The fill area depth is the depth of the fill level, based on the fill analysis. This depth is the resulting difference between the fill DEM and the original DEM. This is a high-resolution raster depth based on the fill area elevation. The fill depths reveal the lowest point of the fill area and the shape of the depression as depth.

Overflow runoff path (ORP): A main runoff path resulting from an overflowing fill area. This path begins at the overflow point and flows into the next fill area. See Figure 2.2 for an illustration of ORPs. This major runoff path connects water between two fill areas during intense rainfall events, especially typhoons. This overflow begins at the lowest elevation of a watershed boundary that meets the edge of a fill area overflow point. Overflow runoff paths are identified using GIS *stream order* hydrologic analysis. Streams with stream order values greater than or equal to 5 tend to be ORPs. ORPs assumes a filled CCD condition. Streams with stream order values within the 1 to 4 range usually constitute normal watershed runoff routes.

<u>Watershed (WS)</u>: A rainfall catchment area that pours into a closed surface depression or fill area, with a surface area greater than or equal to 300 sqm (3,229 sqft), (see delimitations). The hydrologic analysis applied is *watershed*, using the fill areas (≥ 300 sqm) as the pour area.

<u>Focal watershed</u>: A watershed with a closed surface depression that will not overflow. The focal watershed was determined as having a fill area depth greater than 20 ft (6 m). While overflow of fill area depths of 10 ft or less have been observed by watermarks in dolines, we assume that a 20 ft depth is a reasonable maximum to never overflow. A focal watershed is the terminal watershed for tributary watersheds and overflow runoff paths. Also, most focal watersheds have a sinkhole or doline and may be a major route for fast recharge to the aquifer.

<u>Tributary watershed (TW)</u>: A series of watersheds that are connected by verifiable overflow runoff paths from the head watershed to the focal watershed.

<u>Tributary watersheds divide (TWD)</u>: The ridgeline dividing flow between tributary watersheds.

<u>Runoff path</u>: The ephemeral flow paths or throughflow in a karst terrain watershed that route rainwater into the fill areas during high or intense rainfall periods. See Figure 2.2 for an illustration of runoff paths. These runoff paths are delineated as the valley routes, ruts, and channels of a watershed, including storm drain systems, mapped with the GIS hydrologic analysis, *accumulation*. Accumulation analysis is often used to delineate stream paths in a common valley watershed. Runoff paths have stream order values (see section 3.4, Strahler stream order) that identify *watershed runoff paths* and *overflow runoff paths*. Runoff paths may be natural or artificial (storm drains and channels).

<u>Plateau basin</u>: A hydrologic basin that is a collection of tributary watersheds and a focal watershed. However, it is possible that a plateau basin may have a single focal watershed. Recall that northern Guam is an uplifted karst plateau. Plateau basins are first delineated using the GIS, hydrologic analysis, *Basin*. This analysis required a filled DEM. However, the basin program does not account for the focal watershed. The plateau basin is then further refined by determining the focal watershed, which has a fill area depth greater than 20 ft, and is bounding all tributary watersheds that flow into that focal watershed. Plateau basins do not reach the coastline. Basins that reach and discharge to the coastline in this study are called <u>*coastal basins*</u>.

Karst plateau basins in the NGLA vary in areal coverage. Large plateau basins capture large quantities of rainwater. Guam's average annual rainfall ranges from 80 to 120 in/yr. Rainfall intensities may exceed 6 in/hr. A maximum intensity of 8 in/hr was recorded during Typhoon Pongsona (Lander 2021). Rainfall from typhoons has been reported to have exceeded more than 20 in/day. Low rainfall either infiltrates the permeable surface or is evaporated. Runoff is observed on road surfaces with rain intensities greater than 0.03 in/min (1.8 in/hr) (Lander 2021).

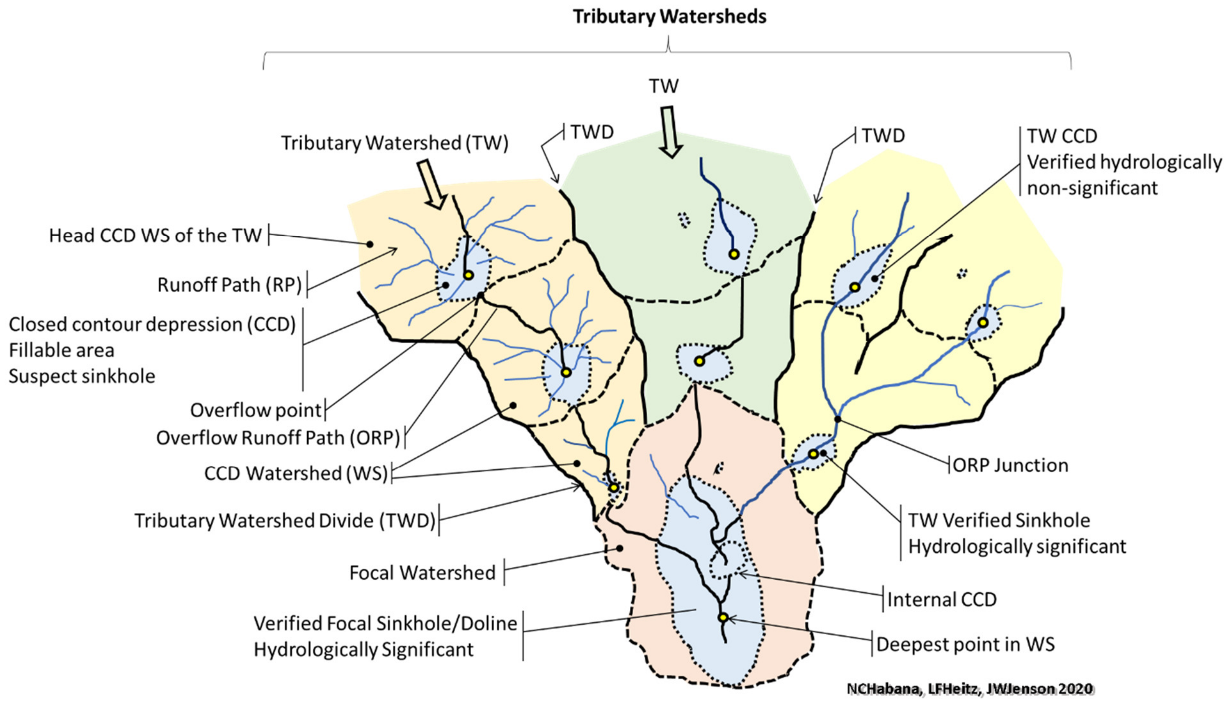

Figure 2.2. Basic schematic of a plateau basin, plan view. Plateau basins have tributary watersheds and a focal watershed.

While storms can result in runoff and ponding, typhoons may cause overflow from a 10 ft deep depression. In 2002, during Typhoon Pongsona, 25.6 in of precipitation was measured in a single day at the University of Guam (Evans et al. 2003), and many ponding basins were nearly filled or overflowed in the village of Dededo, located over the NGLA. Daily rainfall intensities in this range coupled with extremely high hourly intensities in the typhoons outer bands and eye wall were likely to cause the fill areas to overflow and cascade into the next downstream depressions.

During lower rainfall events, a watershed collects rain that infiltrates into the surface. If the rainfall rate exceeds the infiltration rate, runoff occurs and may flow to the watershed's closed surface depression, and can continue infiltrating usually as slow recharge. That is the case if the surface depression does not have a sinkhole. If rainfall is insufficient to fill all watersheds in the tributary watershed, then runoff may terminate at a watershed and never reach the basin's focal watershed. During storms, especially typhoons, overflow runoff cascades through tributary watersheds. Large plateau basins often have several tributary watersheds that may route a high volume of runoff into the focal watershed.

2.1.3 Hydrogeology and utility water production

The subterrain area of the limestone plateau has a vadose and phreatic zone. The vadose zone or unsaturated zone is mostly unconfined, especially at sinkholes, conduits, faults, and fractures. However, quarries and boreholes reveal a variety of porosity from horizontal cavities, leaky hardened limestone strata, massive impervious boulders, and doline and cockpit karst processes (Williams 1985).

The phreatic zone is a freshwater lens that accumulate atop the underlying saltwater. The lens receives autogenic and allogenic recharge. Dougher et al. (2019) analyzed temporal water level and CTD of three deep observation wells that reveal the freshwater lens, transition zone, and saltwater beneath to observe the phreatic response to storms and droughts. Stormwaters from the surface deliver fast recharge to the freshwater lens through closed surface depressions. The freshwater lens is vulnerable to contamination from surface flow related to groundwater transport routes. The focal watershed is a fast flow route (Jocson et al. 2001, Habana et al. 2009) into subterranean fractures and conduits that deliver stormwater into the freshwater lens.

The latest subsurface hydrogeologic map is the NGLA map (Habana and Jenson 2018) that integrates the NGLA groundwater model resulting water table contours (Gingerich 2013). These hydraulic head contours suggest flow direction, which is often used to determine flow direction and likely plumes of transported contaminants. Flow lines from a sinkhole or doline to production wells are often drawn to illustrate potential threats to the wells. Previous reports (Jenson et al. 2019-2020) combined the surface hydrology with the groundwater map to help investigators identify production wells that are down-gradient from closed surface depressions.

The NGLA is a federally registered sole source aquifer designation, and its freshwater lens supplies up to 90% of the 45 MGD utility water production. Blum (1978) noted the aquifer's vulnerability to contamination through recharge zone that can be hazardous for utility drinking water. A total of 90-105 active production wells operated by local and military water authorities produces and distributes a total of about 42 MGD in order to supply the island's water utility demand. The NGLA has 6 aquifer or groundwater basins. Tumhom Aquifer Basin is a major source, producing nearly 20 MGD, which is about half of the total groundwater production. The abundance of water in this basin results the most developed and populated area. Guam EPA and USEPA monitors production wells for regulated levels of turbidity, pathogens, and contaminants. Any exceedance of MCLs will require termination of water production at any well. GEPA also has a well head protection zone and other aquifer protection regulations, referred next.

2.2 Water Resource Protection Regulations and the SEIS

GEPA monitors MCL at production wells and applies aquifer protection regulations. GWA, through WERI, tests its wells and submits water quality reports to GEPA. Heitz (2014), observed select production wells for GEPA and USEPA, to determine if the wells are Groundwater under the Direct Influence of Surface Water (GWUDI) and the Surface Water Treatment Rule (SWTR). GEPA has many regulations that are applied to development over the aquifer. Three of the commonly applied protective and preventive measures for development include: Groundwater Protection Zone, Well Head Protection Zone, and development on or near sinkholes (BHA-CDM 1982, GEPA 1997). In practice, contractors are required to have their planned development investigated to determine water source impacts from developing near wells, in the groundwater protection zone, and on or near depressions and sinkholes.

Development contractors share maps of planned development to regulating agencies for investigation. Maps including the contract area are shown in the ***SEIS*** (Supplemental Environmental Impact Statement). The SEIS is often referred to as a colored perimeter "box": "red box," or "green box." The maps also include closed contour depressions, considered to be suspect sinkholes. GEPA today uses closed contour depressions (Taborosi 2006) as the map guide to suspect sinkholes. Depressions and sinkholes are often considered useful for wastewater and stormwater disposal areas. In Guam they are commonly developed into ponding basins for

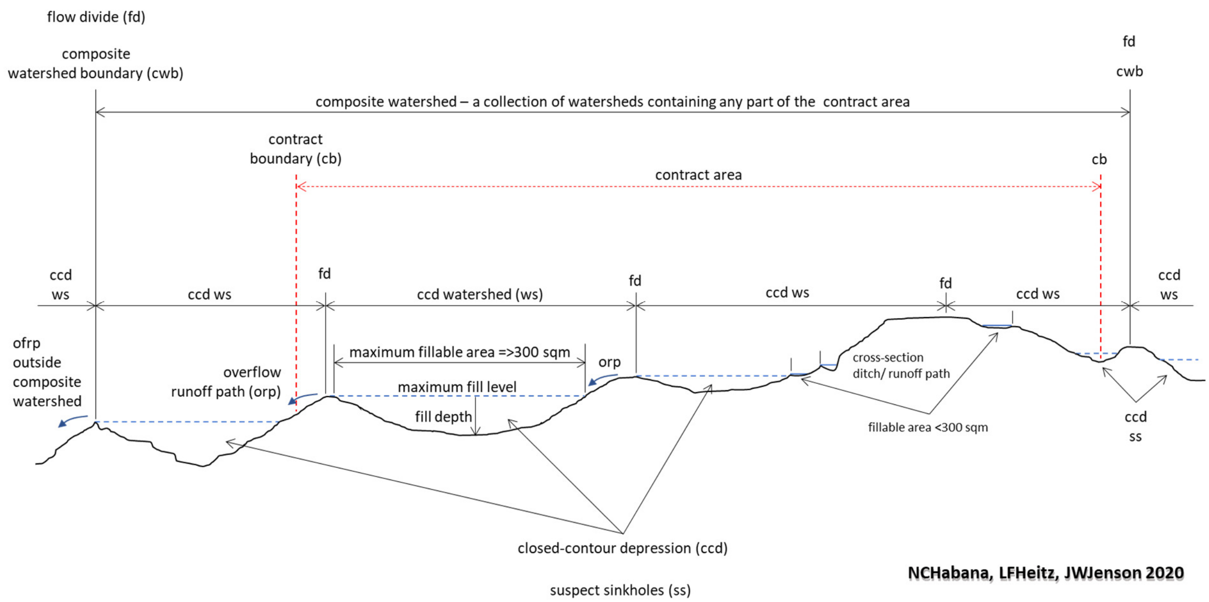

Figure 2.3. Contract area, watershed, and suspect sinkhole.

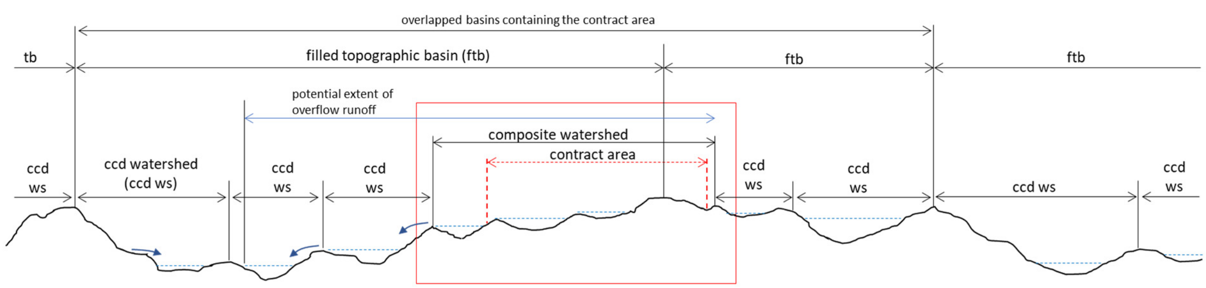

Figure 2.4. Overflow beyond the contract area.

residential and business areas. At the same time, as mentioned, they are concerningly conduits to the freshwater lens. Recent consultant analysis has gone beyond determining whether closed contour depressions are sinkholes to include the investigation of the surface hydrology as well. Figure 2.3 and 4, are schematic diagrams from recent WERI-RCUOG investigations (Jenson et al. 2019, 2020) and illustrate how stormwater may overflow and runoff outside the contract area, and cascade to the lowest elevation. Surface hydrology analysis has changed from the classic manual contour delineation to application of GIS hydrologic spatial analysis to LiDAR (Appendix) based digital elevation models (DEM).

2.3 Data Quality

The key basis for the precise GIS hydrologic analysis is the 2012 Guam DEM, bare-earth. The 2012 DEM is the latest and most precise raster elevation map of Guam. The vertical accuracy assessment of the data has a project requirement to achieve a RMSE of 12.5 cm (0.41ft), a Fundamental Vertical Accuracy (FVA) of 24.5 cm (0.80 ft) at a 95% confidence level, a Consolidated Vertical Accuracy (CVA) of 36.3 cm (1.19 ft) at the 95th Percentile and a target value for Supplemental Vertical Accuracies (SVA) of 36.3 cm (1.19 ft) at the 95th Percentile. The Fundamental Vertical Accuracy (FVA) is determined with checkpoints located only in open terrain where there is a high probability of having LiDAR return from the bare-earth ground surface and where errors are expected to follow a normal error distribution. While FVA values of 24.5 cm (0.8 ft) are not too impressive compared to actual field survey determinations, they are by far the most accurate elevation data available for use in hydrologic spatial analysis. We must keep in mind that the hydrologic spatial analysis is dependent more on the relative elevation of the DEM cells rather than the actual values that could be determined using ground survey or GPS methods. The relative elevations accuracy of the bare-earth DEM can be assumed to be better than the FVA values. We therefore assumed that the bare-earth DEM values are adequate for this study. When and if future new and more accurate DEMs are available the spatial analysis processes described in this report can be easily reapplied to that new data.

The 2012 bare-earth DEM has null values. These null values are found at corners of tile pieces of the DEM, possibly a result of the construction of the entire DEM of the island. Null values are also found at places where large buildings stand. A GIS method to patch these "holes" was applied, resulting in a seamless, smooth filling of elevation values throughout the DEM (details are in section 3.1).

2.4 Application of Surface Hydrology Analysis

The objective of this research is to apply fundamental hydrologic analysis to the latest and best available digital elevation model to determine the hydrologic rain catchment boundaries and runoff paths on the plateau surface. This is most easily achieved and best delineated using GIS and spatial analysis hydrology tools. These tools are based on the development of GIS map algebra packages for advancement of watershed terrain analysis and environmental modeling and management (Guertin et al. 2000, Tomlin 1980).

The analyses first assumes that there are no sinking streams nor infiltration ponds in order to identify an area's ultimate hydrologic boundaries and storm flow paths. However, it is advised that the map products from this report are to be used with discretion and mindfulness of the real hydrology of the NGLA and its limestone plateau basins, expecting high permeability on watershed area, along the runoff paths, and surface depressions. And that surface runoff occurs when rainfall intensity exceeds the permeability or infiltration rate, often observed during major storms. The maps are best used as a first step guide for gaining insight and as an overview for field investigation. Field investigators (Jenson et al. 2015-2019) have expressed the great value in these types of maps, as it assists with maintaining location and bearing, especially with the limited visibility in the thick jungle canopy and magnitude of the dolines.

The products are a map of layers including plateau basin and watershed boundaries, and runoff paths as defined above. The terminology is mostly hydrologic and based on the analytic methods used to determine such boundaries. Basins contain watersheds and a watershed contains a fill area. A stream method was used to delineate runoff paths. Fill depths reveal the lowest point of a fill area that may possibly be where a sinkhole is located.

The products are maps of the surface hydrology that will serve to identify critical areas, natural storm drain systems, and hydrologic boundaries. Ultimately, island developers and regulators can be trained to use the maps, via workshops, in an endeavor towards protecting the water source. We recommend that these hydrologic map products be used by all those proposing development over the NGLA.

Chapter 3

METHODOLOGY

The goal of this project was to map the fundamental hydrologic areas, boundaries, and runoff paths on the NGLA plateau. The objectives were to produce the hydrologic features discussed and defined in the previous chapter. GIS map application and hydrologic analysis tools were applied to the 2012 LiDAR based DEM. The following sections cover the details of the data, applications, and analyses. The fundamental hydrologic features produced were overlayed to map the plateau surface hydrology of the NGLA. This mapping is most integral for determining water resource protection strategies.

3.1 GIS Application, Data Refinement, and Map Analyses

The specific mapping applications for hydrologic analyses are ESRI's ArcMap, ArcGIS Pro, and ArcGIS Online. The GIS tools applied in the following sections can all be accessed through the ArcMap Arc Toolbox, which is available under the menu items in the ArcMap and ArcGIS Pro user interface. The analysis tools used were *Spatial Analyst, Hydrology*. ESRI has documents for applying the hydrology toolset, and the internet has many searchable sources of documents and videos of GIS hydrology methods and techniques as well. The subcategory tool methods were *Fill, Flow Direction, Accumulation, Basin, Watershed, and Strahler Stream Order*. Other Spatial Analysis tools were *Map Algebra, Nearest Neighbor,* and *Extraction*. Other GIS tools included conversion from raster to feature and vice versa. A standard notation is applied for providing information on accessing the tools that were used for each computational process. For example, if spatial analyst *fill* tool is used, it is referenced accordingly (ArcToolBox >Spatial Analyst Tools>Hydrology> fill). A description of the required input files for each tool is also provided.

The DEM described in Chapter 2 is the basis for all the GIS hydrologic spatial analyses that were applied. This DEM represented the bare-earth (vegetation and buildings removed) elevations of the ground surface. The coordinates are in meters, projection UTM WGS 84 Zone 55N, and the metric elevation cell values were converted to feet (ArcToolBox>Spatial Analyst Tools>map algebra). The WERI Hydrologic Web MApp products coordinate system is Auxiliary WGS 84.

3.1.1 Null values, "holes" in the DEM

As mentioned in Chapter 2, the 2012 LiDAR based DEM has null values, or "holes." These null values are found at corners of tile pieces of the DEM, possibly a result of the construction of the entire DEM of the island. Null values are also found at places where large buildings stand. These null values affect the result of the hydrologic analysis and had to be first patched with an interpolation process.

A GIS method to patch these null values was applied. A point-shape perimeter was produced for each raster cell surrounding the holes. This was done by converting the holes into a polygon, and then creating a 1 m (raster cell size is 1 m) buffer to the perimeter of the holes. Then, the buffer polygon is used to extract the raster cells from the DEM, surrounding the holes. The perimeter raster cells were converted into points with elevation values. Next, a *natural neighbor* interpolation analysis (ArcToolBox>Spatial Analyst Tools>Interpolation>Natural Neighbor) is applied using the point perimeter values. The resulting nearest neighbor cells in the hole is then extracted. Finally, map algebra (raster calculator; ArcToolBox>Spatial Analyst Tools>Map Algebra>Raster Calculator) was used to fill the holes with the interpolated values. The result is a seamless elevation patch work that fills into the previous null values and blends well with the surrounding raster cells. This patched DEM was used for all of the GIS analyses applied.

3.1.2 The surface hydrology analysis overview

Various ESRI ArcMap Geographic Information System (GIS) tools were applied to the LIDAR based DEM of the NGLA in order to accomplish the following:

1. delineation of fill areas and fill depth
2. delineation of a watershed surrounding a delimited fill area
3. production of runoff paths to the fill area
4. delineation of plateau basins

Section 2.1.2 defines these hydrologic features and rasters. The features and rasters are then combined to produce interactive internet web browser accessible maps.

3.2 Fill Area and Fill Depth (closed surface depression)

The fill areas and fill depth were processed with fill analysis. These fill areas receive rain induced runoff. Figure 3.1 is an outline of a plateau basin, a sample area for illustrating technical hydrologic analyses that were applied to the entire NGLA. In order to develop a map of the fill areas and runoff paths, it was first necessary to develop a new DEM that filled up all the surface depressions. The *fill* tool (ArcToolBox>Spatial Analyst>Tools>Hydrology>Fill) was applied to the null-removed bare-earth DEM (section *3.1.1*). A flow direction raster file was also developed

Figure 3.1. Large plateau basin used to illustrate the analyses techniques.

from the filled DEM. This file was developed by applying the *flow direction* (ArcToolBox>Spatial Analyst Tools>Hydrology>Flow Direction) to the filled DEM. The flow direction file will be used later to produce the runoff paths. The resulting DEM consisted of the required fill elevations to assure outflow from each cell. Next, the raster calculator tool was applied to subtract the original DEM from the fill elevation DEM.

The result was a DEM with the *fill depths* for values for all the surface depressions. The fill depth raster was converted to polygon features, as *fill areas*, using *raster to polygon* (Conversion Tools>From Raster>Raster to Polygon). The first process for fill area resulted in many small polygons that were too much and unmanageable, requiring delimitation. An area distribution analysis provided the selection of the most manageable size, and 300 sqm fill area was determined minimum as the frequency distribution of greater than 300 sqm was manageably reduced, and later would contribute to produce reasonable sized watersheds. Also, most fill areas less than 300 sqm was found shallow, was considered to simply fill and overflow, thus less significant. However, the first process (unfiltered fill) was used in the final maps as a selectable layer. The smaller depressions were filtered using the select option (ArcToolBox>Analysis Tools>Select) with a selection criterion of greater than 300 sqm. Figure 3.2 shows the resulting polygon map of the fill areas. This delimited fill area was used to reconstruct the fill DEM (used in the runoff path feature process) into to a filled DEM of delimited fill areas, a process of adding (raster calculator) the delimited fill depths to the DEM, referred to in the runoff section as the *300 raster file*.

Figure 3.2. Fill area (area of closed surface depression).

3.3 Surface Watersheds of Delimited Fill Areas

Watersheds were produced using the watershed tool and delimited fill areas. This is accomplished with the hydrologic analysis *watershed* (ArcToolBox>Spatial Analyst Tools>Hydrology>Watershed) applied to the Northern Guam filled DEM Flow Direction and the delimited fill polygon files. The result is a raster of *watersheds of delimited fill areas* that was then converted to polygons (Raster to Polygon). Figure 3.3 shows a sample of the results of applying the watershed tool as specified.

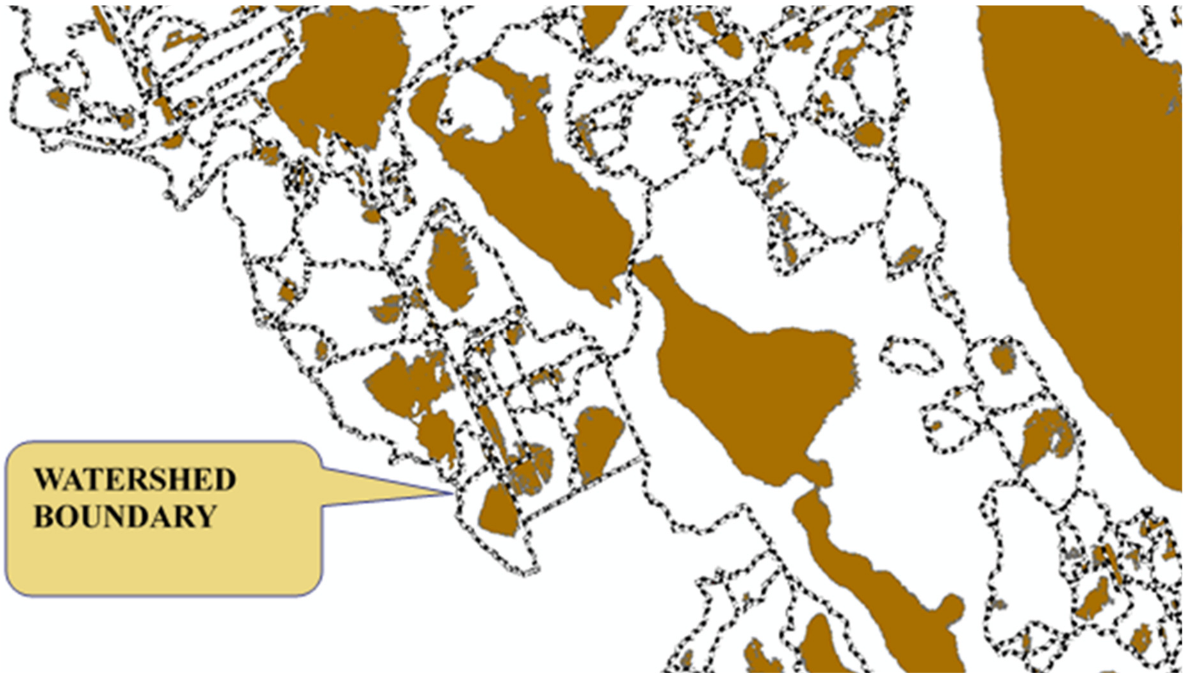

Figure 3.3. Watershed boundary of a delimited fill area.

A watershed is a rain catchment area (thus, has a boundary) where runoff and overland flow move to the fill area. Notice where the fill area meets the watershed boundary—that is the overflow point should the fill area ever reach its fill capacity and overflow to the next watershed fill area (overflow runoff path).

3.4 Runoff Paths

The approach used to obtain runoff paths was to first apply the flow accumulation tool (ArcToolBox>Spatial Analyst Tools>Hydrology>Flow Accumulation) to the previously developed filled DEM flow direction raster file (section 3.2). This tool creates a new raster containing the number of accumulated upstream cells for each cell in the flow direction DEM. Next, the map algebra tool (ArcToolBox>Spatial Analyst Tools>Map Algebra) was used to form a subset of the cells contained in the original accumulation raster. The stream to feature tool (ArcToolBox> Spatial Analyst Tools>Hydrology>Stream to Feature) to the accumulation greater than 300 raster file to obtain a polyline file of the rainwater flow pathways. The derived runoff paths are shown in Figure 3.4. The line widths of the runoff paths are plotted proportionally to the logarithm of the cell accumulation in the path.

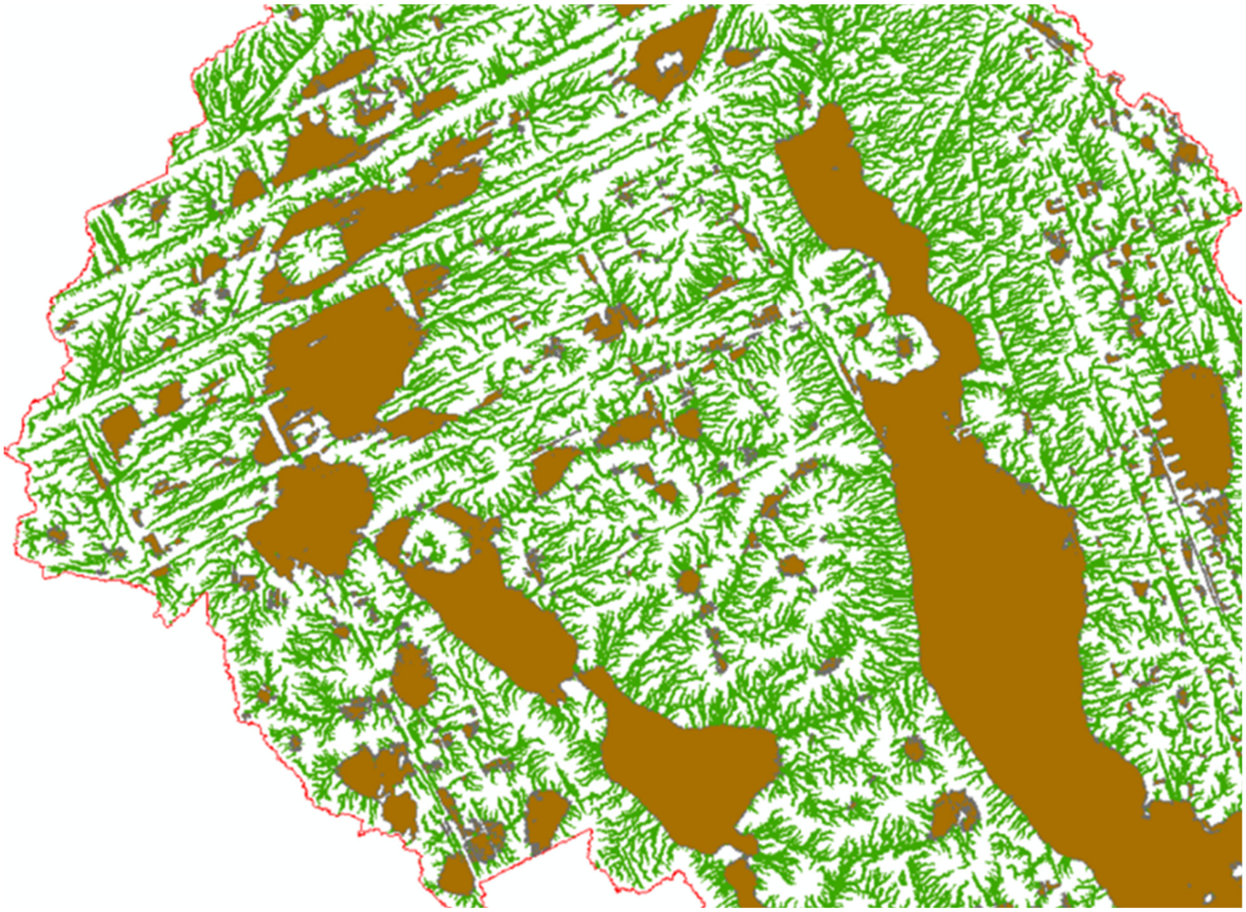

Figure 3.4. Derived runoff paths.

Figure 3.5 is a closeup view of runoff paths. Next process was *stream order* (ArcToolBox> Spatial Analyst Tools>Hydrology>Stream Order) to the previously developed accumulation analysis of the greater than 300 cells filled DEM flow direction raster files. Stream order provides a mean to describe the hierarchical location of stream segments withing a stream system. Figure 3.6 is the concept of the Strahler stream order system. This resulted in a new raster file of the stream order for all the segments of the previously identified runoff paths. The result is a set of polylines of stream order values. Polylines less than 5 (Strahler order) are watershed runoff paths, higher order paths represent the paths connecting the fill areas across watersheds—as overflow runoff paths.

3.5 Plateau Basins

The plateau basin is derived from the filled DEM. It is a basin where no water can escape on the surface. These basins are defined by applying the *basin* tool (ArcToolBox>Spatial Analyst Tools>Hydrology>Basin) to the previously developed filled flow direction raster files. Figure 3.7 shows the basin outlines for all the surface basins located over the NGLA. The area delineated in blue is the example basin shown in the previous figures. The real depth capacity required to overflow from the storms intensities that occur in Guam is difficult to determine for each fill area. The basin analysis is not programmed to determine that as well, thus the actual basin may be smaller than computed. To simplify this condition, a delimitation was set at closed surface

Figure 3.5. Closeup view of runoff paths.

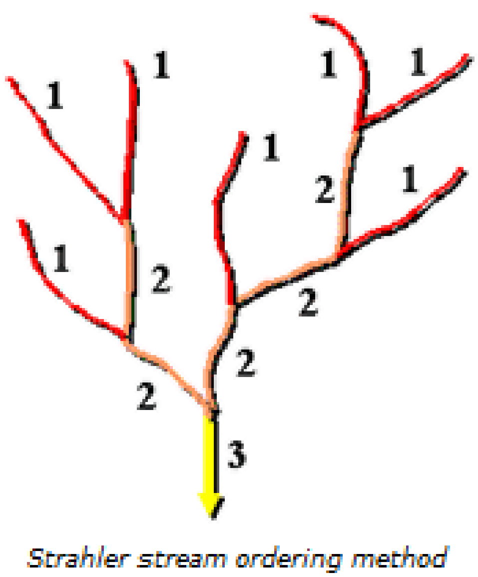

Figure 3.6. Concept of Strahler Stream Ordering Method.

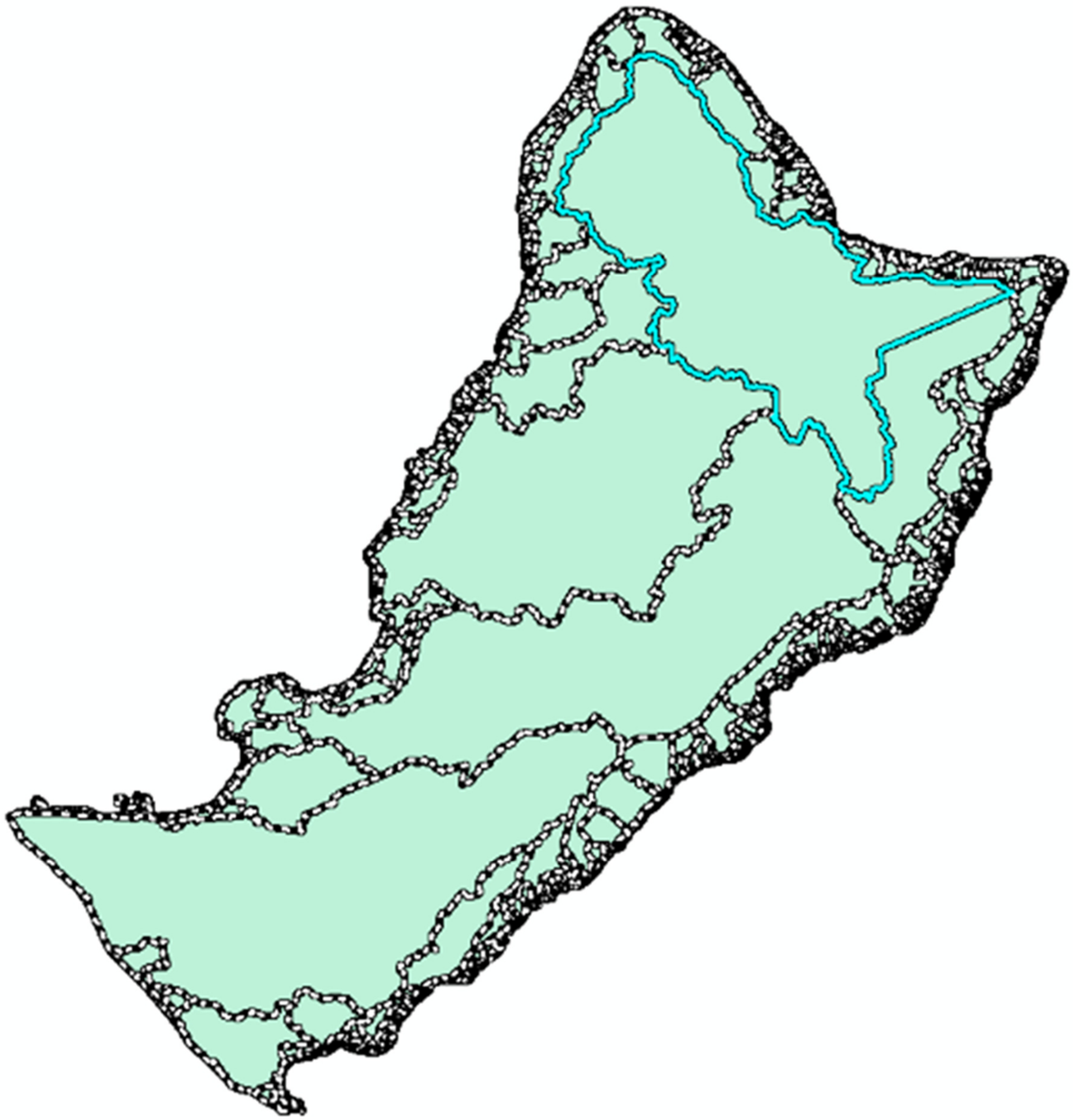

Figure 3.7. Basin analysis.

depressions of depths greater than 20 ft and its watershed define focal watersheds. It is considered that these deep surface depressions do not overflow into the next watershed under the most intense storm. These were identified from the fill depth (section 3.2) of a fill area. These delimited focal watersheds and its tributary watersheds enclose the basin. Since there are basins that contained more than one focal watershed within their delineation, the basin boundary was redefined manually to either contain only one focal watershed, or as basins considering CHamoru name place basin areas. Thus, the plural plateau basins (e.g., Mokfok basins) may have more than one focal watershed. Manual editing of the basin polygon was accomplished using trace and append to divide and redefine the boundaries (see Figure 3.8). The basins were given CHamoru names in collaboration with Kumisión i Fino' CHamoru and WERI-RCUOG (see Figure 3.9).

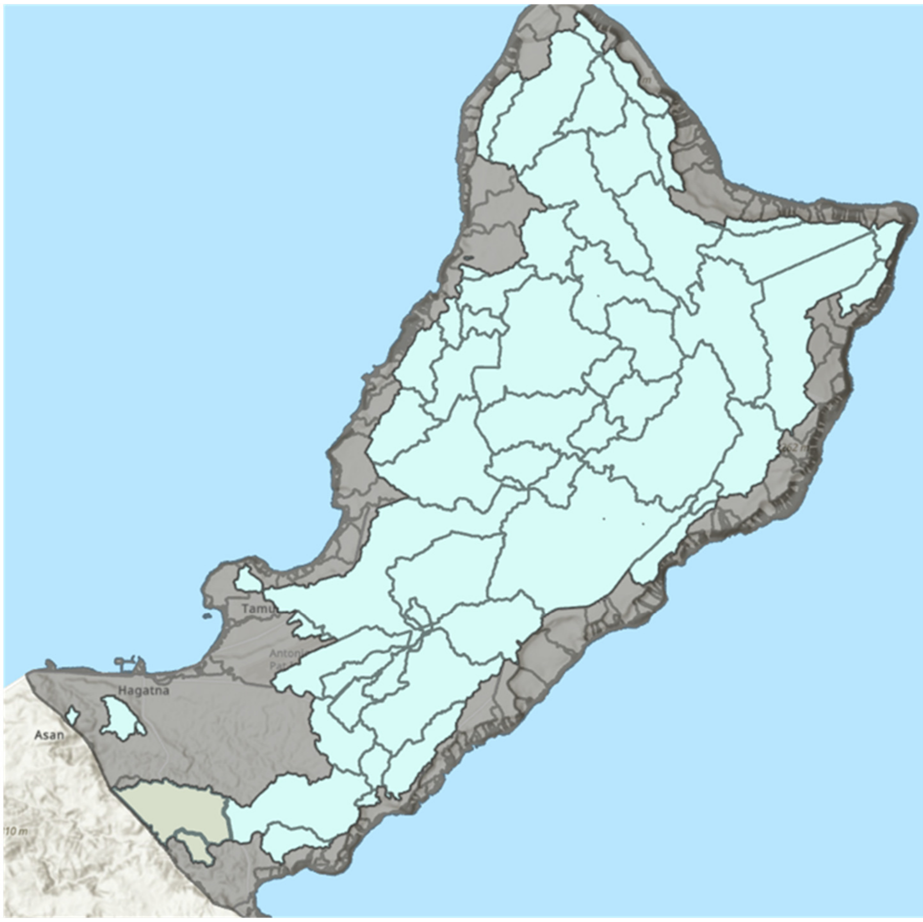

Figure 3.8. Final basin analysis redefined with respect to delimited focal watershed and the consideration for CHamoru name of plateau basins.

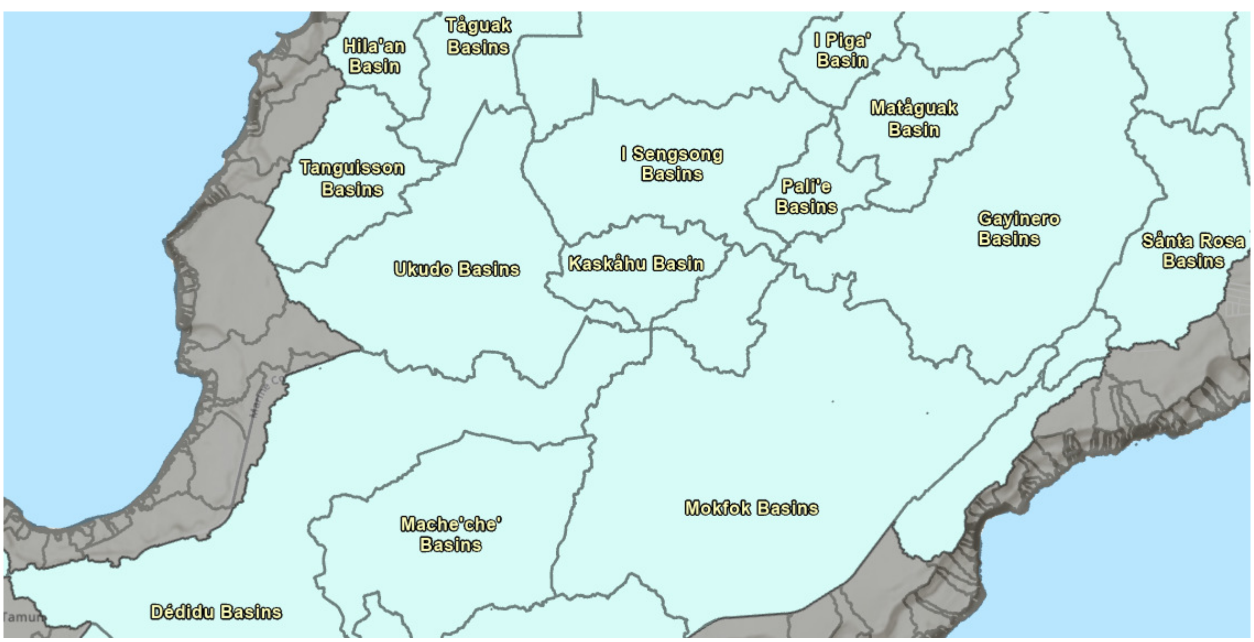

Figure 3.9. CHamoru names of plateau basins. Plateau basin names were determined by the Kumisión I Na'an Lugåt Guahan (Guam Place Names Commission) and WERI-RCUOG, 2021.

3.6 Hydrologic Web MApp Products

The GIS shapefiles (basins, watershed, runoff paths, fill area, and contours) and map rasters (fill depth and flow direction) were combined to create a useful map of the NGLA surface hydrology. This was then uploaded into ArcGIS Online to create an interactive web mapping application, as WERI Web MApps: Surface Hydrology of the NGLA (Figure 3.10). The next chapter (Results) shows how to use the Web MApp interface and internet access to four hydrologic map products.

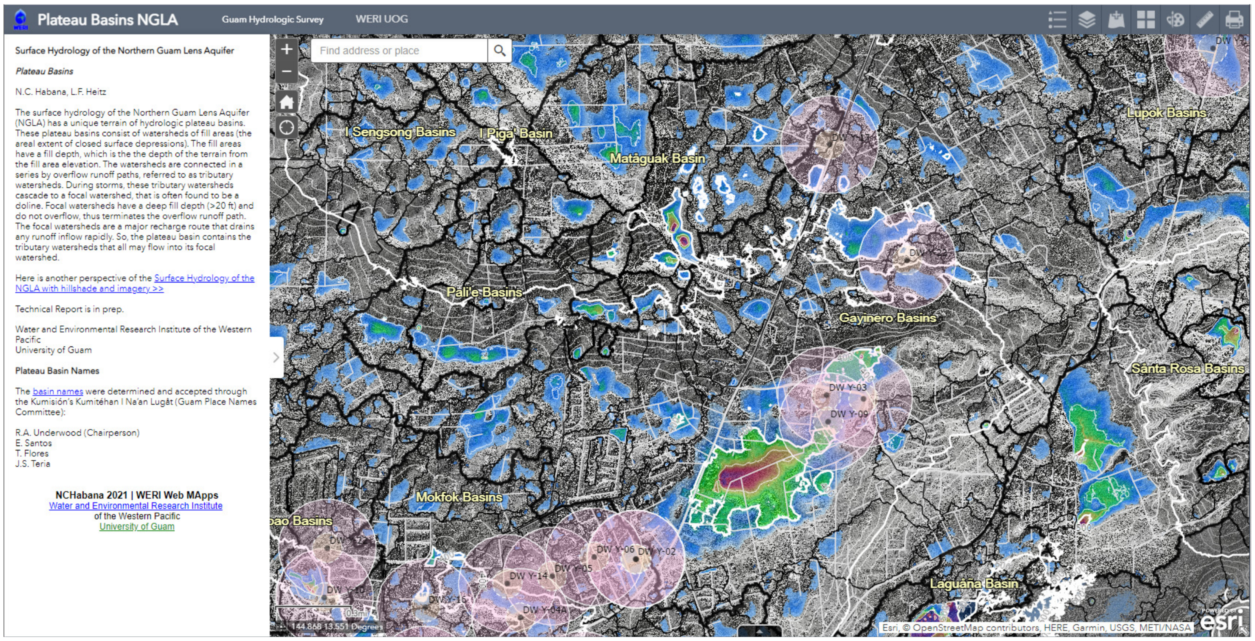

Figure 3.10 WERI Web MApps: Surface Hydrology of the Northern Guam Lens Aquifer.

Chapter 4

RESULTS

Findings for each hydrologic spatial analysis and the resulting map products are briefly discussed and illustrated in this chapter. The four main hydrologic analyses resulting in shape features and raster of the 2012 LiDAR based DEM of northern Guam are: fill area, watershed, runoff paths, and plateau basins, and a raster map for fill depth. Plateau basins were given CHamoru names, determined and approved by the CHamoru name place Kumisión (commission). Sample result figures of each hydrologic analysis are illustrated in the following sections. The final products are a combination of these map features and rasters, overlaying a select background with surface elevation contours. Four map products were then uploaded to WERI's ArcGIS Online account and developed into interactive web map applications as *WERI Web MApp* products. These hydrologic WERI Web MApp products were first unveiled in the Guam Advisory Council Meeting, November 2021, and made available on the Guam Hydrologic Survey website.

4.1 Fill Areas (closed surface depression) Analysis

Application of GIS' hydrologic fill analysis is the best method to delineate fill areas or *closed surface depressions*, also referred to as *closed contour depressions*. Fill analysis is the most precise method versus the classic extraction of topographic depression contours since the elevation of a fill may be between contour intervals. As described in the methods section, fill hydrologic spatial analysis of the 2012 DEM (LiDAR based, bare-earth) of northern Guam was applied to obtain a filled DEM. Then, a raster calculation difference of the filled DEM and the original DEM was made to produce a hydrologic fill depth (Figure 4.1) measured from the fill area elevation to the original DEM. After converting the fill depth to a single value (e.g., multiply by zero), the fill depth may be converted into a polygon shapefile. The unfiltered fill analysis produced a large number of small fill areas (Figure 4.2). This was then delimited (see Chapter 1) to fill areas greater than 300 sqm (Figure 4.3). The largest fill area is located in the northwest region of the island and the deepest are two quarry sites near Barrigada Heights. The average fill area is 8 sqm.

4.2 Watersheds

The watersheds were produced using the delimited fill areas. Figure 4.4 shows that each watershed contains a fill area greater than 300 sqm, and the overflow point is where the fill area meets the watershed boundary. The largest watershed on the NGLA covered 4.88 sq mi and is located in the northwest area. However, fill areas have varying depths of more than 20 feet within a watershed, and their boundaries may be subject to basin delineation (see Section 4.4). The average area of a watershed is 0.025 sq mi (16 acres). There are more than 3,000 watersheds scattered across the plateau basins.

4.3 Runoff Paths

To obtain runoff paths, several GIS spatial analysis hydrology tools were applied. These tools included flow direction, flow accumulation, and Strahler stream order. Figure 4.5 shows two kinds of runoff paths, watershed runoff paths and overflow runoff paths.

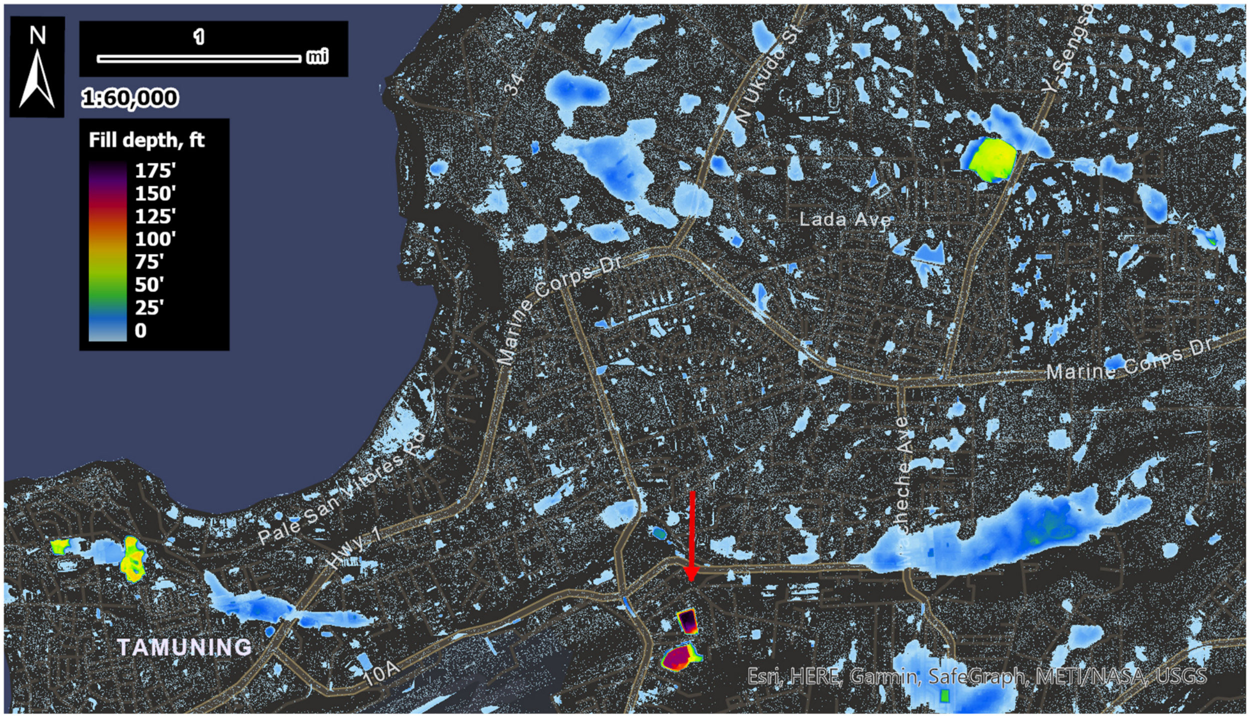

Figure 4.1 Fill depth. The deepest fill depth is at the old *Perez Bros Inc. Quarry*, 175 ft (red arrow).

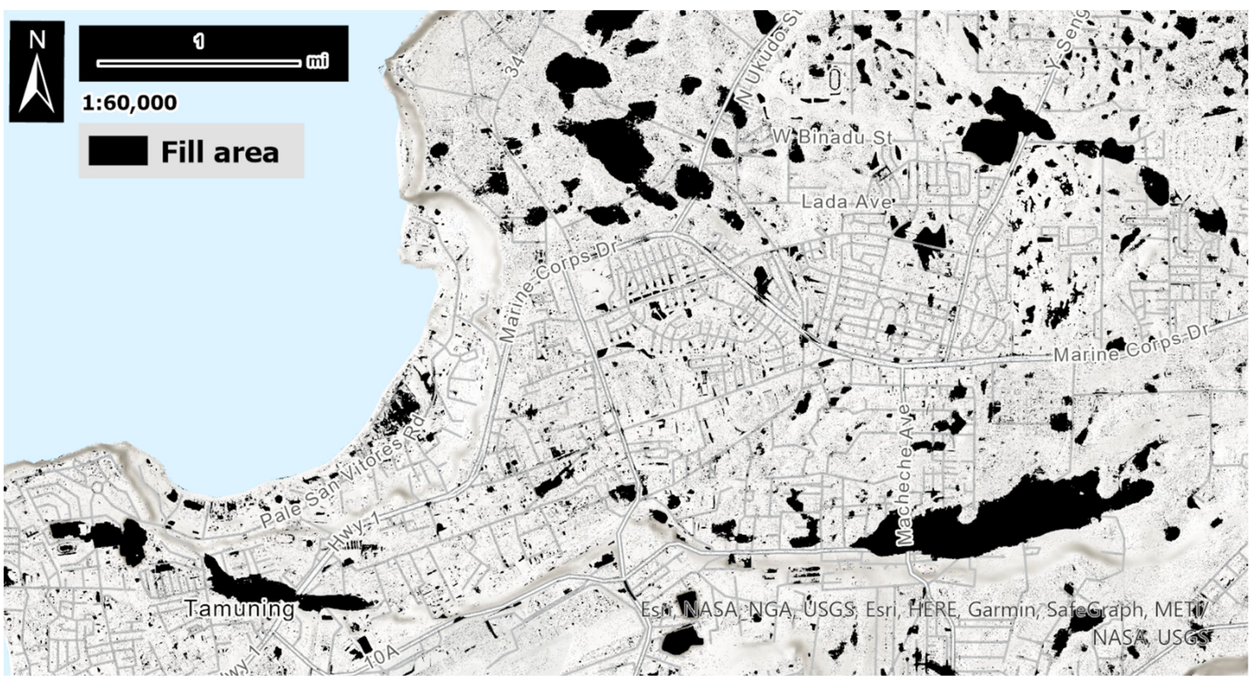

Figure 4.2 Fill area analysis feature, unfiltered. An undelimited fill analysis includes fill areas of less than 1 sqm that would produce an overwhelming delineation of insignificant watersheds. However, since sinkholes can be smaller than 1 sqm, a fill area or closed surface depression suggest that there may be a sinkhole within. Fill areas are often considered suspect sinkhole, as it may or may not have a sinkhole. Most surface depressions have a high probability of resulting in dolines in a karst terrain.

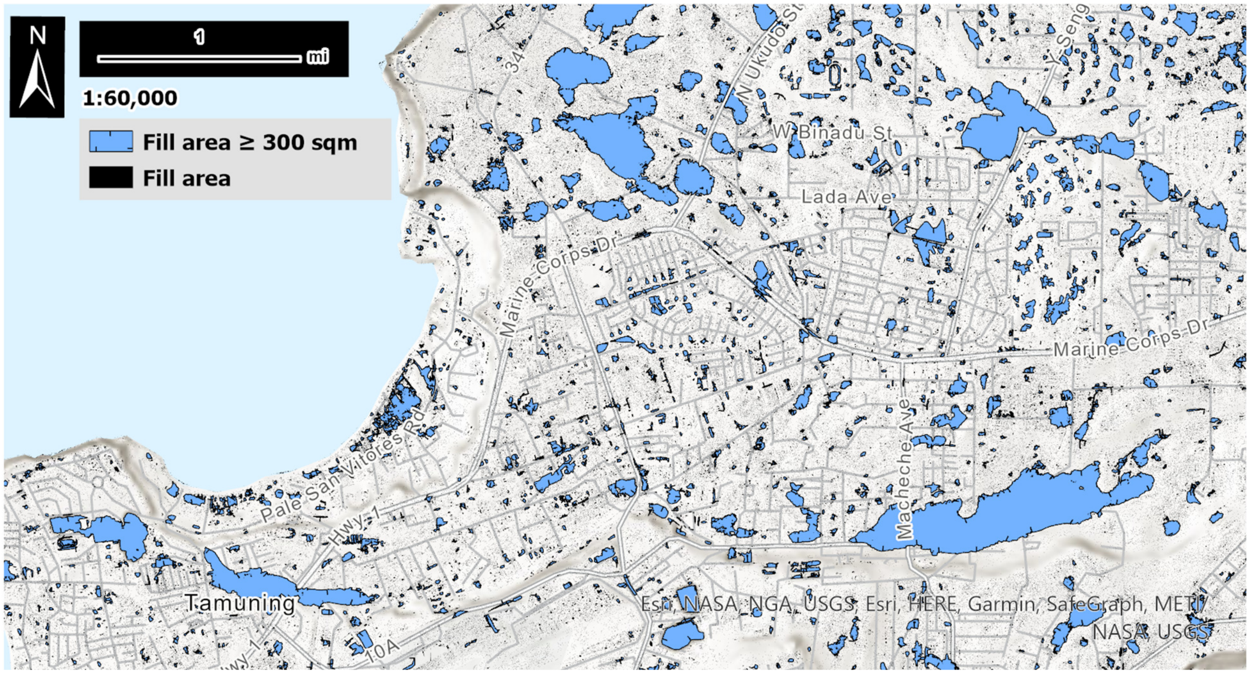

Figure 4.3 Fill area delimited—greater than 300 sqm. In a statistical analysis, 300 sqm appear to be a proper minimum area for delineating watersheds, as each watershed contains a single fill area in the analysis.

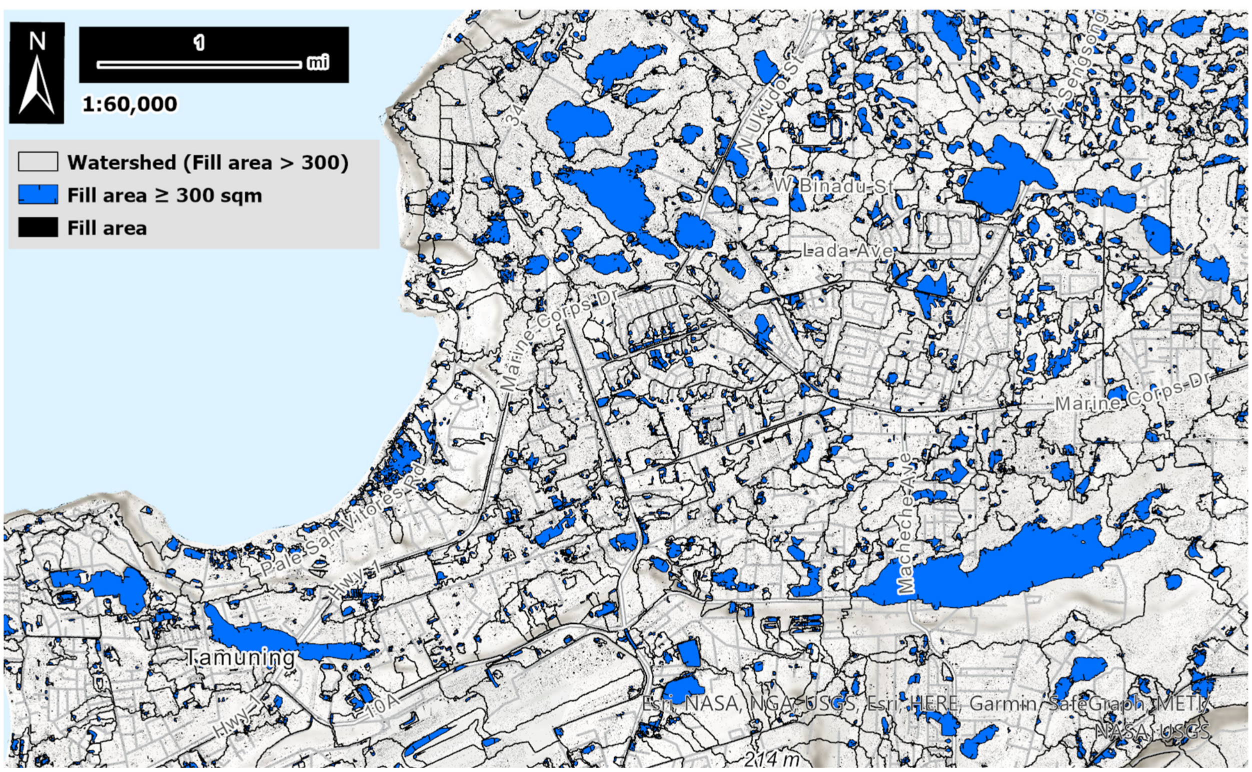

Figure 4.4 Watersheds of delimited fill areas. Fill area less than 300 sqm (black) are layered beneath the blue fill area. The overflow point is where watershed meets the blue fill area, with the exception of fill areas greater than 20 ft deep as delimited, further discussed in the plateau basin delineation.

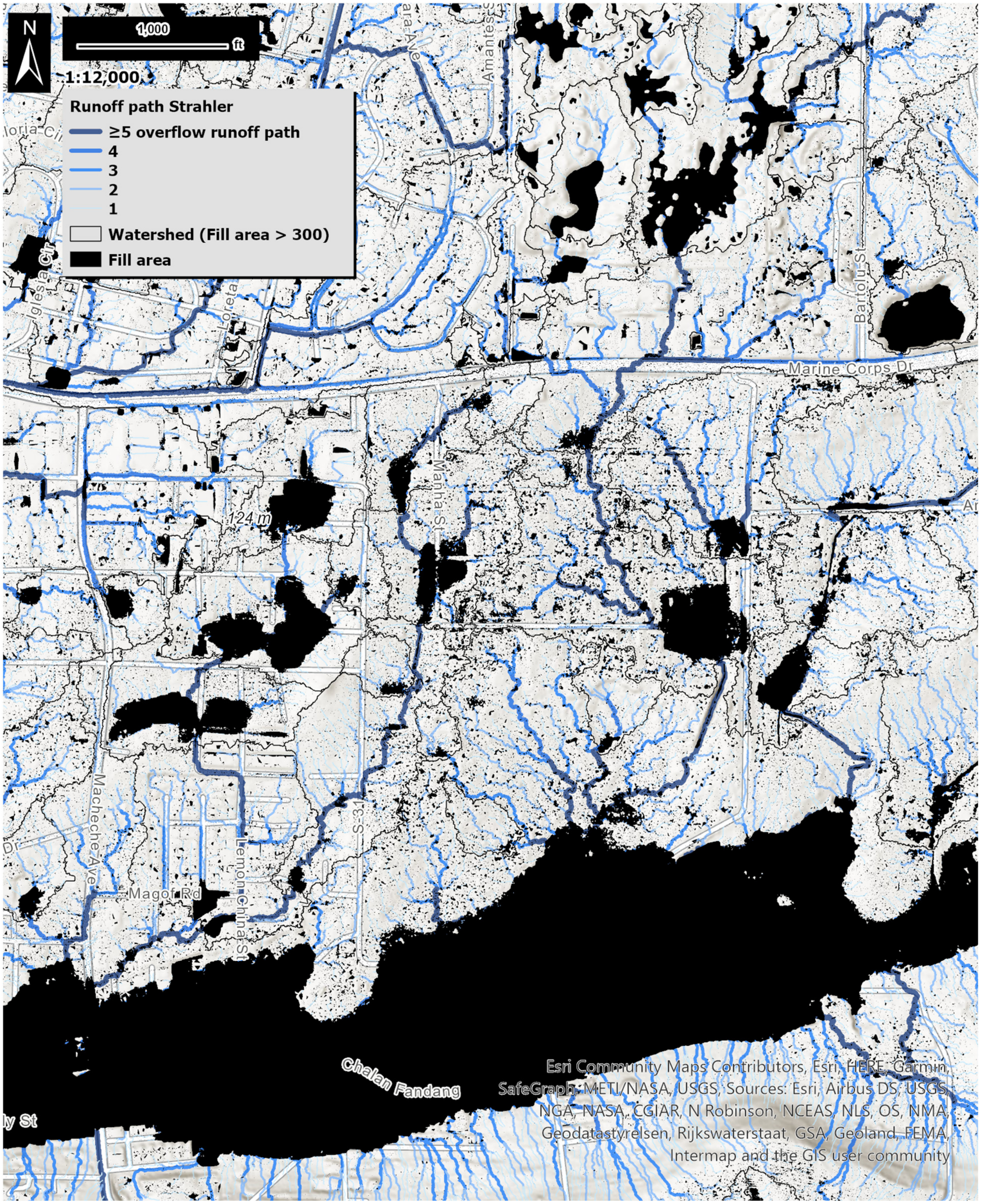

Figure 4.5 Runoff paths. Strahler stream order values less than 5 are watershed runoff paths, greater than or equal to 5 are overflow runoff paths, which assumes the fill area is shallow enough to overflow into the next watershed fill area. The watersheds and its runoff paths resemble a polygonal karst terrain (Ford and Williams, 2007).

Watershed runoff paths are flow paths within the watershed that may carry runoff rainwater from the watershed boundaries to the fill area in the watershed. The watershed layout and watershed runoff paths are characteristic of a polygonal karst landscape (Ford and Williams 2007). Overflow runoff paths connect a series of watershed fill areas that have fill depths less than 20 feet deep (see delimitation, Chapter 1). Overflow runoff paths may link a series of watersheds as *tributary watersheds* that terminate at the focal watershed. A focal watershed may have several tributary watersheds. Tributary watershed delineation are set for a next project phase.

4.4 Plateau Basins

Plateau basins were derived from a filled DEM. A plateau basin contains tributary watershed(s) and a focal watershed (see Figures 1.2 and 2.2), and at minimum contain a single focal watershed. A plateau basin with several focal watersheds with a deep fill depth greater than 20 feet, a delimitation (Chapter 1), was further divided along a tributary watershed divide, where the neighboring tributary watersheds flowed into different focal watersheds.

A total of 60 plateau basins were delineated. These basins define a total plateau area of 68.88 sq mi. The Mokfok Basin is the largest plateau basin identified with an area of 5.3 sq mi. Figure 4.6 and Figure 4.7 illustrate the focal watershed of the Mokfok Basin and the Mokfok Focal Watershed. The fill area of this focal watershed has a maximum fill depth of more than 36 ft. The fill area extends into the Mache'che' Basins, since the fill area has several depressions that are greater than 20 ft. Thus, the Mokfok doline fill area may be further divided, considering the runoff paths and watersheds as boundaries for selecting the division.

The plateau basins were given CHamoru names by the Kumisión I Na'an Lugåt Guåhan (Guam Place Names Commission, Underwood et al. 2021). Figure 4.8 illustrates the official Plateau Basin Map with CHamoru names determined by the commission committee. Table 4.1 lists, by area size, the 60 Plateau Basins identified and named. The coastal basins were left as originally delineated and not officially named, with the exception of Achai coastal basin, in the northwest point area, and Sesonyan Basin that span over the Hagåtña, Ma'ina, Barrigada, and Mongmong-Toto-Maite areas. The Mokfok Basin is the largest Plateau Basin with an areal coverage of 5.3 sq mi (Figure 4.7). Five additional large area plateau basins are Dédidu (4.08 sq mi), Gayinero (3.79 sq mi), Guaguayon (3.37 sq mi), Upi (3.17 sq mi), and Lupok (2.65 sq mi). Figure 4.9 illustrates the plateau area as defined by plateau basins.

4.5 Background Maps, Contours, and Production Wells

The two background images used were flow direction and first-return hillshade. Gray shade flow direction (derived from bare-earth DEM) provides great contrast, revealing faults and slopes very well (Figure 4.10). LiDAR based bare-earth DEM derived contours of 10 ft, 50 ft, and 100 ft were added for quantifying grades and elevations. First-return hillshade (LiDAR based) reveals structures, useful for storm drain management in urban areas (Figure 4.11). However, the online Web MApps allow the user to select from several other background base maps such as areal imagery and other ESRI available products. Other additional features include the production wells and their GEPA regulation well head protection zones (300 ft and 1000 ft, radial buffers). Other map features are available, and their availability is discussed in the next section.

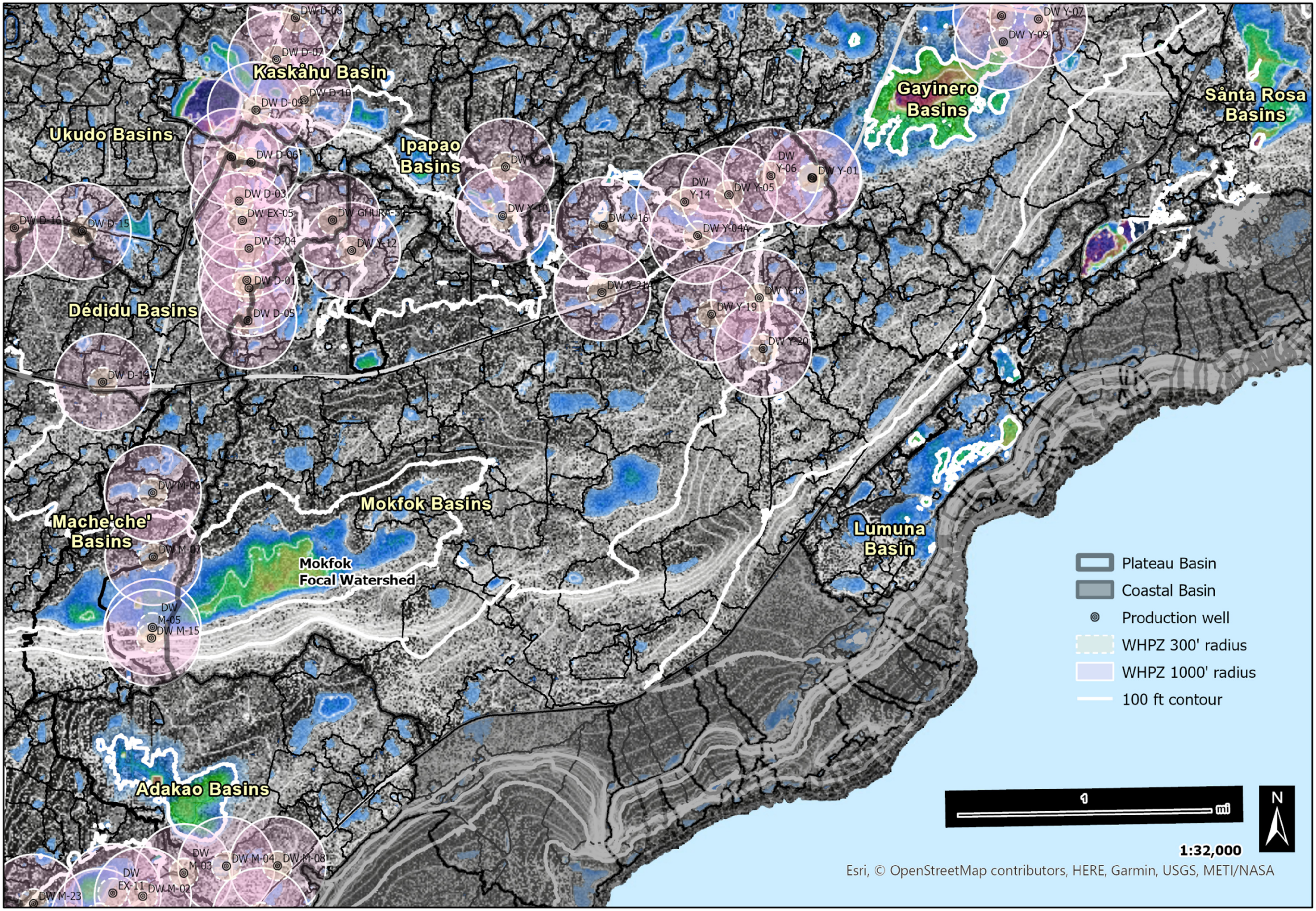

Figure 4.6 Mokfok Plateau Basins, GWA production wells, and well head protection zone.

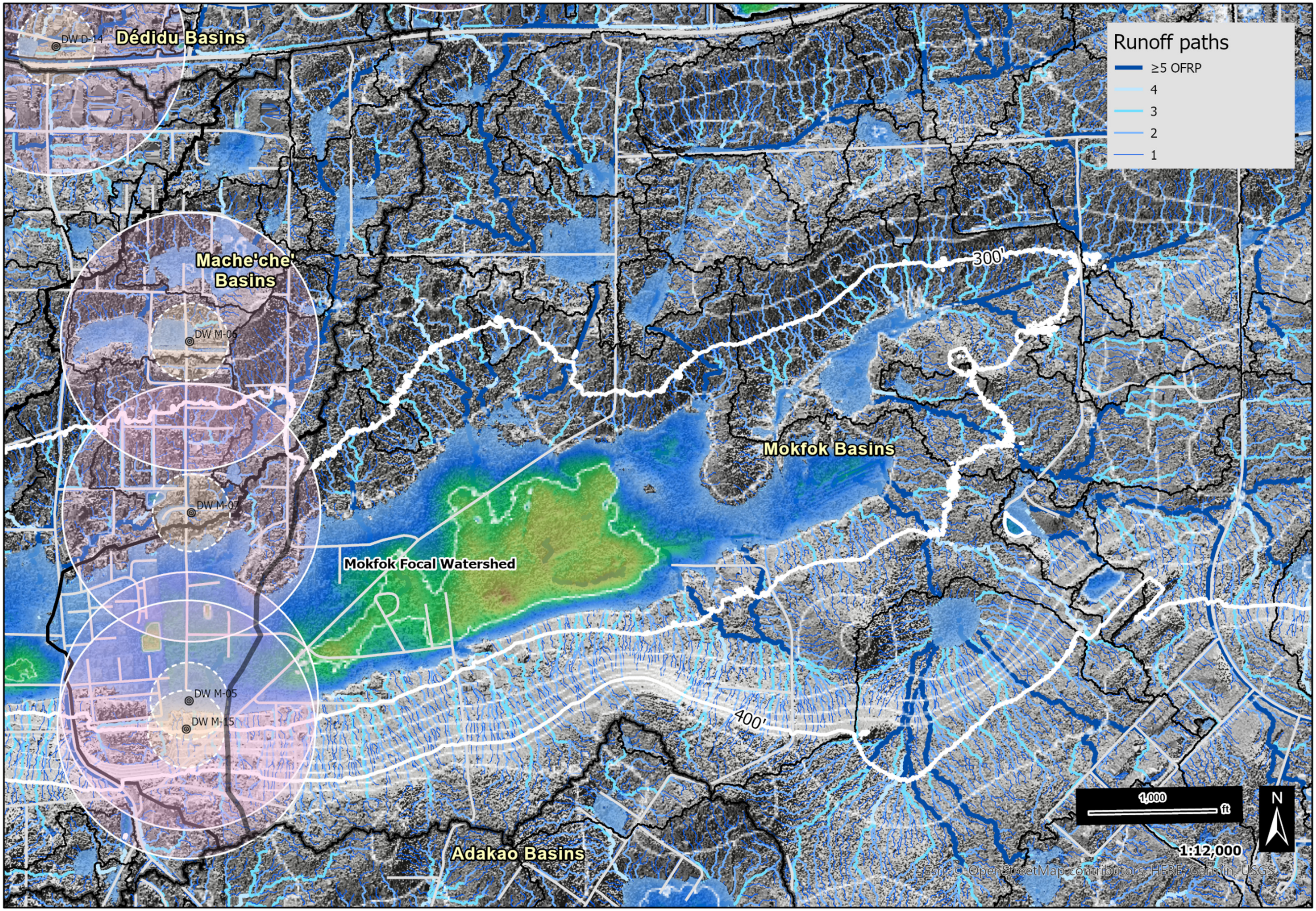

Figure 4.7 Mokfok focal watershed and runoff paths.

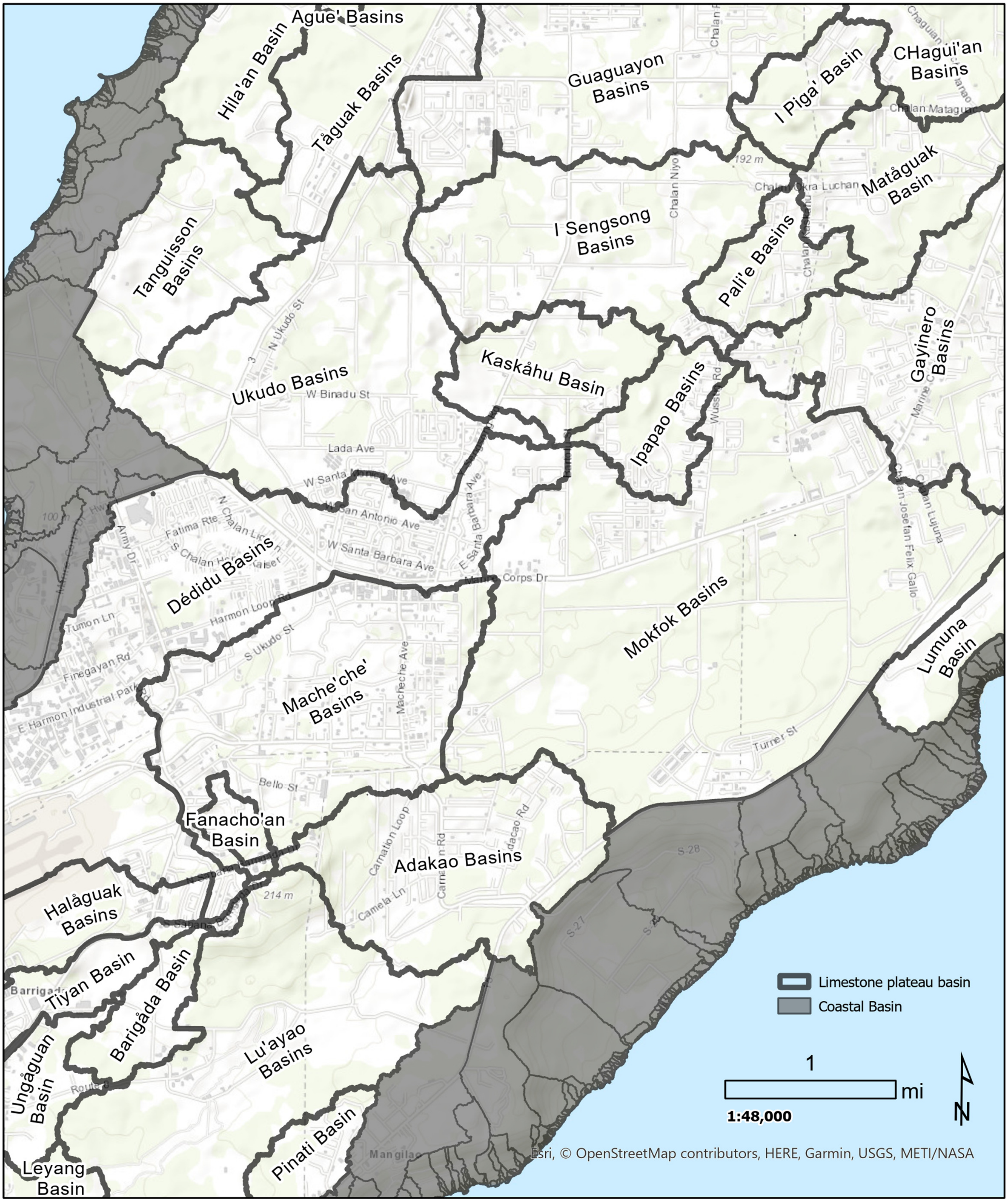

Figure 4.8 CHamoru name of Plateau Basins (Underwood et al. 2021). A total of 60 plateau basins were named.

Table 4.1 Plateau Basins of the NGLA (sorted by area size).

Plateau Basin Name	Area sq mi	Plateau Basin Name	Area sq mi
Mokfok	5.30	Mågua’	0.74
Dédidu	4.09	Kaskåhu	0.67
Gayinero	3.79	Lumuna	0.55
Guaguayon	3.37	Urunao	0.54
Upi	3.17	Tiyan	0.49
Lupok	2.65	Metgågan	0.48
Ukudo	2.50	Hinapsan	0.48
Machanao	2.44	Maga' Basin	0.47
Lu'ayao	2.37	Ipapao	0.46
Alakunao	2.32	I Piga'	0.46
Mache'che'	2.15	Pali'e	0.46
Mangilao	2.13	Ungåguan	0.42
As Tobias	2.10	Lafak	0.39
I Sengsong	1.77	Barigåda	0.35
Togua'	1.65	Tutuhan	0.32
Adakao	1.57	Tålagi	0.30
Otdot	1.56	Haputo	0.30
Finagua'yok	1.49	Lålo'	0.29
CHagui'an	1.30	Ague'	0.28
Sånta Rosa	1.29	Patai	0.25
Fafalu	1.28	Pågu	0.23
Halåguak	1.16	Litekyan	0.20
Tåguak	1.09	Sosiu	0.17
Kaiguat	1.06	Tamuneng	0.16
Tanguisson	0.97	Laguåña	0.15
Tailalo'	0.94	Fanacho'an	0.12
Matåguak	0.93	Pugua'	0.09
Pinati	0.88	Fadi'an	0.09
Leyang	0.87	Ma'ina	0.05
Hila'an	0.72	Sinahånña	0.03
		Total	**68.9**

Figure 4.9 The Northern Guam Plateau area as defined by plateau basins. The dark gray areas are coastal basins. The plateau area is about 68.9 sq mi.

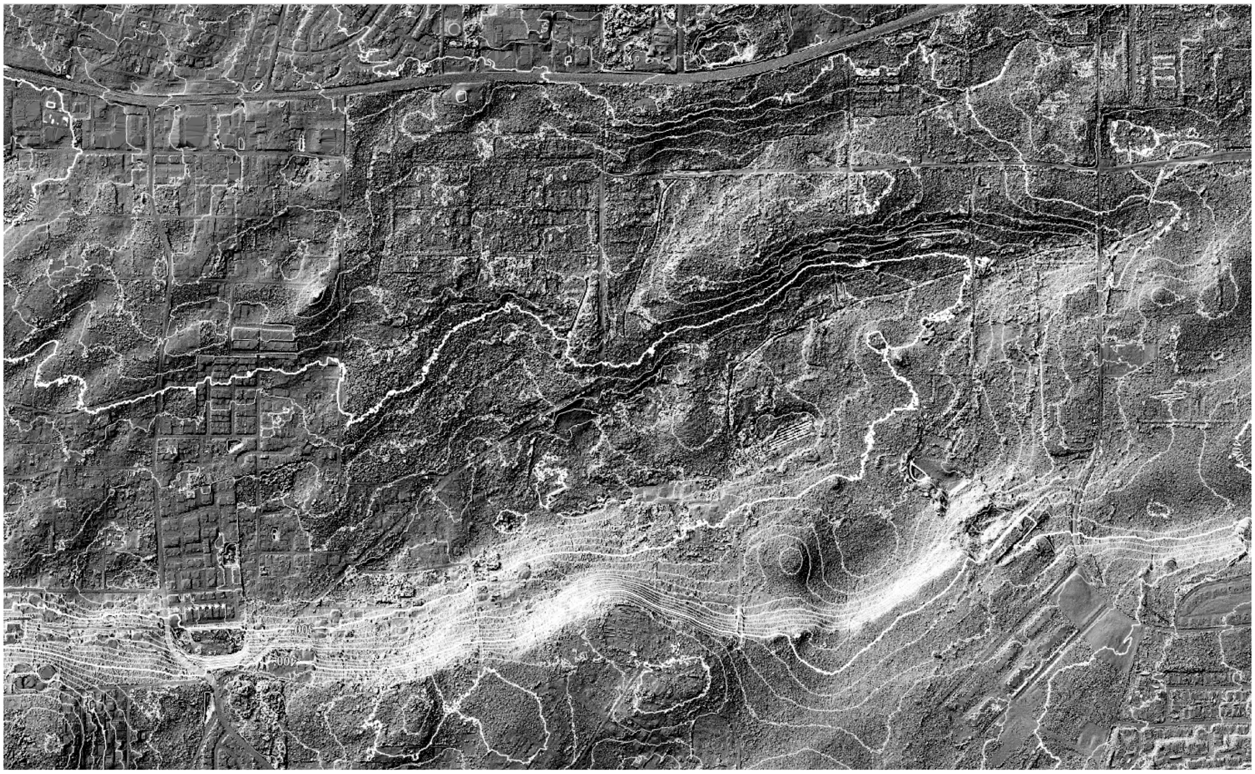

Figure 4.10 Flow direction basemap and contours.

Figure 4.11 First return hillshade with imagery basemap and contours.

4.6 WERI Web MApps: Surface Hydrology of the NGLA

WERI Web MApps are a collection of interactive web-based map applications. These online maps are made available on the Guam Hydrologic Survey website, in the main drop-down menu, under Library, select Interagency Maps:

https://guamhydrologicsurvey.uog.edu/index.php/interagency-maps/

Under Maps by Organization, WERI, select Surface Hydrology to open its map information site:

https://guamhydrologicsurvey.uog.edu/index.php/2021/08/23/surface-hydrology/

Scroll down the page to the Web MApp View section and select either Mobile View for a QR code or Desktop View to open the Surface Hydrology of the NGLA Web MApp, link:

https://werinch2018.maps.arcgis.com/apps/webappviewer/index.html?id=7f506c88a95747aa8774b0c0d311d7da

Or simply select the large sample image at the top of the page.

This hydrologic Web MApp has an "About" panel on the left, containing general information of the map (Figure 4.12). The panel can be made hidden by selecting the left arrow button at the middle right edge tab of the panel. Basic map widgets are on the top left: zoom (+ and -) and default extent (home icon). Bottom center of the Web MApp is a tab (upright arrowhead) when selected opens a panel of feature attribute tables, organized in a feature table tab interface. Notice some basic features have no attribute information. Select the down arrowhead tab to close the attributes panel. There are several hydrologic Web MApps, and all have *map widgets* (app function icons) that toggles an app function, located at the right side of the top bar (see example figure 4.12). Selecting any of the widgets opens/closes a panel. The first widget from the left is the Legend (symbology). The next widget is the Layer List. Notice that other map features (e.g., buildings, landmarks, etc.) are also available, but are turned off upon opening the Web MApp. Select the checkbox of a layer to make it visible or uncheck to turn it off. The third widget from the left is Add Data, which prompts a Search that includes URL access, or file upload of selected formats. These formats include shapefiles (shp) and CSV, KML, GPX, and GEO JSON file types. The fourth widget provides access to the Basemap Gallery which includes a collection of ArcGIS Online basemaps (e.g., Imagery, Streets, etc.). The next widget is Draw, which allows the user to mark up the map with draw mode toggles for markers, lines, shapes, and text. Second to the last is the Measurement widget. This widget can be applied to measure distance, area, and coordinate point position with a choice of degrees minutes and seconds (DMS) or in decimal degrees. The last widget allows printing. A menu is provided to select printing layout and file format.

Three hydrologic Web MApps are available in the Interagency Maps web page. Figures 4.13 through 4.15 show these as the surface hydrology with production wells and well head protection zones, a first-return LiDAR background imagery (excellent for urban stormwater development), and a CHamoru name of basins map in the Kumisión agency section. A fourth Web MApp, in the WERI section is a terrain analysis with the hydrologic features, see section 4.7 below.

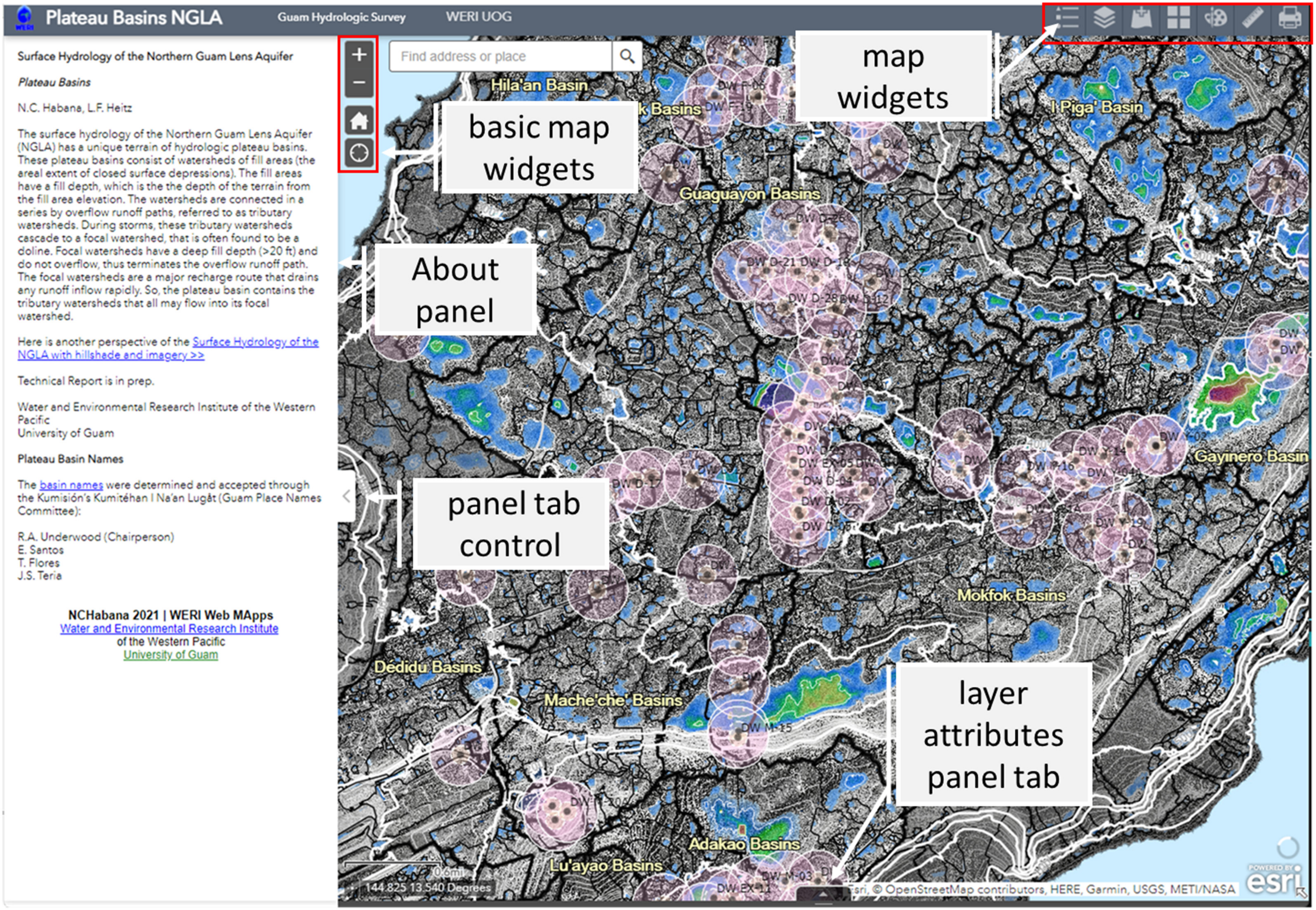

Figure 4.12 WERI Web MApp interface.

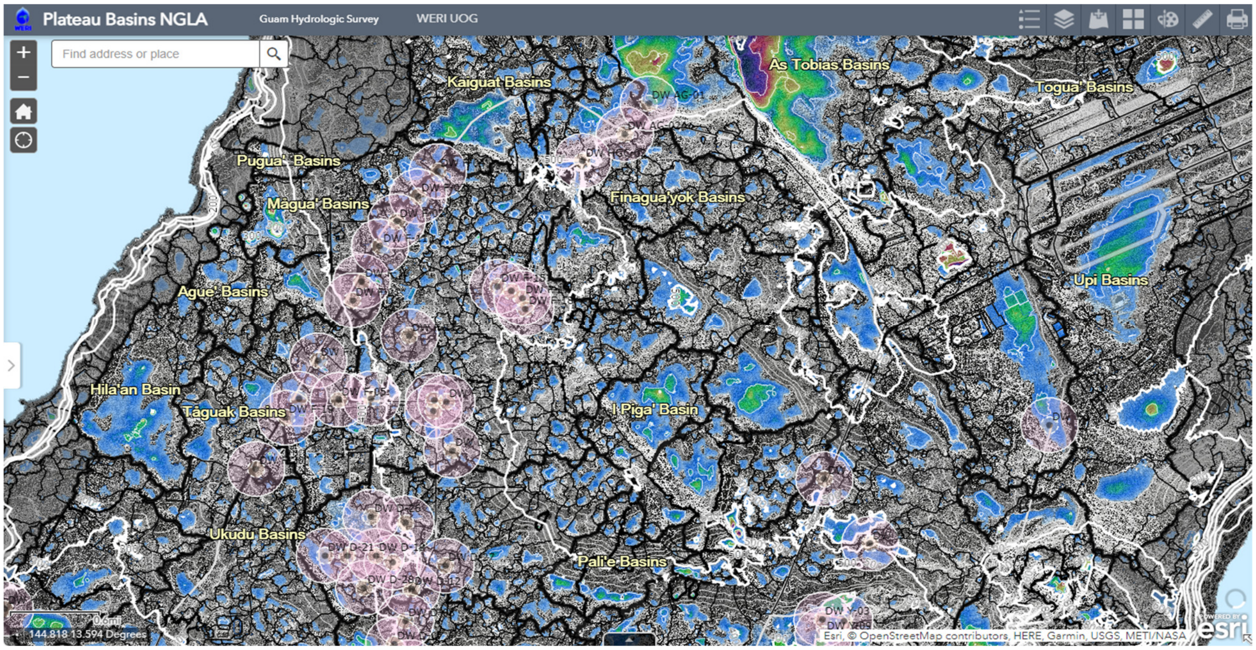

Figure 4.13 WERI Web MApp: Surface Hydrology of the NGLA (flow direction basemap).

Figure 4.14 WERI Web MApp: Surface Hydrology of the NGLA (first return LiDAR based hillshade).

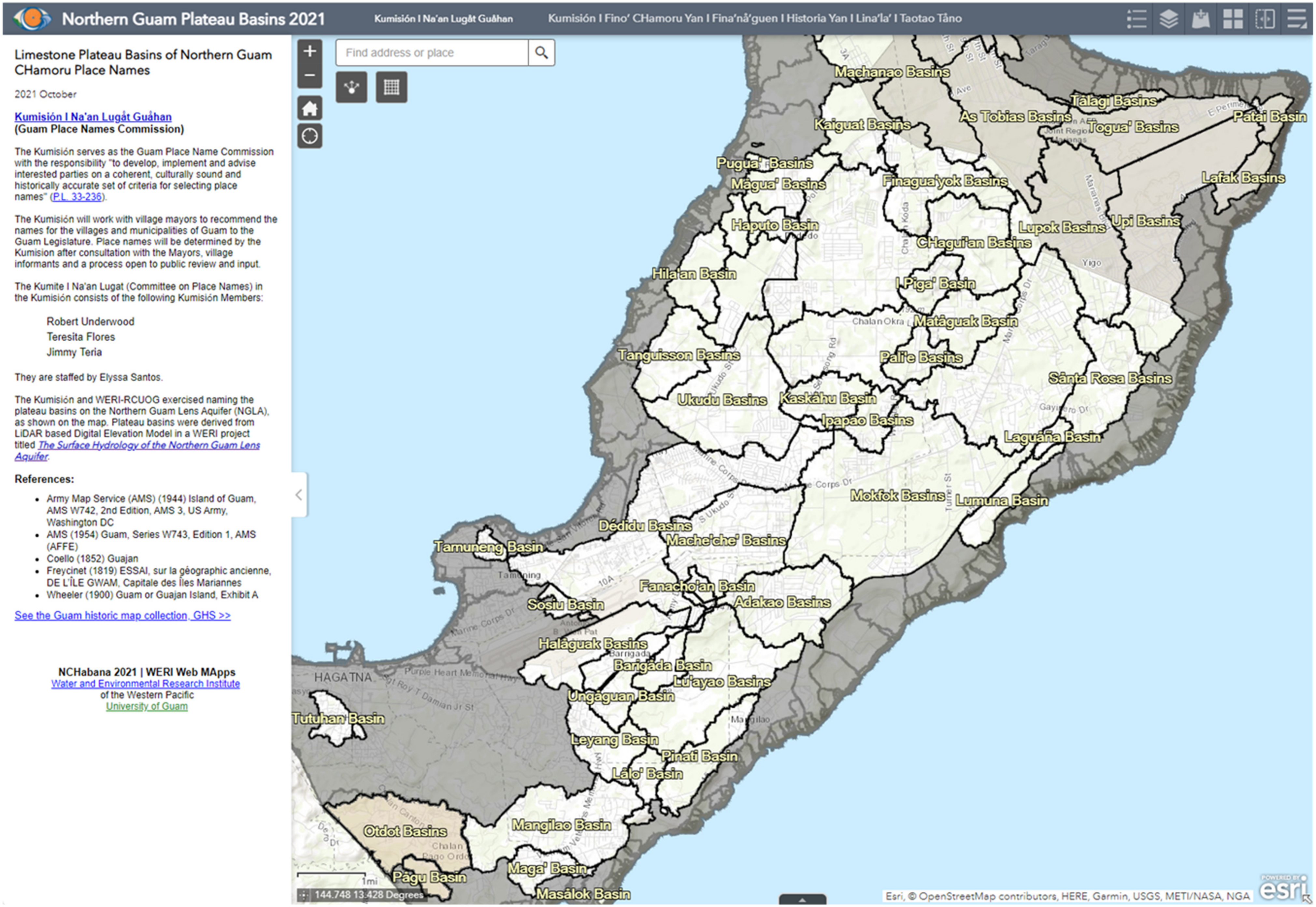

Figure 4.15 WERI Web MApps: Limestone Plateau Basins of Northern Guam, CHamoru place names.

4.7 WERI Web MApps: Terrain Analysis of the NGLA

In the process of developing the surface hydrology, a terrain analysis was also made to study the geomorphology and fundamental geologic features. A preparatory hydrologic spatial analysis flow direction map provided a background that revealed an interesting enhancement of the terrain. LiDAR based contours helped in drawing interesting lineaments which may possibly be geologic fault strikes. It was also found that large natural surface depressions and a string of surface depressions tend to run along these lineaments. The terrain analysis also identified parasitic faults found near large surface depressions, such as the Mokfok Doline. These map features, as shown in Figure 4.16, may be helpful in explaining the occurrence of dolines and sinkholes in the NGLA and provide further understanding of the karst terrain.

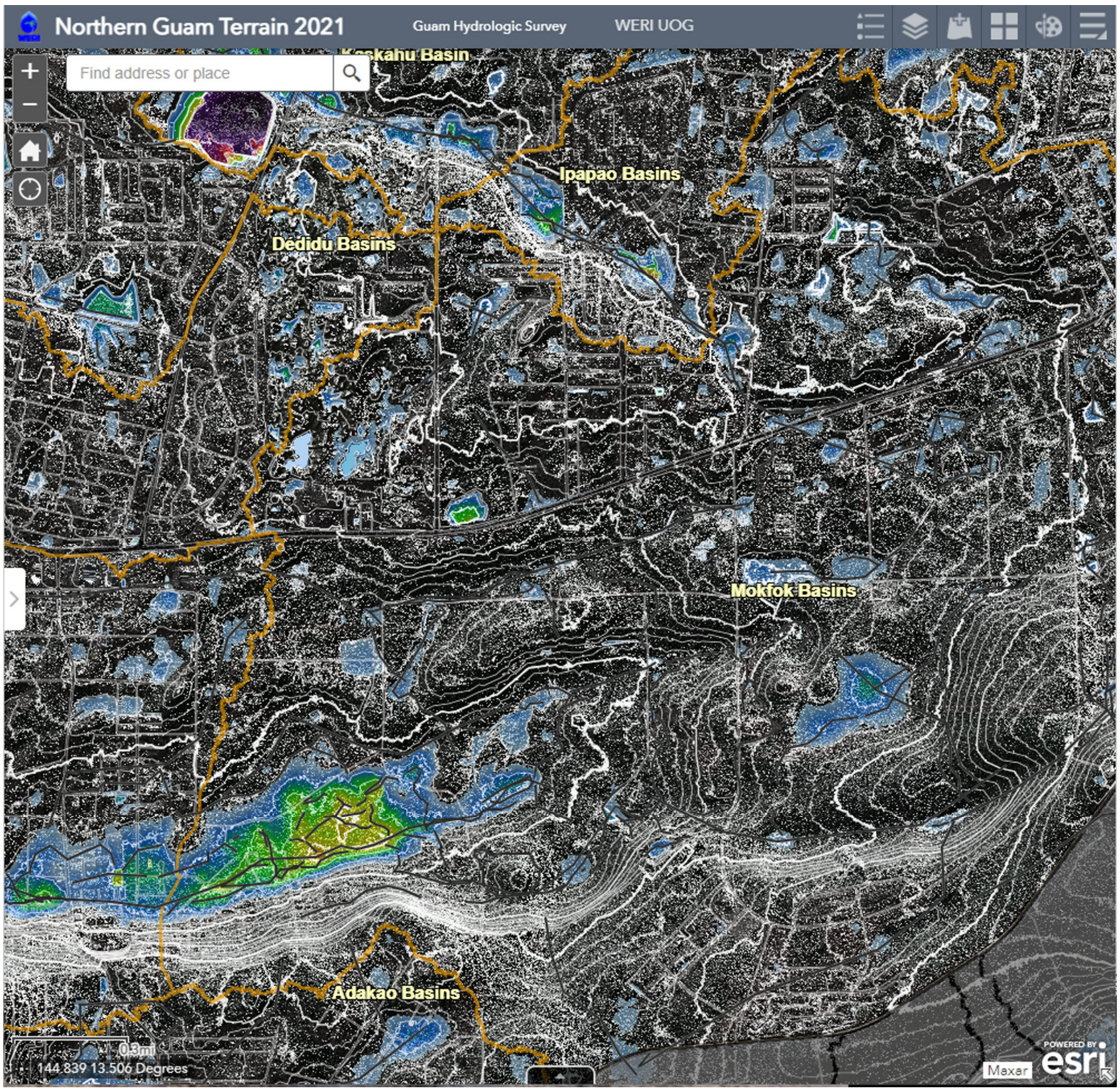

Figure 4.16 WERI Web MApps: Terrain analysis of the NGLA.

Chapter 5

DISCUSSION

This chapter provides discussion of resulting surface hydrologic features of the NGLA. The development of these features and results were described in detail previously in Chapters 3 and 4. The discussions include the usefulness of the mapped features, especially for developers, regulators, and investigators. The technical applications refer to the geologic, hydrologic, and hydrogeologic nature of the NGLA. Additionally, the fundamental and well-defined hydrologic map products will prove to be integral for all and any future NGLA research and development of future groundwater protection strategies.

5.1 Fill Areas (closed surface depressions)

Not all resulting fill areas are sinkholes. All fill areas on the map are considered as *suspect sinkholes* that there may be a chance that water accumulates into the closed surface depression where a sinkhole may have developed. It is a suspect sinkhole on the map unless it has been field verified as a sinkhole. These fill areas are thought of as suspect sinkholes because surface depressions in a karst terrain are usually a result a subterranean cavity collapse. It is suspect, however, because some of the closed surface depressions have been field verified to be sinkholes and some as non-sinkholes. Large fill areas are dolines that occur along a major fault. The major faults often have parasitic faults that add to the extent of the doline and other surrounding surface depressions (Jenson et al. 2019). These dolines may be (often are) larger than the fill area since the analysis only takes the fill elevation to the watershed overflow point. If a mapped fill area is verified as a sinkhole, then contaminants transported by stormwater runoff from tributary watersheds may have a possible direct pathway to the fresh groundwater source.

Regulators should require plan development over a fill area (suspect sinkhole) to be flagged, requiring further analysis and field investigation. A verification is finding geological characteristics of a sinkhole in and around the fill area. As an investigator's map, a more accurate fill areas with fill depth delineation are very informative and useful. Surrounding fill areas may give insight to a larger surface drainage system. Deep fill areas with sharp drops in elevation are very characteristic of sinkholes, and very deep ones may suggest a possible focal watershed (no chance of filling and overflowing). The map provides a "big picture" view that is useful for planning a well strategized field trek and investigation. An investigator should also look at the size of the fill area's watershed and its content, which includes scanning for potential sources of contaminants. For developers and all authorizing parties at stake, these surface hydrologic maps are the best way to begin any development plan over the NGLA.

5.2 Watersheds

Surface watersheds (fill area watersheds), determined using the techniques described in Section 3.5 above, are the areas that can capture and infiltrate rain/stormwaters. Intense rainfall in a watershed can cause overland flow and runoff to the watershed's fill area. Any contaminant producing activities in these areas could result in possible contaminant flow into that fill area. If that fill area happens to contain a sinkhole, then contaminants released in the watershed have a possible direct pathway to the NGLA.

As defined in chapter 2, there are three watershed classes: a unit watershed, tributary watershed, and a focal watershed. The watersheds that overflow a fill area and connects to a series of downstream watersheds are called the tributary watersheds. A tributary watershed is a natural structure for cascading runoff to occur and deliver a large collection area of watersheds to overflow into a focal watershed. Focal watersheds are considered as a major source of stormwater drainage into the aquifer.

For developers and regulators, watersheds delineate the extent of the rain catchment area. A large catchment area means more water accumulation. It spans a larger area of coverage if the watershed is a part of a tributary watershed. Even though a plan to build and have contaminant generating activities are not in a suspect sinkhole, the plan should include assessment of contaminant generating activities. These activities can produce contaminants that can be carried away by stormwater, along runoff paths in the watershed.

5.3 Watershed Runoff Paths

Watershed runoff paths, determined using the techniques described in Section 3.4, are flow paths that transport rainwater runoff directly into the previously described fill areas. Any contaminants released by activities in areas upstream of a runoff flow path could travel downstream through these runoff paths. Again, this could result in possible contaminant flow downstream through the flow paths. Also, if the flow path eventually leads to a verified as a sinkhole, then contaminants flowing in the runoff path are provided a possible direct pathway to the NGLA.

5.4 Overflow Runoff Paths

Overflow runoff paths, determined using the techniques described in Section 3.4, are determined using an accumulation analysis of a filled DEM. This accumulation is only accurate if the surface depressions completely fill with runoff water. Large sinkholes may or may not fill depending on rainfall intensities, total storm rainfall accumulations, and antecedent ground moisture conditions. Most questionable are closed surface depressions (fill areas) of depths over 10 feet. Not all fill areas may be verified by observation during intense storms. It also may not be possible to observe the actual performance of these surface depressions during intense storms. The estimation of storm related infiltration rates that could depend on location, size, and depth require thorough field investigations. Observable clues may be noticeable during field investigations. These clues could include items such as watermarks, sediment, nostoc alga, and abraded rocks. Actual field practice should also include investigating the natural overflow points for evidence of overflow, erosion, and abrasion. Interviews with residents and flood first responders can also be helpful. Upon field verification of an unfillable watershed, the overflow runoff path is reported as a disconnect, and the watershed is terminal and becomes a focal watershed. The following downstream watershed is then considered the head watershed as it continues the overflow runoff path.

5.5 Plateau Basins

Plateau basins, determined using the techniques described in Section 3.5, are delineated using a basin analysis of the filled DEM. Plateau basin contains some if not all of the features previously described including: fill area, watershed, tributary watershed, focal watershed, watershed runoff paths, and overflow runoff paths. At minimum, a plateau basin contains only a focal watershed and watershed runoff paths. Plateau basins also delineate an area's top ridges, where the collection of runoff paths stay within the basin that also all connect to the basin's focal watershed fill area. The two types of basins that were mapped included coastal basins and plateau basins. Coastal basins have runoff that reach coastal marine waters and plateau basins contain runoff waters that move into its infiltration sites and routes. Sixty plateau basins were mapped with respect to the delimitations set for the surface hydrology analyses, and each of the plateau basins were named by the Kumite of CHamoru name place.

5.6 Coastal Basins

Presently areas located within 4000 ft. of the shoreline are not considered to be in the Groundwater Protection Zone by GEPA. This 4000 ft. definition could be fine-tuned by using the topographic basin edges closest to the shoreline as the boundary of a new Groundwater Protection Zone. Those areas outside the designated plateau basins might also be of interest to those who are evaluating coastal zone impacts on the near shore environment.

5.7 Practicality of the Surface Hydrology Map of the NGLA

This map depicts the results of an initial all-encompassing surface hydrologic analysis of the area overlying the NGLA. The map also provides a framework for future more complete and detailed investigations.

Large development contracts provide a project/contract boundary. This SEIS or "green box" describes the area of direct impact by the project under consideration. The surface hydrology maps developed by this study will help contractors and agency officials to evaluate the affects that can occur beyond the SEIS because of water movement from the project area into adjoining downstream surface watersheds and possibly directly into the NGLA.

The surface hydrologic maps and Web MApps of the NGLA developed for this project provide a common and easy to use source of overlayed and detailed hydrologic information. Contractors and agency officials can use this common set of maps to develop successful strategies for management of new development over the NGLA. This same information can also help agency officials develop long term strategies for managing and mitigating development impacts over the aquifer.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This project examined and produced surface hydrologic features for areas over the NGLA. The hydrologic WERI Web MApp products modernizes the way we evaluate and proceed with groundwater protection as the island continues to develop atop our most valuable freshwater source.

6.1 Accomplished Objectives

The goals, purpose, and specific objectives in section 1.3 were accomplished. Fundamental hydrologic areas of fill, watershed, and basins of the NGLA plateau were delineated with respect to select conditions and delimitations, using the best available DEM. Runoff paths were produced, and overflow runoff paths and focal watersheds were identified.

The generated hydrologic features, rasters, and background layers were overlayed in order to produce a clear and useful multilayered set of hydrologic maps. Four hydrologic maps were uploaded into ArcGIS Online, made into web maps, and then to web map apps. The four online hydrologic maps are one of the first sets of WERI Web MApp products that are made available on the Guam Hydrologic Survey website (sections 4.6 and 6.1). These Web MApp products are intended for use for anyone interested in the surface hydrology of the NGLA. These hydrologic Web MApps, including the terrain analysis, was first unveiled at the WERI Guam Advisory Council Meeting, November 2021. Training for interagency partners and anyone interested in learning to use the WERI Web MApp products was announced in the meeting, and a workshop is scheduled for 2022.

6.2 Summary Conclusion

An innovative hydrologic spatial analysis procedure was developed to identify various features of the NGLA plateau that determine how water travels across the land surface and eventually makes its way to the groundwater. The features developed included fill areas and depths, fill area watersheds, runoff paths, and plateau basins (Chapter 4). Tributary watersheds are identifiable and connected by overflow runoff paths that lead to a focal watershed. Some of the fill areas had already been identified as dolines and fill areas with swallow holes. Evidence of collapse was also found. These surface depressions and sinkholes may very well serve as contaminant pathways to the freshwater source.

The hydrologic maps developed in this study updates the methods of assessment and re-evaluates and fine tunes previously used procedures for protecting the aquifer. Map features and rasters are orderly overlaid to produce a hydrologic map of storm accumulation/collection paths and areas. This map is organized as a truly valuable tool for assessing and determining the best water source protection strategies. This in turn will help GEPA and GWA promote cooperative project development of areas of interest overlying the NGLA.

And now island developers have a very useful hydrologic map to make better construction plans with water source protection in mind. In the past, impact assessments were primarily evaluated within the boundaries of a project area. The maps provided in this study show how development activities in one area can impact areas downstream and completely outside the project area's boundaries. It is imperative that these possible off-site impacts be considered when evaluating the possible environmental impacts of a proposed project and to develop mitigation plans to minimize any possible impacts. The hydrologic Web MApps developed by this project will be key to providing evaluation of both on-site and off-site environmental impact considerations.

Another key aspect of the project is that the user of these hydrologic Web MApp does not have to be an expert in using GIS. The online product has a common app and GIS layers framework. The workshops and training that are proposed will ensure that the data are useful and available to both regulating agencies and those proposing development over the aquifer. Once users are familiar with using the application, they will be able to easily evaluate the hydrologic environmental effects of any proposed development. The bottom line is that the NGLA will be better protected both now and in the future for all the people of Guam.

6.3 Recommendations

The hydrologic WERI Web MApps should be considered as part of a living document. As new projects are proposed, new field investigation will uncover information that can be easily included in the existing WERI Web MApp products. The maps included in this investigation should not be considered as end point determinations, but the starting point for a living and updated data document.

6.3.1 Annual Workshop, Recommended Use

In order to take advantage of the data and online hydrologic maps, it is necessary that a series of workshops be held. These workshops will include a short introduction to the GIS techniques used and detailed instruction on how to access and use the maps available in the web application. The workshops will be designed for developer engineering staff, Federal agency officials overseeing planning and construction of new facilities, and for agency officials at Guam EPA, GWA, and Guam Land Management who are involved in regulating development over the aquifer. It is proposed that the first workshop be held in 2022 with follow-ups on an annual basis. Mini workshops on special topics concerning the WERI Web MApp hydrologic products could be provided on an as requested basis.

6.3.2 Dissemination of Report and Maps

This report is available on both the WERI, University of Guam (https://weri.uog.edu) and Guam Hydrologic Survey (https://guamhydrologicsurvey.uog.edu/) web sites. WERI Hydrologic Web MApp products can be found at the Guam Hydrologic Survey web site, under the Library Menu, Interagency Maps (see section 4.6 and 6.1).

6.3.3 Findings for Further Study

The maps produced in this investigation is not the end point determinations, rather a starting point for a living and updated data document. A second phase will pursue further refinements, specifically to delineate tributary watersheds and define the runoff paths within fill areas. Also, verifying focal watersheds is a recommendation. Furthermore, there is a continued need to identify which fill areas are truly sinkholes and provide quick flow paths to the aquifer.

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Appendix

2012 Guam LiDAR Metafile

The LiDAR data was captured using a twin-engine fixed wing aircraft equipped with an Optech ALTM Gemini LiDAR system. This system consists of Airborne Global Position System (ABGPS), inertial measurement unit (IMU), and laser sensor. The ABGPS collects XYZ coordinates of the laser sensor and the IMU calibrates the orientation of the aircraft. During flight, laser pulses are reflected from features on the surface and the system collects this data. The acquired LiDAR data receives a preliminary review to assure that complete coverage is obtained and to ensure the absence of data gaps.

Acquisition parameters:

- Scanner - Optech Gemini SN# 03SEN145 and 07SEN201
- Flight Height: 450 to 600 meters above mean terrain
- Scan Rate: 45 Hz
- Field of View: 22 degrees
- Pulse Rate: 70 kHz

Inertial Measurement Unit (IMU) processing parameters:

- Processing Programs and versions: Applanix - POSGPS and POSProc, versions 4.4, MMS version 5.2
- Max separation between base stations during LiDAR collection: 0.12 m
- IMU processing monitored for consistency and smoothness: Yes
- GPS and IMU processing software: Optech's Dashmap version 5.20 and Applanix version 4.4

This study used topographic Digital Elevation Model (DEM) data gathered using Light Detection and Ranging (LIDAR) techniques in 2012 as the basis for determining the geometry of all drainage features over the Northern Guam Lens Aquifer (NGLA). This data was gathered by AeroMetric, Inc. Complete documentation for the data is contained in the meta data files that accompany the DEM GIS files. Following are pertinent excerpts from the meta files:

> This task order was for production of surface model products of The Territory of Guam. The models are produced from data acquired using airborne Light Detection and Ranging (LiDAR) sensors. The data is calibrated, classified, and processed to produce surface models and products including Classified LAS, bare-earth Digital Elevation Models (DEM), intensity raster images, shapefiles of road centerlines, forest canopy, building footprints and breaklines of surface hydrology.
>
> The United States Geological Survey requested surface data products and models that indicate surface conditions, drainage, vegetation, transportation routes and building structures to aid in analysis of land use, transportation, hydrologic, forest vegetation and recreational management. Data and products are referenced to the Universal Transverse Mercator (UTM) Coordinate System - Zone 55,

based on the World Geodetic System of 1984 (WGS84) in meters. The vertical reference is Guam Vertical Datum of 2004 (GUVD04) in meters.

The vertical accuracy assessment of the data has a project requirement to achieve a RMSE of 12.5 cm (0.41), a Fundamental Vertical Accuracy (FVA) of 24.5 cm (0.80 ft) 95% confidence level, a Consolidated Vertical Accuracy (CVA) of 36.3 cm (1.19 ft) 95th Percentile and a target value for Supplemental Vertical Accuracies (SVA) of 36.3 cm (1.19 ft) 95th Percentile.

The Fundamental Vertical Accuracy (FVA) listed above is determined with checkpoints located only in open terrain where there is a high probability of having LiDAR return from the bare-earth ground surface and where errors are expected to follow a normal error distribution. While FVA values of 24.5 cm (0.8 ft) are not too impressive compared to actual field survey determinations, they are by far the most accurate elevation data available for use in hydrologic spatial analysis. Note that that the hydrologic spatial analysis is dependent more on the relative elevation of the DEM cells rather than the actual values that could be determined using ground survey or GPS methods. The relative elevations accuracy of the bare-earth DEM and can be assumed to be better than the FVA values. We therefore assumed that the bare-earth DEM values are adequate for this study. When and if future new more accurate DEMs are available the spatial analysis processes described in this report can be easily be reapplied to that new data.

<u>LiDAR DEM</u>: A second text file accompanied the LIDAR data. Following is an excerpt from that file:

- Lidar 2012 data by USGS.
- DEM was created by Ross Winans from NOAA OCM upon request by Maria Kottermair March 2016.
- DEM was then clipped with polygons derived from the lidar data itself (provided by Ross Winans) to get rid of the interpolation artifacts along the coastline.
- NOTE: there are some small gaps in the interpolated dataset that was provided by NOAA and may have to do with gaps in the original data.
- Credit for lidar data: USGS