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Reconnaissance Study of the Hydrology of American Memorial Park, Island of Saipan, Commonwealth of the Northern Mariana Islands

Scientific Investigations Report 2007–5042

U.S. Department of the Interior
U.S. Geological Survey

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to mean sea level.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Reconnaissance Study of the Hydrology of American Memorial Park, Island of Saipan, Commonwealth of the Northern Mariana Islands

By Jeff A. Perreault

Abstract

American Memorial Park, a unit of the National Park Service on the Island of Saipan, includes among its features a 27-acre estuarine system that has become a rarity within the Commonwealth of the Northern Mariana Islands. The estuarine system's mosaic of marshy areas interspersed with emergent wetlands and mixed wet forests provides critical habitat for various migratory and resident waterfowl, including two Federally listed endangered species: the Marianas gallinule (*Gallinula chloropus guami*) and the nightingale reed warbler (*Acrocephalus luscinia*). With sensitivity to the park's ecologic assets and the uncertainty associated with locally rapid urbanization, a need to better understand the hydrology of American Memorial Park was recognized. To address that need, a reconnaissance study of the park was undertaken during August and September 2005. The goals of the study were (1) to describe the occurrence and salinity of surface and ground water within the park; (2) to develop a hydrologic model of the park area of the island, with emphasis on the 27-acre estuarine system; and (3) to identify additional data needed to further develop this model.

With regard to surface water, three freshwater inputs to the park's natural wetland are possible: direct rainfall, seaward-flowing ground water, and overland flow. Direct rainfall, which is an important source of freshwater to the wetland, commonly exceeds evapotranspiration both seasonally and per storm. The seaward flow of ground water is likely to be a source of freshwater to the wetland because ground water generally has an upward vertical component in the nearshore environment. Overland flow upgradient of the park could potentially contribute a significant input of freshwater during periods of intense rainfall, but roads that flank the park's perimeter act as a barrier to surficial inflows.

During the reconnaissance, four discrete bodies, or zones, of surface water were observed within the park's natural wetland. Conductivity within these surface-water zones typically ranged from 1,540 to 4,370 microsiemens per centimeter (µS/cm) at 25°C, although values as low as 829 and as high as 8,750 µS/cm were measured. As a result of these observations, the American Memorial Park wetland area meets the definition criteria of an estuarine system that is dominantly oligohaline. Conductivity was also measured in a constructed wetland that was built within the park to augment the storm-drainage infrastructure of the village of Garapan. Reverse-osmosis facilities, in operation at hotels adjacent to the park, have historically discharged highly saline wastewater into the storm-drainage system. This collective storm and wastewater flow is routed into the constructed wetland and from there into the ocean. The conductivity of water in the constructed wetland ranged from 45,000 to 62,500 µS/cm, exceeding nominal seawater values by as much as 25 percent, with the highest conductivities recorded near discharging storm drains.

With regard to ground water, the reconnaissance included installation of a ground-water-monitoring network. Data collected from this network identified the presence of freshwater underlying the park and indicated that surface water is directly connected to ground water in the natural wetland because the water levels of both surface water and ground water directly varied with the tide. Conductivities of ground-water samples from wells in the monitoring network indicated that ground-water salinity was geographically related: conductivities were lower (801–2,490 µS/cm) in surficially dry areas, intermediate (6,090–9,180 µS/cm) in natural-wetland areas, and higher (18,250–27,700 µS/cm) in areas adjacent to the constructed wetland and its associated ocean-discharge channel.

Synoptic water-level surveys were made to enhance understanding of the spatial expression of the water table; they were scheduled to overlap with peak and trough tidal signals to enable limited characterization of local hydrologic properties. The water-level surveys indicated that ground-water levels were directly influenced by ocean tides because tidal fluctuations were reflected in ground-water levels. The surveys also indicated that at any given time ground-water levels were higher than ocean-water levels and that this water-level offset was greater at low than at high tide and greater in the western

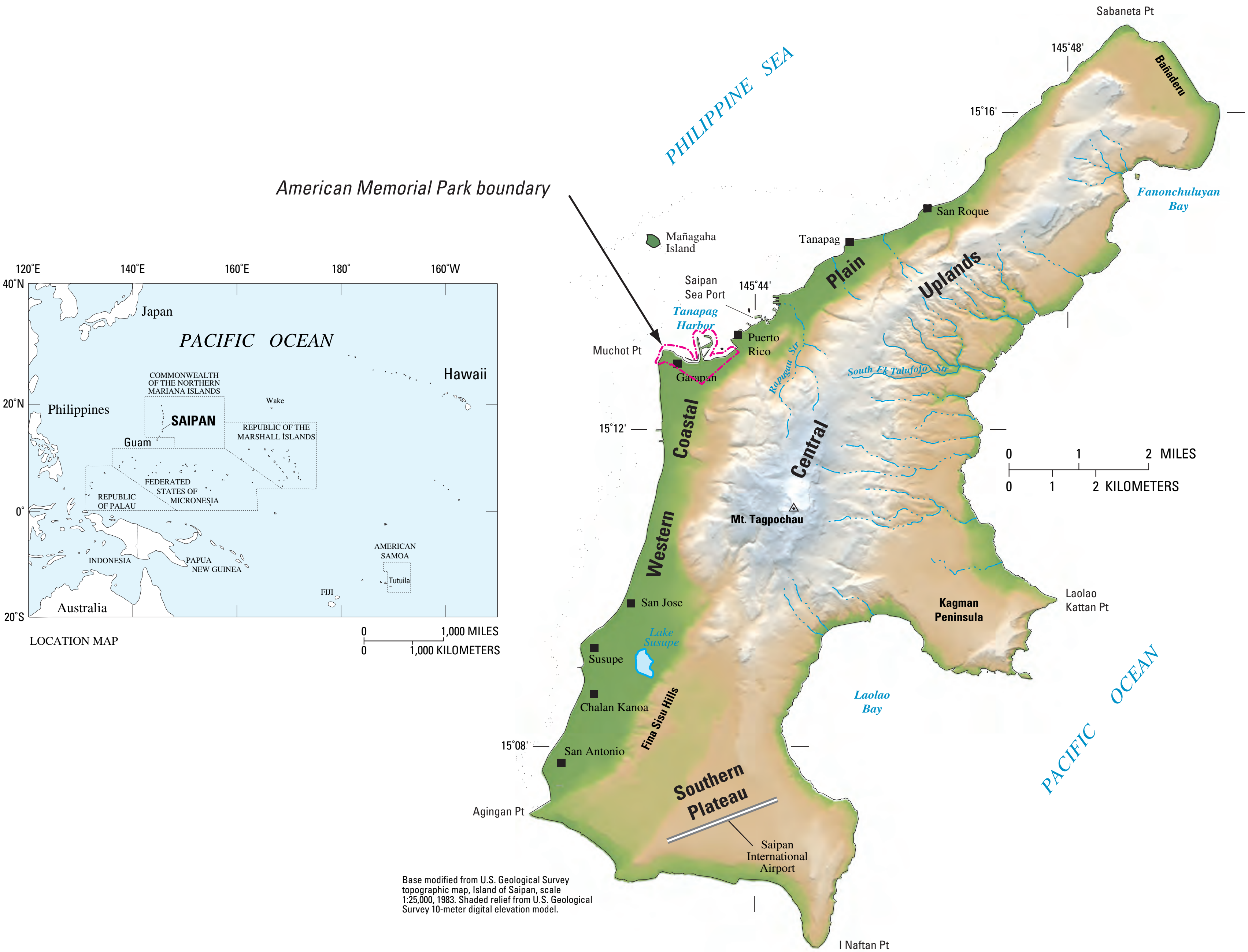

Figure 1. Location map of American Memorial Park on the Island of Saipan, Commonwealth of the Northern Mariana Islands.

than in the eastern part of the park. Tidal lags were calculated for the entire park, and tidal efficiencies were calculated for the natural-wetland area. These data suggest that hydraulic conductivity in subsurface strata may be higher in the eastern than in the western part of the park; mean lag time in the eastern part of the park was 21 minutes, in contrast with 115 minutes in the western part. Tidal efficiencies in the eastern part of the park ranged from 0.38 to 0.85, with a mean of 0.64.

With regard to continuing information gaps, additional monitoring wells would need to be installed to constrain ground-water flow through the park, including the vertical flow component, and to improve understanding of the effects of nearby faults and injection wells on local hydrology. Understanding of the effects of the perimeter-flanking roads on freshwater flow, both surface and subsurface, could be enhanced by expanding the ground-water-monitoring network and by monitoring surface flows that are being artificially diverted around the park to the ocean. A long-term plan that includes monitoring of surface and subsurface water levels and salinities could be useful to identify trends that could affect the park's critical habitat, including its endemic and endangered species. Development of a numerical model, addressing coupled surface-water/ground-water flow and solute transport, could assist in assessing hydrologic changes and serve as a communication tool to inform interested parties of such changes to the park's hydrologic characteristics, including those changes that may affect critical habitats.

Introduction

American Memorial Park is centrally located along the western coastal plain of the Island of Saipan in the Commonwealth of the Northern Mariana Islands (CNMI) (fig. 1). Land on which the park now resides was set aside as part of a 1977 Covenant between the United States and the fledgling CNMI Government that established the commonwealth as an independent nation. The 133-acre park contains a combination of constructed and natural features (fig. 2). In addition to such recreational facilities as athletic fields, jogging paths, tennis courts, a public marina, and a 1,200-seat amphitheater, the park features numerous World War II structures and memorials and contains the landing site of the first major Carolinian immigration to Saipan.

The western part of the park, in which many of the aforementioned manmade features are located, is approximately bisected by a constructed wetland that was built to augment the storm-drainage infrastructure of the village of Garapan. Reverse-osmosis facilities, in operation at hotels adjacent to the park, have historically discharged highly saline wastewater into the storm-drainage system. This collective storm and wastewater flow is routed into this recently (ca. 1990s) constructed wetland within the park and from there into the ocean. A phaseout of surface disposal of reverse-osmosis wastewater in favor of subsurface disposal by way of injection wells has been planned. Data collected during the reconnaissance indicated that such a phaseout had not yet been completed, but were inconclusive with regard to evidence of subsurface injection.

Whereas much of the western part of the park is dominated by manmade features, the eastern part is predominantly within a Protected Natural Area Zone that contains a 28-acre expanse of mangrove shoreline and a 27-acre estuarine system (Wagner, 1990). By definition, an estuarine system has an ocean-derived salinity greater than 5 parts per thousand (ppt) and is at least intermittently tidally flooded (Cowardin and others, 1979). The park's natural wetland meets this definition because it is dominantly oligohaline (conductivity, 800–8,000 µS/cm), its salinity is ocean derived, and it is intermittently tidally flooded; however, this flooding is extremely infrequent and may occur only during large tropical cyclones and associated storm surges, or by a tsunami.

Viable estuarine systems have become rare within the CNMI, and as a result, the park's natural wetland has been designated a Mitigation Policy Resource Category 2 site by the U.S. Fish and Wildlife Service (Wagner, 1990). The natural wetland and its mosaic of marshy areas are interspersed with emergent wetlands and mixed wet forests of mangrove, casuarina, and pandanus that provide critical habitat for various migratory and resident waterfowl, including two Federally listed endangered species: the Marianas gallinule (*Gallinula chloropus guami*) and the nightingale reed warbler (*Acrocephalus luscinia*). Human activity and development are reducing or eliminating similar wetlands throughout the CNMI, leaving American Memorial Park as the only known Federally protected area possessing viable populations of these species (U.S. Fish and Wildlife Service, 1991, 1998).

The park wetland is being threatened by Saipan's rapid population expansion and associated urban development (Wagner, 1990). Official population figures indicate a growth of 329 percent between the years 1980 and 2000 (from 14,549 to 62,392; U.S. Census Bureau, 2003); other sources cite continuing growth, placing the 2006 population at more than 82,000 (U.S. Central Intelligence Agency World Factbook, URL https://www.cia.gov/cia/publications/factbook/geos/cq.html, accessed Sept. 15, 2006). The park is undergoing a commensurate increase in visitation as a direct result of this population expansion (Charles Sayon, National Park Service, oral commun., 2005).

The motivation for this study came from recognition of the ecologic value of the American Memorial Park wetland, the loss of similar wetlands within the CNMI, and the increasing threat posed by rapid development of areas adjacent to the park, specifically urbanization of the village of Garapan and commercialization of the Puerto Rico harbor facilities. To address this concern and to identify the need for additional data, the U.S. Geological Survey (USGS), in cooperation with the National Park Service (NPS), conducted a reconnaissance study of the hydrology of American Memorial Park, the results of which are described in this report.

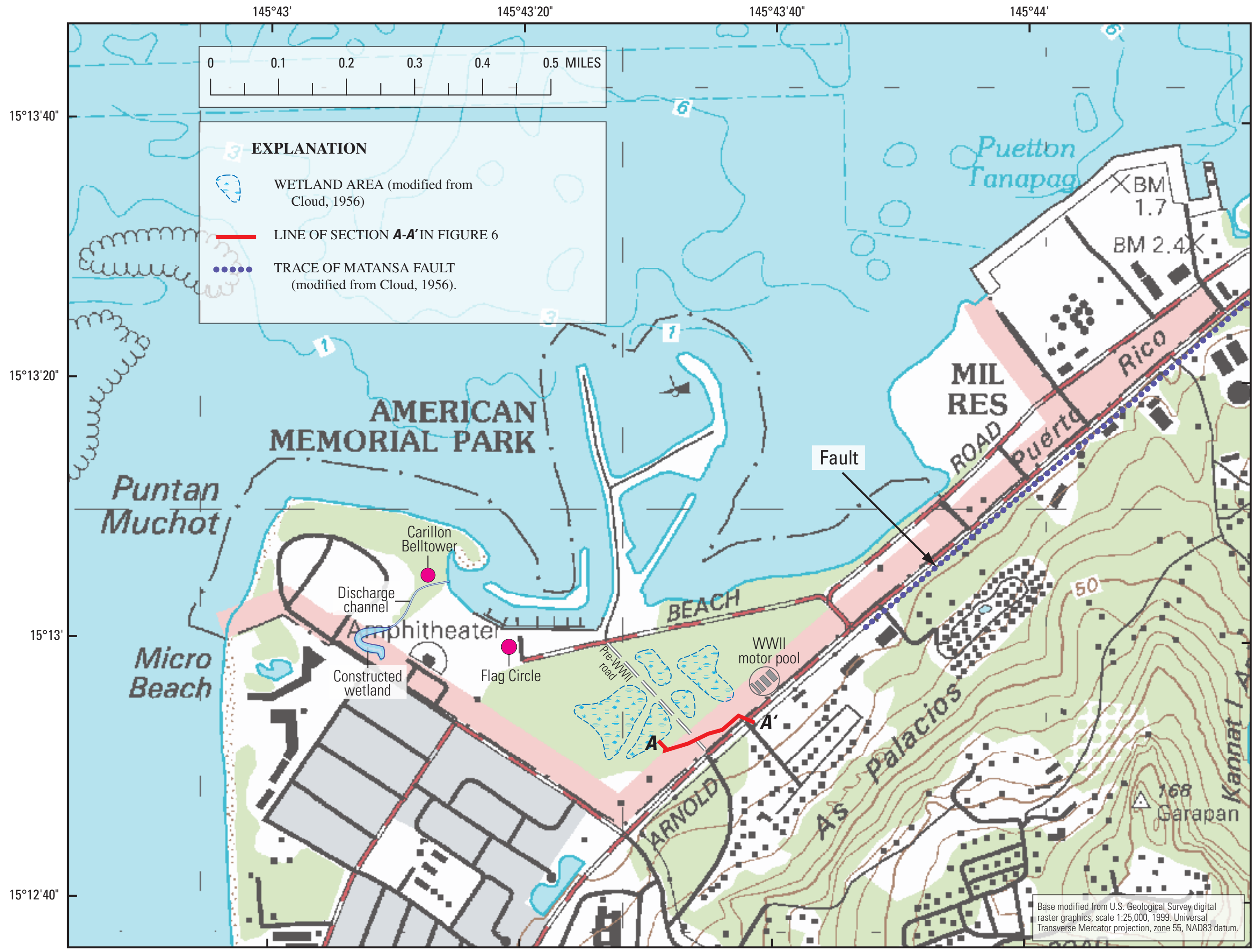

Figure 2. American Memorial Park on the Island of Saipan, Commonwealth of the Northern Mariana Islands, showing locations of selected features and facilities. The eastern part of the park is in a dominantly natural condition, and includes a 27-acre estuarine wetland, the last known example of this ecosystem in the Northern Mariana Islands. The western part of the park is largely developed, and includes the park's administrative infrastructure, numerous athletic fields and recreational beach facilities, and a small-boat harbor. A constructed wetland was built within the park in the 1990s to moderate the effects of storm runoff from the adjacent village of Garapan. Additional features shown include the trace of the Matansa Fault flanking the park's southeast perimeter, and the location of a geologic transect developed in 1998 (see fig. 6).

Purpose and Scope

The purpose of this report is to (1) describe the occurrence of ground water and the salinity of ground and surface water within American Memorial Park; (2) present a hydrologic model of the park area of Saipan, with an emphasis on the 27-acre estuarine system; and (3) identify additional data needed to further develop this model. To determine the occurrence of ground water, a 13-well ground-water-monitoring network was configured, incorporating two preexisting monitoring wells coupled with 11 new piezometers. The piezometers were installed during the reconnaissance and were used not only for monitoring water levels but also for collecting water samples to measure ground-water salinity. Manual synoptic water-level surveys were performed, and continuous-record pressure transducers (hereafter referred to simply as transducers) were installed in selected wells, and at the nearby harbor for use as a tide gage. The salinity of both ground water and surface water, as indicated by conductivity measurements made at most of the ground-water sites and selected surface-water sites, was used to assess the mixing of fresh ground water with ocean-derived saltwater. The hydrologic model presented in this report, developed through compilation and analysis of previous investigations and publications, in combination with measurements and observations made during the 2005 reconnaissance, is intended to be a foundation upon which future efforts will be built. This report concludes with a list of additional data and analyses that would be needed to augment the model's development. This report in not intended to suggest and (or) prioritize specific future actions but rather to provide a list of topics and efforts that would, if undertaken, enhance understanding of the hydrology of American Memorial Park.

Description of Study Area

The Island of Saipan, with an area of 48 mi^2, is the largest of the 14 islands composing the CNMI. Situated in the western Pacific Ocean between longitude 145°40′–145°50′ E. and latitude 15°05′–15°18′ N., Saipan is about 3,700 mi west-southwest of Honolulu, Hawaii, and about 120 mi north-northeast of Guam (Carruth, 2003). American Memorial Park lies on the western coastal plain and is centrally situated along the long, north-south axis of the island. The village of Garapan borders the park along its south boundary, and the major port facilities of Puerto Rico are less than 1 mi northeast of the park (fig. 1).

Climate

The climate of Saipan is typical for the western Pacific region, and this report will capitalize on this similarity to use climate data from nearby islands, most notably Guam, when local data are absent. Mean annual rainfall ranges from about 75 in. on the southern plateau to more than 90 in. on the central interior highlands (fig. 3). Rainfall along the western coastal plain is toward the low end of this range, with rainfall in the area of the park averaging 78 in/yr. Rainfall varies seasonally, with the wet-season months of July through December receiving more than 72 percent of the mean annual total (fig. 4; Lander, 2004).

Evapotranspiration is the volume of water directly evaporated from soil and water surfaces and transpired from vegetation through a plant's stomata (Brutsaert, 1982). Potential evapotranspiration, the maximum rate possible given sufficient moisture in the soil and on the surface, can be assumed equal to evaporation on the basis of pan experiments on Hawaii (Ekern, 1966). Actual evapotranspiration is the rate at which true vaporization is occurring, given inplace available water in the soil (for evaporation as well as plant uptake) and on the surface. The distinction between potential and actual evapotranspiration is important, owing to the punctuated frequency (seasonality) and intensity (per storm) of rainfall on Saipan; actual evapotranspiration will, by definition, always be less than or equal to potential evapotranspiration.

Evapotranspiration rates have not been directly studied within the CNMI; however, previous research has indicated that pan-evaporation rates in Guam, about 120 mi south-southwest of Saipan, are about 77 in/yr (Gingerich, 2002). Additional studies have suggested that evapotranspiration rates change minimally in this tropical region, by about 0.4 in/yr per degree of latitude, decreasing with distance from the Equator (Nullet, 1987). Therefore, an evapotranspiration rate for Saipan of about 76 in/yr, or about 0.21 in/d, is a reasonable approximation. The daily rate is critical with regard to the park wetland because it represents an amount that commonly is exceeded by direct rainfall, both seasonally and per storm; rainfall in excess of the evapotranspiration rate represents a net freshwater input to the wetland. For example, in the 2 months during which the reconnaissance took place (Aug.–Sept. 2005) hourly rainfall, as measured at Saipan International Airport, equaled or exceeded 0.21 in/d on 18 of 61 days, on which days the average rainfall was 1.29 in/d. Though not intended to represent a rigorous analysis of long-term rainfall patterns on Saipan, these data do indicate that direct rainfall on the island commonly exceeds the approximate rate of 0.21 in/d; therefore, direct rainfall likely represents a frequent net freshwater input to the wetland.

The Northern Mariana Islands lie within the formative region for the northwestern Pacific tropical-cyclone basin and so may be threatened on a year-round basis by such storms. (The northwestern Pacific tropical-cyclone basin is unique among global formation basins in this regard.) This is significant in that the primary cause of above-average rainfall in the region is tropical cyclones. For example, when Tropical Cyclones Carmen, Winnie, and Tess passed over the island in August 1978, Saipan recorded its highest monthly rainfall total of 73.25 in., almost 95 percent of the mean annual rainfall for this area (Lander, 2004). Typhoon Carmen was also responsible for Saipan's largest single-storm rainfall total when 44.5 in. fell during a 48-hour period on August 10–12, 1978 (van der Brug, 1985). During the reconnaissance, Saipan was affected by Supertyphoon Nabi; though not on the order of the 1978 series of tropical cyclones, it is still illustrative that more than 7 in. of rainfall was recorded at Saipan International Airport in association with this storm, an amount that represents approximately 10 percent of mean annual rainfall for the island.

An additional climatically driven factor affects relative sea level in the western Pacific basin. El Niño/Southern Oscillation (ENSO) events have been recognized as causing interannual changes in Pacific Basin weather patterns (U.S. National Oceanic and Atmospheric Administration, URL http://www.elnino.noaa.gov/, accessed Sept. 15, 2006), but they also cause local ocean-level variations that can equal or exceed that of astronomic influence. For example, on Saipan, diurnal astronomic tides commonly vary by about 2 ft. In comparison, the 1997 El Niño event resulted in a local relative ocean-level variation of about 1.5 ft (Lander, 2004). These variations are expressed as a drop in relative sea level in the western Pacific Basin that reaches its lowest levels in December of an El Niño year, recovering by the following spring. Conversely, a La Niña event describes a rise in relative sea level in the western Pacific Basin. A La Niña event that closely follows an El Niño event compounds the change in local relative sea level. Therefore, with regard to American Memorial Park, although the effects of an El Niño and (or) La Niña event on relative sea level can make it difficult to discern long-term trends, the

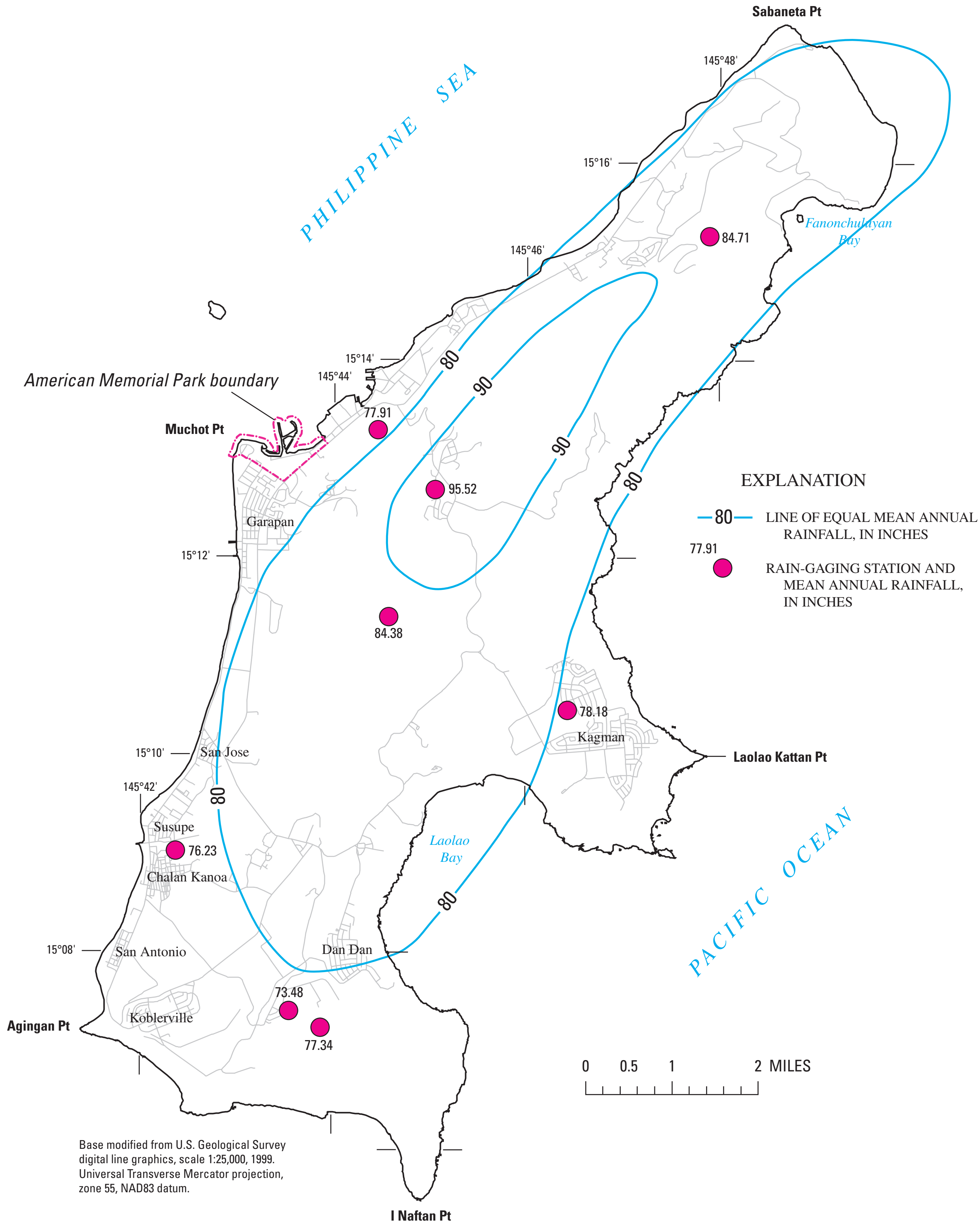

Figure 3. Distribution of mean annual rainfall on the Island of Saipan, CNMI (modified from Lander, 2004).

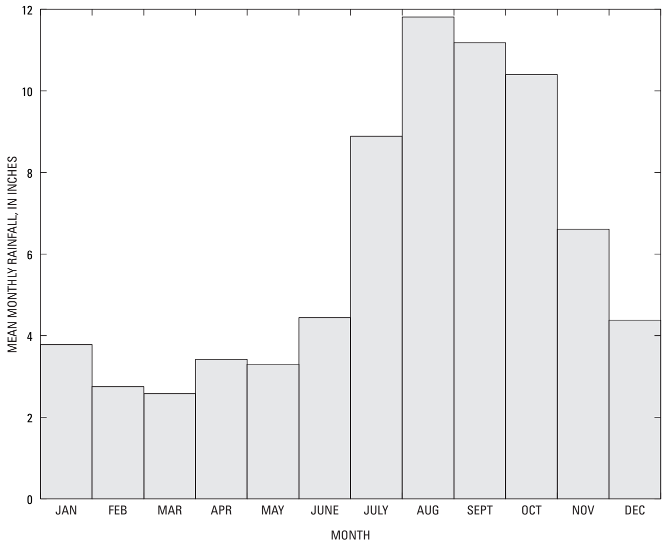

Figure 4. Mean monthly rainfall at Saipan International Airport (SIA) during period 1954–99 (data from Lander, 2004).

direct connection between ground water and surface water in the wetland makes the identification of such trends critically important.

Geology

The Island of Saipan is a subareal expression of the 1,565-mi-long Mariana volcanic island arc, itself the result of the Izu-Bonin-Mariana subduction zone wherein the Pacific Plate is being subducted beneath the Philippine Plate. The island's ancient volcanic core is dominantly overlain by a series of terraced limestone formations (fig. 5). The axial uplands descend to the coast in a series of terraced benches, some of which are sheer on the seaward side. On the west side of the island the limestone formations give way to a coastal plain of calcium carbonate (lime) sand and volcanic outwash (clay). Furthermore, most of the punctuated topography described by these terraces is probably related to axially aligned faults, including the interface between the western coastal plain and the uplands to the east (Cloud and others, 1956).

Saipan's volcanic core is of Tertiary origin, as are many of the Mariana Islands (Cloud and others, 1956). The oldest exposed geologic unit, represented by the volcanic Sankakuyama Formation, is of mid-Eocene origin, radiometrically dated at ~41 m.y. Significant active volcanism appears to have ended during the Miocene, as evidenced by K/Ar ages of the youngest volcanic rocks, represented by the Fina-Sisu Formation, of 13 m.y. (Meijer and others, 1983).

Changes in relative sea level since the volcanic emplacements have resulted in the island's volcanic core being overlain with numerous and distinct limestone formations, the age of the oldest of which, the Tagpochau Limestone, has been constrained through fossil analysis as Miocene, most likely early Miocene (~23 m.y.). The youngest rocks, the Tanapag Limestone, are Pleistocene but remain locally constructional (Cloud and others, 1956).

These changes in relative sea level have been episodic, and the island's limestone formations have a typical geometry as a result; the formations are typically terraced, and are characterized by horizontal or slightly eastward sloping benches separated by seaward-facing scarps or steeply sloping surfaces (Cloud and others, 1956). Additionally, the abundance of rainfall has resulted in the formation of significant karst topography, evidence of which is plentiful throughout the island but most striking in the extensive subterranean caverns along the South Kalabera Cliffs, and in the shoreline sinkholes dotting Saipan's northeast and east coast.

Seismic activity is common in the Mariana Trench region, and some of the episodic changes in relative sea level may be related to tectonic events, as well as being of glacioeustatic origin. As evidence of such events, numerous trench-parallel faults dissect the island, generally trending south-southwest and dipping west-northwest. Some exposed faults are expressed as weathered gaps in the limestone country rock, suggesting the presence of subsurface structures that may be acting as zones of locally higher permeability. Conversely, cuttings from boreholes drilled adjacent to some faults have shown compressional deformation of the country rock, suggesting areas of locally lower permeability. Cloud and others (1956) identified faults on the southern part of the island as purely dip-slip from examination of observable slickensides, suggesting that the fault-plane surfaces have been altered through compression to a more erosion resistant state, a condition that has been equated with locally lower permeability in other areas. Cloud and others observed evidence of a major nearshore fault complex, identified as the Matansa, and suggested that this fault complex extends to the present-day boundary of American Memorial Park (fig. 2); the fault complex approximately describes the interface between the western coastal plain and the topographic rise to east. The fault complex is generally colinear with Pale Arnold (also known locally as Middle Road), which itself describes the southeast boundary of the park. Because it is parallel to, proximal to, and upgradient of the southeast boundary, the fault complex may affect ground-water flow patterns with regard to the park as a whole and to the natural-wetland area in particular.

Cloud and others (1956) also suggested that the western coastal plain has been seismically downdropped below existing sea level and is therefore in a constructional phase, and that this plain is the most westward of the subaerial terraced limestone structures formed by trench-parallel faults. This suggestion is supported by the U.S. Department of Agriculture (1989), who identified the soil in the western part of the park, and in the eastern part seaward of its wetland, as Shioya loamy sand "formed in water-deposited coral sand" areas parallel to the shoreline. They further identified the wetland-area soil

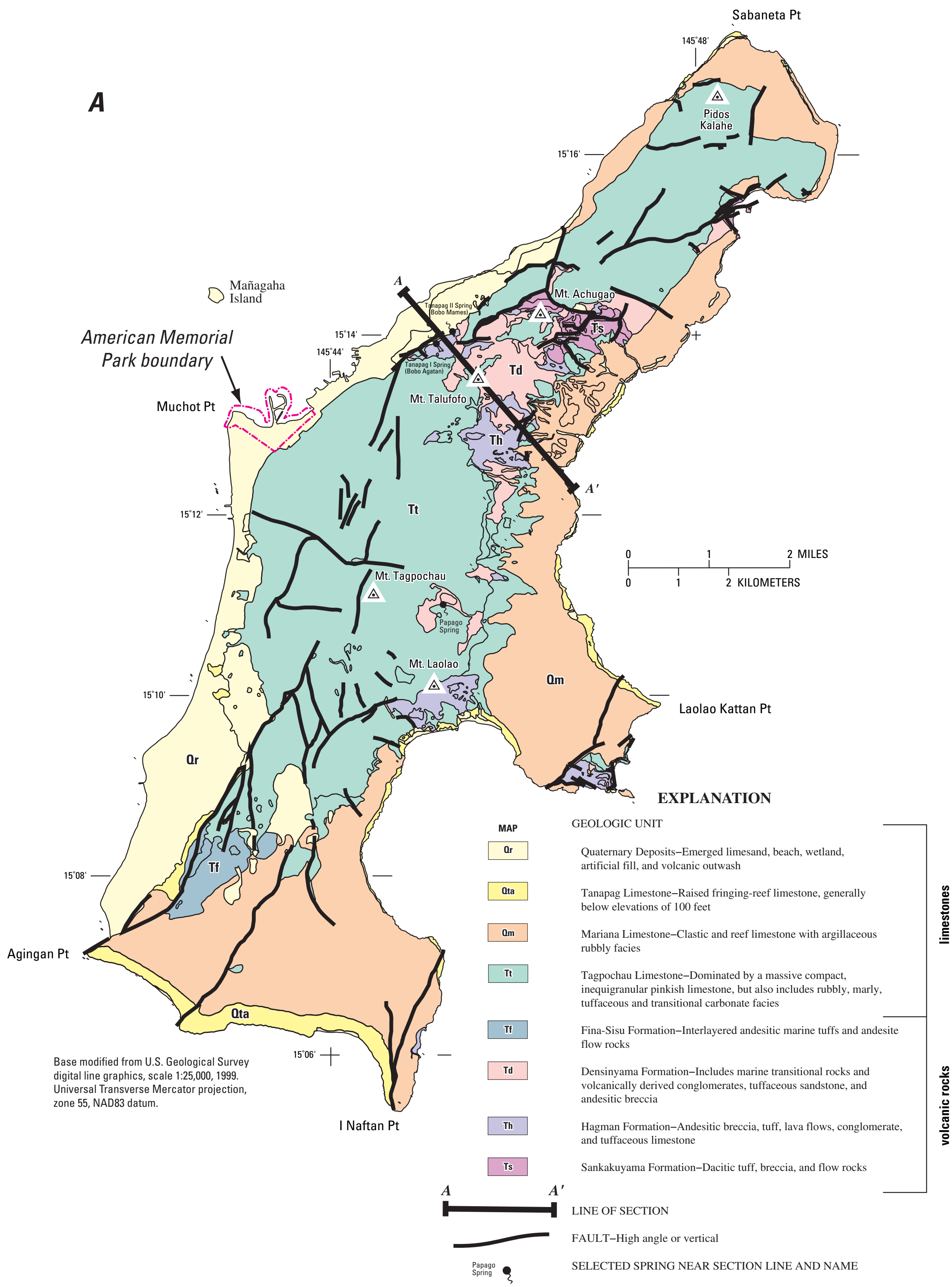

Figure 5. Generalized geologic map of the Island of Saipan, showing (*A*) surficial geology, and (*B*) a geologic cross section (modified from Cloud and others, 1956; Carruth, 2003).

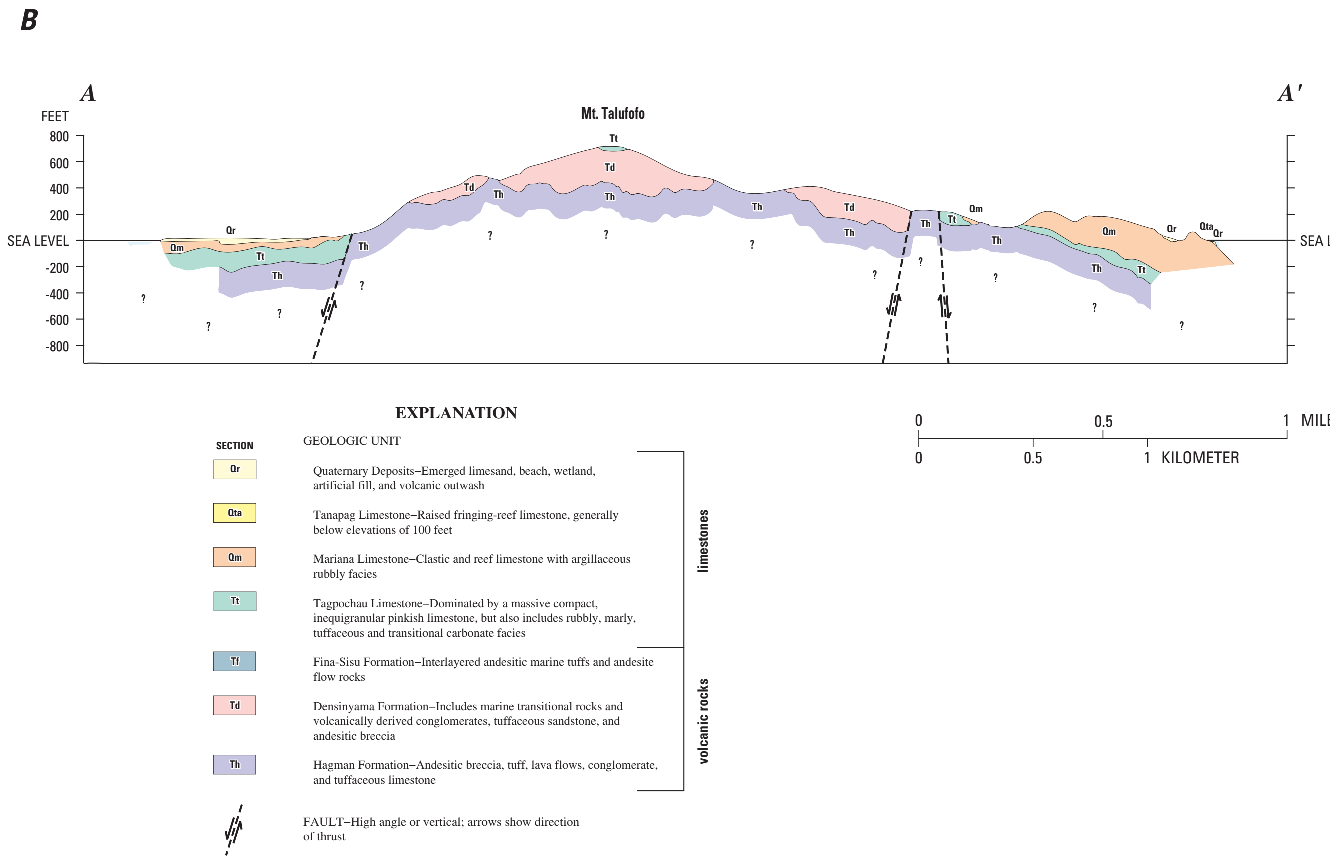

Figure 5. *Continued.*

as Mesei Variant muck, with a surface typically below the high water-table elevation, and areas inland of the wetland as Chinen very gravelly loam, a well-drained soil developed over limestone plateau formations.

At the behest of the U.S. Army Corps of Engineers, several studies were undertaken in and around American Memorial Park during the period 1980–2004, the earlier of which focused on finding solutions to problems associated with frequent flooding of the village of Garapan. The later studies, beginning in 1992 and continuing through 2004, were intended to assess and document the composition and extent of hydrocarbon pollutants anthropogenically introduced into soils and ground water in and adjacent to the park, to develop remediation methods to address the pollution, to track the progress of remediation as it was implemented, and to plan for and document the removal of infrastructure associated with the remediation effort (Woodward-Clyde Consultants, 1992; Matrix Remedial Technologies, Inc., 1995; Ogden Environmental and Energy Services Co., Inc., 1997, 1998, 1999a, b, 2002; Wil Chee-Planning, Inc., 2004a–c). Ogden Environmental and Energy Services Co., Inc.'s (1998) study included trenching in and inland of the park wetland for the purpose of identifying shallow lithologic units, the presence of cultural artifacts, and evidence of introduced hydrocarbons. Monitoring wells were then installed to assess the spatial extent of introduced hydrocarbons. The results of that study indicate that the soils beneath and adjacent to the wetland grade from silty clay (underlying the wetland), through silty coralline sandy fill, to poorly sorted, gravelly coralline sand (fig. 6). These results agree with previous studies by Cloud and others (1956) and the U.S. Department of Agriculture (1989).

Hydrogeology

The hydrogeology of Saipan, on an island scale, is well understood and documented on the basis of previous studies in the Mariana Islands and other places that are generally analogous to Saipan geologically (Gingerich, 2002; Carruth, 2003). The basic conceptual model for an ocean-island aquifer describes a basal freshwater lens overlying ocean-derived saltwater, a configuration resulting from fluid-density differences; freshwater has a density of about 1 g/mL, whereas saltwater has a density of about 1.025 g/mL. This fluid-density difference, under hydrostatic conditions, would result in a sharp interface at a depth below sea level that is 40 times the height of the water table above sea level, commonly referred to as the

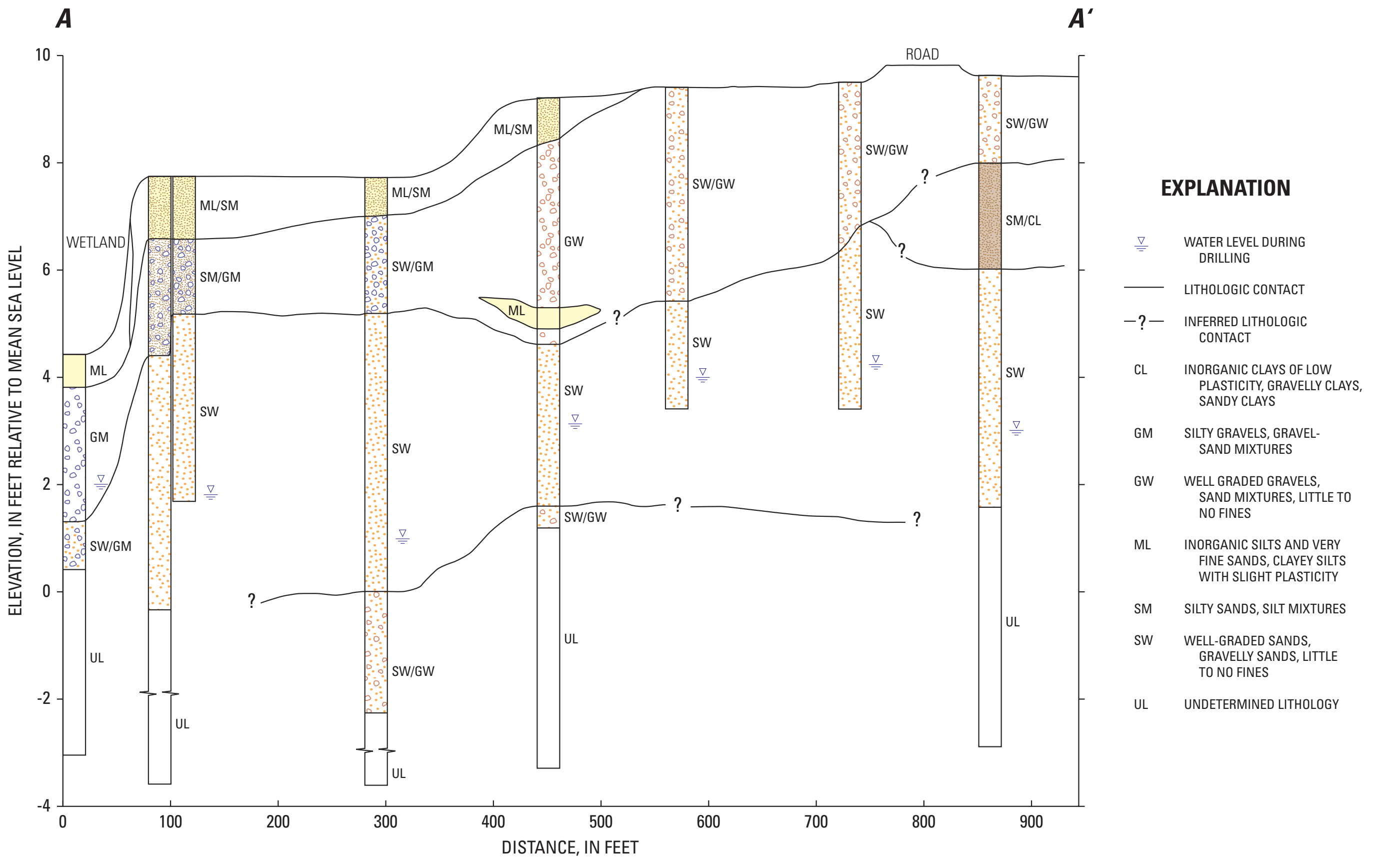

Figure 6. A geologic cross section *A–A′* (see fig. 2 for location) was developed near the southeast perimeter of the American Memorial Park's natural wetland in conjunction with a series of environmental impact and remediation studies undertaken in the 1990s (modified from Ogden, 1998).

Ghyben-Hertzberg relation (Todd, 1980). Under typical field conditions of mixing influences, a salinity gradient is present instead of the theoretical sharp interface.

On Saipan, this basic conceptual model is augmented by the presence of higher-level freshwater bodies, used for domestic production, on the east-central Kagman Peninsula, and in the volcanic basement rocks and overlying limestone in the central highlands (fig. 7; Carruth, 2003). In general, the limestone has a relatively high permeability due to its method of formation and (or) postdepositional dissolution, whereas the volcanic basement rocks have a relatively low permeability, a factor that has so far precluded their use as a developable resource. Additionally, previous studies have generalized that the basal freshwater lens becomes brackish inland of the shoreline, owing to the highly permeable limestone that encircles the island's volcanic core.

History

Saipan was the site of intense conflict during World War II, when vast tracts of the island were so extensively bombed that surface soils were stripped away, leaving only exposed bedrock. The wetland area of the (as yet undesignated) park was said to have been spared this level of damage (Israel Sablan, National Park Service, oral commun., 2005), an assertion supported by aerial photographs taken before, during, and after the conflict that all show the wetland with approximately the same position and geometry as at present (fig. 8). Additionally, postconflict studies funded by the U.S. Department of Defense identify the wetland as Quaternary marshes, citing it as "once a brackish pond closed off by the [Point Muchot] spit" (Cloud and others, 1956; Davis, 1958).

American Memorial Park was created as part of a 1977 Covenant with the United States to grant CNMI its independence. Article VIII, section 803(e) of Public Law 94–241 set aside 133 acres "to honor the American and Marianas people who died in the World War II Marianas Campaign" (CNMI Law Revision Commission, URL http://cnmilaw.org/covenant.htm, accessed Sept. 15, 2006).

Land Use

Historically, the areas of highest population density on Saipan have been clustered along the southwestern coastal plain and the southern upland peninsula. Recent development has shifted toward the central part of the island: the Kagman

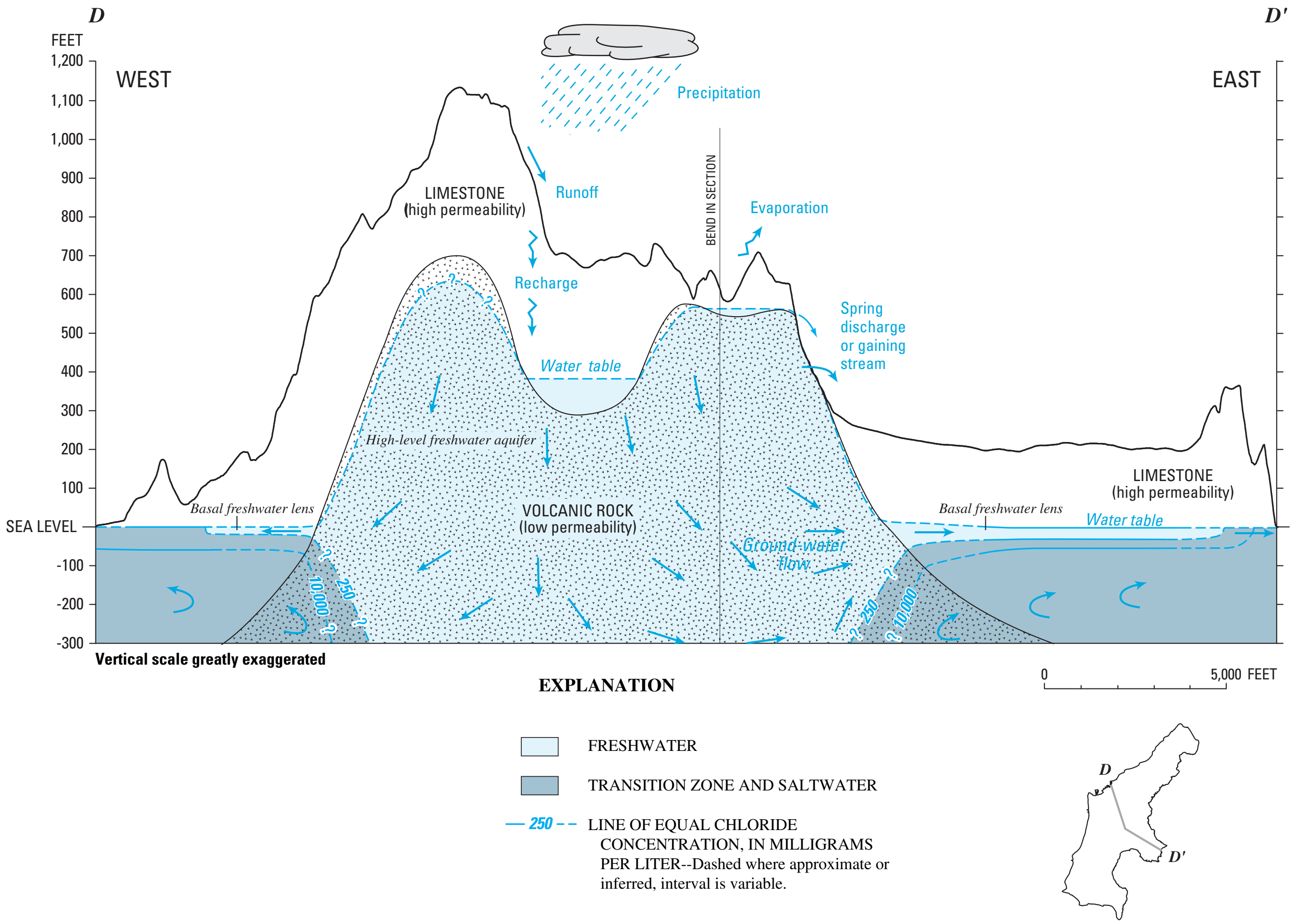

Figure 7. Hydrogeologic cross section *D–D′* through the Island of Saipan, showing details of the ground-water-flow system (modified from Carruth, 2003).

peninsula on the east and the Garapan area on the west. The village of Garapan has become a center of commerce, with most tourism-focused development on its north end (directly adjacent to the southwest boundary of the park), the island's primary hospital and medical facilities (directly adjacent to the south-central boundary of the park), a small-boat marina (within the park but administered by the CNMI Department of Fish and Wildlife), and a large commercial port facility. Separating the park from this port facility is an abandoned solid-waste dump along the northeast boundary of the park.

Production wells fields, providing water for domestic and nondomestic supply, are located upgradient of the park (fig. 9). Numerous private wells, including production (withdrawal) and waste-disposal (injection) wells that have been drilled on hotel properties adjacent to the southwest boundary of the park, are largely unmonitored, with regard to their condition and rates of withdrawal or injection, by government agencies.

The easternmost area of the park was used as a motor pool by the U.S. military during, and for a brief period of time after, World War II (figs. 2, 8*B*). Clustered across what is now the southeast boundary of the park were fuel-service facilities used for both military and civilian purposes (Ogden Environmental and Energy Services Co., Inc., 1998). Additionally, numerous fuel pipelines ran the length of the park's southeast perimeter alongside what is now Pale Arnold. All of these features were known to have been the source of chemical spills (Ogden Environmental and Energy Services Co., Inc., 1998). In the 1990s, several studies were undertaken at the behest of the U.S. Army Corps of Engineers to assess the contamination, including the installation of monitoring and remediation (injection) wells (Woodward-Clyde Consultants, 1992; Matrix Remedial Technologies, Inc., 1995; Ogden Environmental and Energy Services Co., Inc., 1997, 1998). Remediation efforts were completed in 2002 (Ogden Environmental and Energy Services Co., Inc., 2002). The monitoring wells were subsequently sealed by the U.S. Army Corps of Engineers (Wil Chee-Planning, Inc., 2004c).

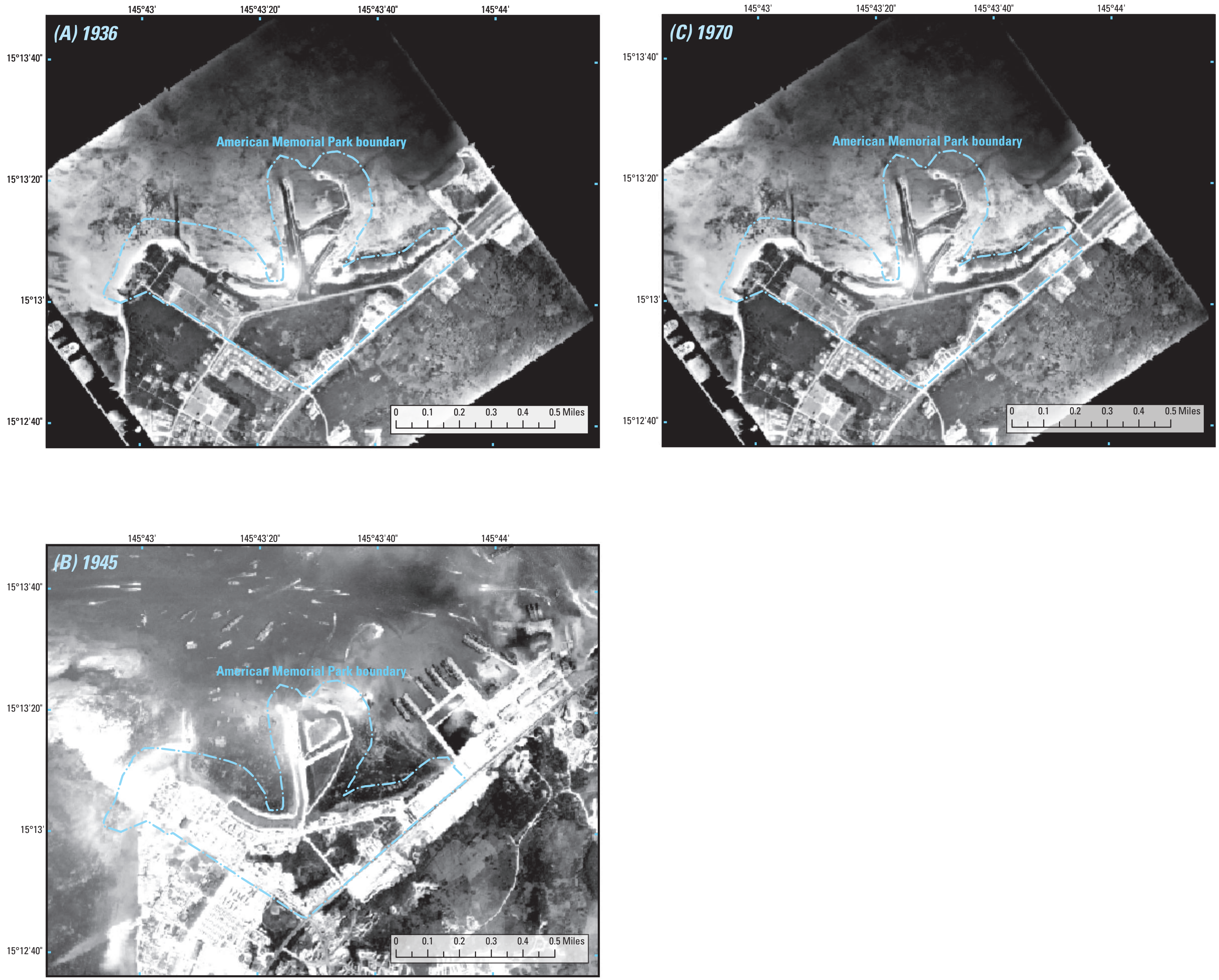

Figure 8. Aerial photographs of the Island of Saipan taken before (ca. 1936), during (ca. 1945), and after (ca. 1970) World War II provide long-term evidence of a persistent natural wetland within the current boundaries of American Memorial Park (provided by D. Minton, 2006).

Previous Investigations

The principal documents describing Saipan's geology and hydrology are USGS publications (Cloud and others, 1956; Davis, 1958; van der Brug, 1985; Carruth, 2003). Cloud and others described the island's geology but also touched upon other topics, including Saipan's potable-water resources. Davis addressed Saipan's hydrology and provided the first complete list of surface- and ground-water resources on the island. Van der Brug built on these early efforts by compiling a comprehensive assemblage of Saipan's hydrologic resources and data. Most recently, Carruth brought together the numerous factors influencing ground-water availability, including land use, geology, geography, climate, aquifer configuration, and current production facilities.

Acknowledgments

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Reconnaissance

The hydrology of Saipan is well documented on an island scale; however, local areas, such as American Memorial Park, generally are poorly understood. To improve understanding of the hydrology of the park and to enable identification of additional information needs, a reconnaissance of the park was conducted from August 24 through September 19, 2005. The primary goal of the reconnaissance was to determine whether surface- and ground-water bodies were connected within the park wetland. A secondary goal was to determine the spatial distribution of salinity with regard to ground water and, to a lesser extent, surface water. Conductivity was measured to enable this determination; the results of such measurements are commonly used as a proxy for salinity, as in this report.

Network Components and Installation

To achieve the goals of the reconnaissance, a 13-well ground-water-monitoring network was configured, incorporating two preexisting monitoring wells coupled with 11 new piezometers (fig. 10). The piezometers, which were installed during the reconnaissance, were used not only for monitoring water level but also for collecting water samples for measuring ground-water salinity. Four of these wells (AMP01, AMP02, AMP05, AMP13) were located in surficially dry areas of the park; two wells (AMP03, AMP04) were located adjacent to, and strongly influenced by, the constructed wetland and its associated discharge channel; and the other seven wells (AMP06 through AMP12) were located in or near the natural wetland. The 11 newly installed piezometers were manually driven to depths ranging from 6 to more than 19 ft (table 1). Locations where significant driving resistance was encountered at depths less than 6 ft below grade, or which did not achieve a minimum depth of 3 ft below observed water level, were rejected to accommodate expected tidal variation. A measuring point referenced to mean sea level was established on each wellhead, and all the measuring points were surveyed to a vertical precision of 0.01 ft, using U.S. National Geodetic Survey (NGS) stations (resurveyed in 2003) as reference points.

Although the method of piezometer installation (impact slidehammer) did not produce cuttings that could be examined, site preparation included excavation of material to a depth of 12 to 18 in. Materials observed during the excavation ranged from coarse calcareous sand to coralline cobbles, as much as 6 in. in diameter. At places along the southeast boundary of the park, coherent layers of Tanapag Limestone were encountered, which precluded the installation of piezometers.

At a site within the natural wetland a surface-water-stilling well (AMP09S) was paired with a ground-water-monitoring well (piezometer AMP09G) to determine whether surface water and ground water were connected. The stilling well, which was directly attached to the piezometer riser pipe, was constructed of polyvinyl chloride (PVC), with holes drilled at regular intervals to allow for the free flow of water (fig. 11).

A tide gage, installed in the immediate vicinity of the park, was used to constrain the effects of ocean tides on the local ground-water system. The gage, which was included in the monitoring-network leveling effort, was similarly surveyed to a precision of 0.01 ft, using NGS stations as reference points. The tidal data used throughout this report were collected at this site.

Collection Methods

Surface- and Ground-Water Salinity

Conductivity, commonly used as a proxy for salinity, was measured, and data were collected, in both surface water and ground water, using a calibrated handheld conductivity meter. Surface-water measurements were made as the wetland and surrounding park areas were initially reconnoitered. Ground-water measurements were made after the ground-water-monitoring-network wells were installed and purged.

Wells were purged in accordance with USGS protocols, as described by Wilde and Radtke (2005). The primary

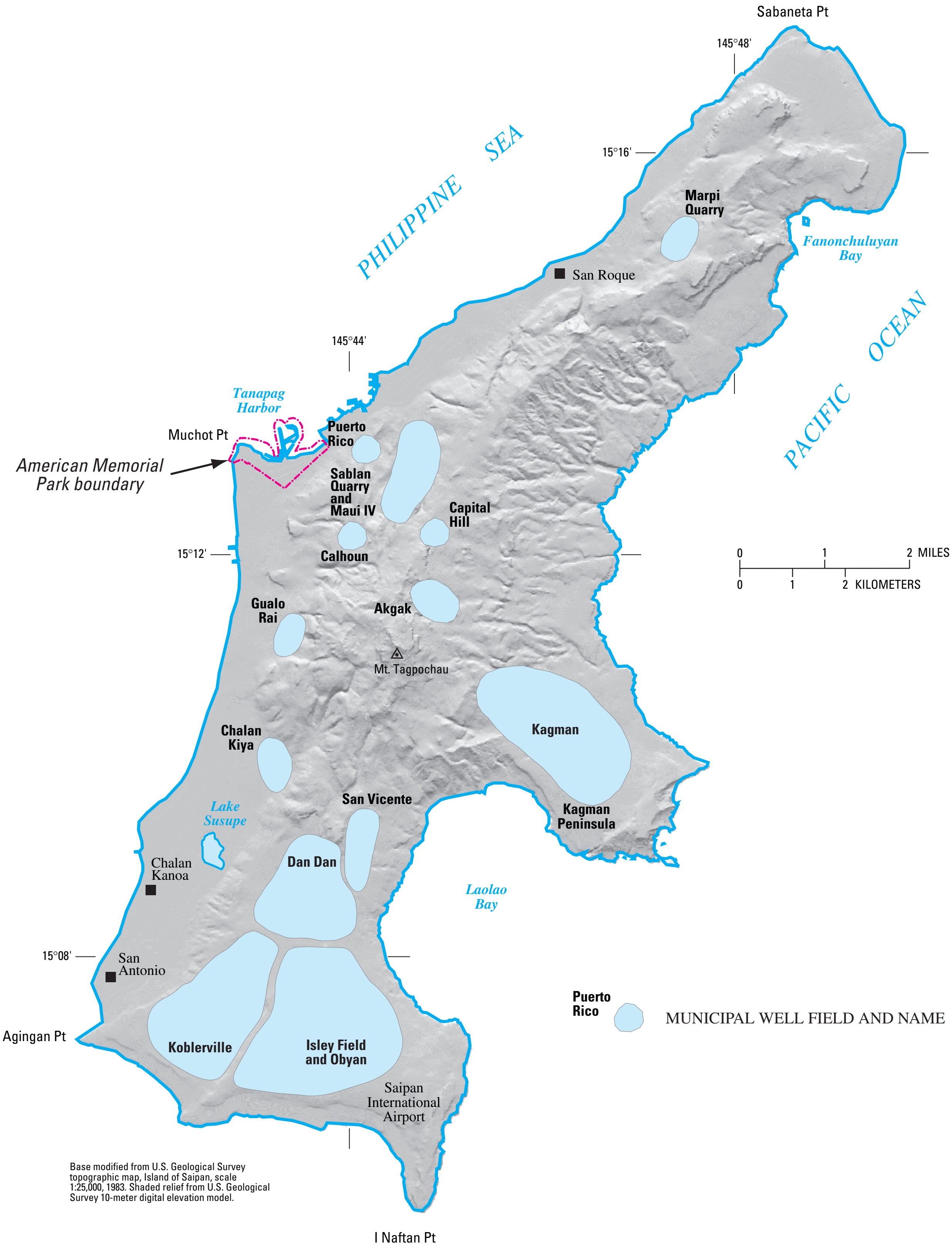

Figure 9. Numerous municipal well fields have been developed on the Island of Saipan, including the Calhoun, Sablan Quarry, and Maui IV fields that are hydrologically upgradient from American Memorial Park (modified from Carruth, 2003).

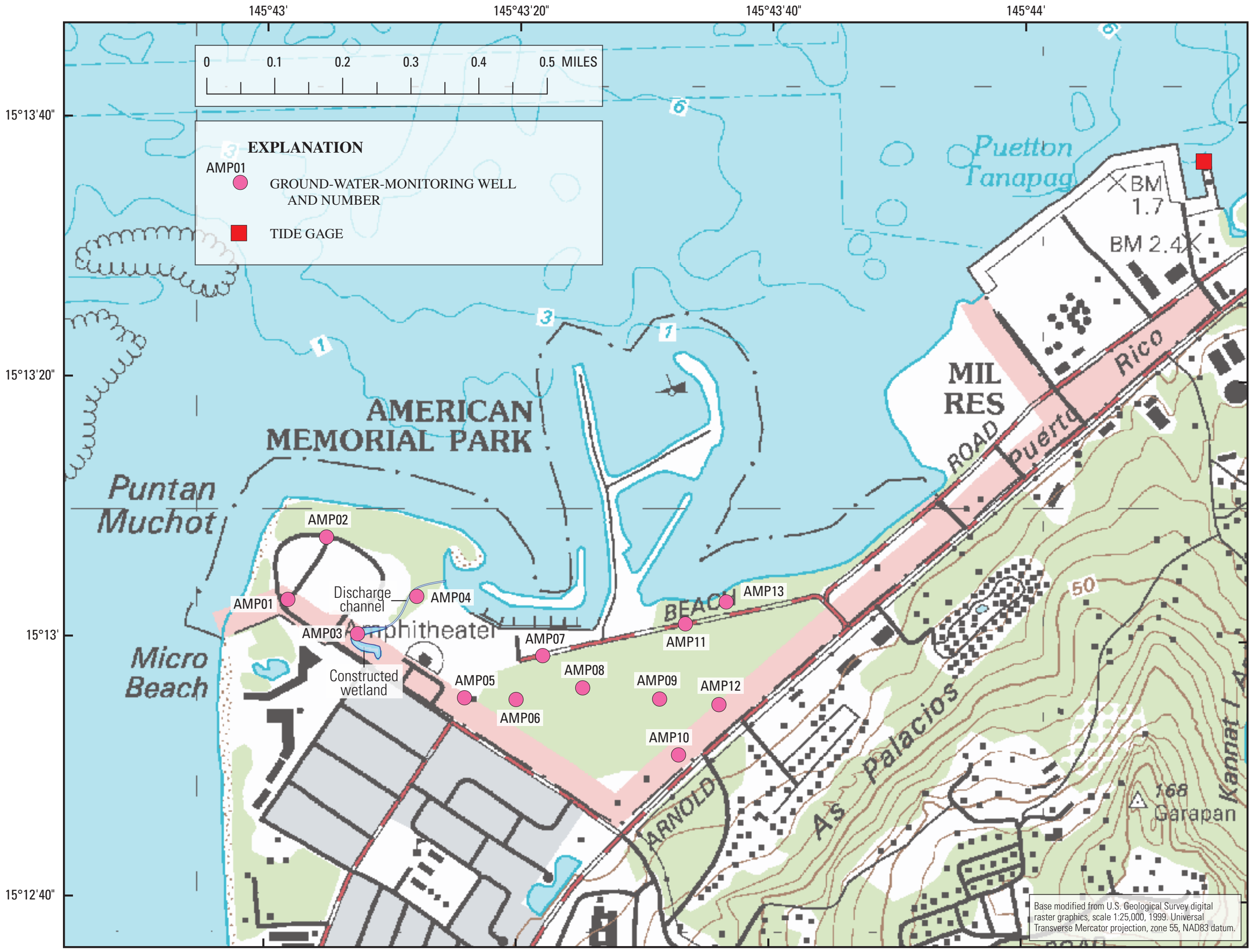

Figure 10. The American Memorial Park ground-water-monitoring network was installed to enable the collection of ground-water data (water-level and salinity). A tide gage was installed at Tanapag Harbor to enable tidal lags to be calculated from water-level data collected during the synoptic surveys.

protocol requires purging a minimum volume of water equal to 3 times the casing volume before withdrawing a sample for measurement. Secondary protocols allow for exceptions to this method for wells with sluggish recovery rates. When the rate of purging is high, the permeability of the aquifer is low, or the connection between the monitoring well and aquifer is poor, water can be completely evacuated from the well. In such situations, water quality can be measured after the water level has recovered to at least 90 percent of the level measured before evacuation, provided that full recovery occurs within 24 hours of evacuation. Of the 13 wells employed for the reconnaissance, 4 qualified for this exception.

Ground-Water Elevations

To develop a spatial representation of ground-water elevations within American Memorial Park and, most importantly, within the natural wetland, water-level data needed to be collected from spatially distributed sites over a broad range of temporal conditions. Two methods were used in the collection of these data: installation of transducers, and manual synoptic water-level surveys.

Transducers were installed in the surface-water-stilling well (AMP09S), in its colocated ground-water-monitoring well (piezometer AMP09G), and in the tide gage. Initially installed

Table 1. Ground-water monitoring network configuration. Depth to water measurements were collected on September 15, 2005.

[ft, feet; AMSL, above mean sea level; dd/mm/ss.s, degrees/minutes/seconds; µS/cm @ 25°C, micro Siemens per centimeter at 25°C; °C, degrees Celsius; – –, not available; N/A, not applicable]

Well ID	Well depth (ft)	Screened-interval elevation[1] (midpoint) (ft AMSL)	Measuring-point elevation (ft AMSL)	Depth to water			Latitude (NAD83)	Longitude (NAD83)
				Water depth (ft)	Water level (ft AMSL)	Time of measurement[2]		
AMP01	8.63	–2.56	5.57	4.88	0.69	12:00 p.m.	N. 15°13 02.9"	E. 145°43'01.8"
AMP02	7.66	–1.83	5.33	4.61	0.72	12:04 p.m.	N. 15°13 07.7"	E. 145°43'04.8"
AMP03	11.81	–4.77	6.54	6.25	0.29	12:10 p.m.	N. 15°13'00.3"	E. 145°43'07.3"
AMP04	8.80	–3.33	4.97	4.45	0.52	11:49 a.m.	N. 15°13'03.2"	E. 145°43'12.0"
AMP05	6.21	– –	3.65	1.85	1.80	11:53 a.m.	N. 15°12'55.4"	E. 145°43'15.8"
AMP06	19.53	–15.56	3.47	3.39	0.08	10:51 a.m.	N. 15°12'55.3"	E. 145°43'19.9"
AMP07	9.62	–4.16	4.96	4.51	0.45	11:47 a.m.	N. 15°12'58.7"	E. 145°43'21.7"
AMP08	11.81	–5.48	5.83	5.67	0.16	11:53 a.m.	N. 15°12'56.2"	E. 145°43'25.2"
AMP09G	12.45	–7.42	4.53	4.11	0.42	10:34 a.m.	N. 15°12'55.4"	E. 145°43'31.3"
AMP09S	N/A	N/A	1.52	N/A	N/A	N/A	N. 15°12'55.4"	E. 145°43'31.3"
AMP10	14.87	–4.13	10.24	10.03	0.21	11:21 a.m.	N. 15°12'51.1"	E. 145°43'32.8"
AMP11	12.63	–7.76	4.37	4.43	-0.06	12:01 p.m.	N. 15°13'01.2"	E. 145°43'33.3"
AMP12	6.24	–2.72	3.02	2.66	0.36	12:09 p.m.	N. 15°12'55.0"	E. 145°43'36.0"
AMP13	6.59	– –	3.45	3.12	0.33	12:04 p.m.	N. 15°13'02.9"	E. 145°43'36.5"

[1] Midpoint of the screened interval is 0.5 ft less than well depth. Configurations of pre-existing monitor wells AMP05 and AMP13 are unavailable, so midpoints are unknown.

[2] All times are Chamorro Standard Time (ChST). For context, a reading of −1.31 ft AMSL was recorded at the tide gage at 12:00 p.m. ChST, September 15, 2005.

on September 7, 2005, the transducers at the colocated site were intended to determine whether ground water and surface water were connected. However, ground-water data from this site were unavailable because of equipment failure; nonetheless, the surface-water data do provide evidence indicative of, and consistent with, connection to ground water. The transducer used as a tide gage, installed at a former U.S. National Oceanic and Atmospheric Administration (NOAA) site from 15:15 Chamorro standard time (Ch.s.t.) September 14 through 17:30 Ch.s.t. September 18, 2005, continuously collected data at 5-minute intervals.

The other ground-water-monitoring wells (AMP06, AMP10) that were installed with transducers were selected to expedite synoptic water-level surveys of the wetland area. Later analysis indicated that these wells may have been completed in areas of very low permeability, on the basis of the attenuated amplitude of the tidal signal and the long recovery times observed during well purging. Water-level data from these wells have not been incorporated into this report because of these anomalies; however, these sites merit further study because they may represent distinct hydrogeologic regimes within the park.

Water-level data were collected by way of synoptic water-level surveys at the 10 ground-water-monitoring wells not installed with transducers. These 10 wells were subdivided into two clusters: a western group (wells AMP01 through AMP05) and an eastern group (wells AMP07, AMP08, AMP11, AMP12, AMP13). Characterization of the natural wetland was a priority of the reconnaissance; accordingly, both high- and low-tide data were collected from the eastern (natural-wetland) group, whereas only high-tide data were collected from the western group.

On the final day of the reconnaissance, an attempt was made to constrain head differences with depth by temporarily installing an additional piezometer at each of the 13 network sites until ground water was encountered. Comparative water-level measurements were then made in both the network well and the additional piezometer, after which the additional piezometer was removed for reuse.

Figure 11. A surface-water-stilling well (AMP09S) was paired with a ground-water-monitoring well (piezometer AMP09G) to determine whether surface water and ground water were connected within the park's natural wetland. Weather-resistant boxes contained vented transducer cable "tails" that accommodated changes in barometric pressure.

Results

During the reconnaissance, four discrete bodies, or zones, of surface water were observed within the natural wetland (fig. 12). Surface-water salinity was comprehensively measured in all four surface-water zones on August 26, 2005. Further surface-water salinity measurements were made as needed throughout the park during the reconnaissance, including in the constructed wetland and its associated discharge channel. Ground-water water level and salinity were measured throughout the reconnaissance.

Surface-Water Salinity

Surface-water salinity was observed to vary spatially and temporally. The standard conceptual hydrologic model for an island aquifer system suggests that surface-water salinity should increase with proximity to the ocean. Contrary to this expectation, field measurements in the wetland surface-water zones displayed a general pattern of decreasing salinity with proximity to the ocean except in surface-water zone 4, as discussed below (fig. 12, table 2). Conductivities within surface-water zone 2, the largest and most central zone, ranged from 1,540 to 4,370 µS/cm. The lowest salinities were measured in surface-water zone 1, the most seaward zone, where conductivities were less than 1,000 µS/cm, with a minimum of 829 µS/cm; the highest salinities were measured in surface-water zone 3, the most inland zone, where conductivities were greater than 5,000 µS/cm, with a maximum of 8,750 µS/cm, the single highest conductivity measured within the wetland during the reconnaissance. Note that these measurements were made after an 8-day period during which less than 0.5 in. of rainfall was recorded at the Saipan International Airport climate station. (The long-term average for an 8-day period in August on Saipan is slightly more than 3.0 in.) Given the

Table 2. Surface-water specific electrical conductance (µS/cm @ 25°C) data collected in the natural wetland zones on August 26, 2005.

[µS/cm @ 25°C, micro Siemens per centimeter at 25°C; °C, degrees Celsius]

Surface-water zone	Number of measurements	Median	Range	
			Low	High
1	[1] 3	873	829	973
2	[2] 9	3,220	1,540	4,370
3	[3] 3	5,760	5,510	8,750
4	[4] 13	6,910	4,430	8,290

[1] Discrete measurements in zone 1: {829; 873; 973}.

[2] Discrete measurements in zone 2: {1,540; 2,200; 2,540; 3,160; 3,220; 3,310; 3,490; 3,780; 4,370}.

[3] Discrete measurements in zone 3: {5,510; 5,760; 8,750}.

[4] Discrete measurements in zone 4: {4,430; 4,540; 4,600; 6,620; 6,620; 6,820; 6,910; 7,640; 7,760; 7,980; 8,010; 8,060; 8,290}.

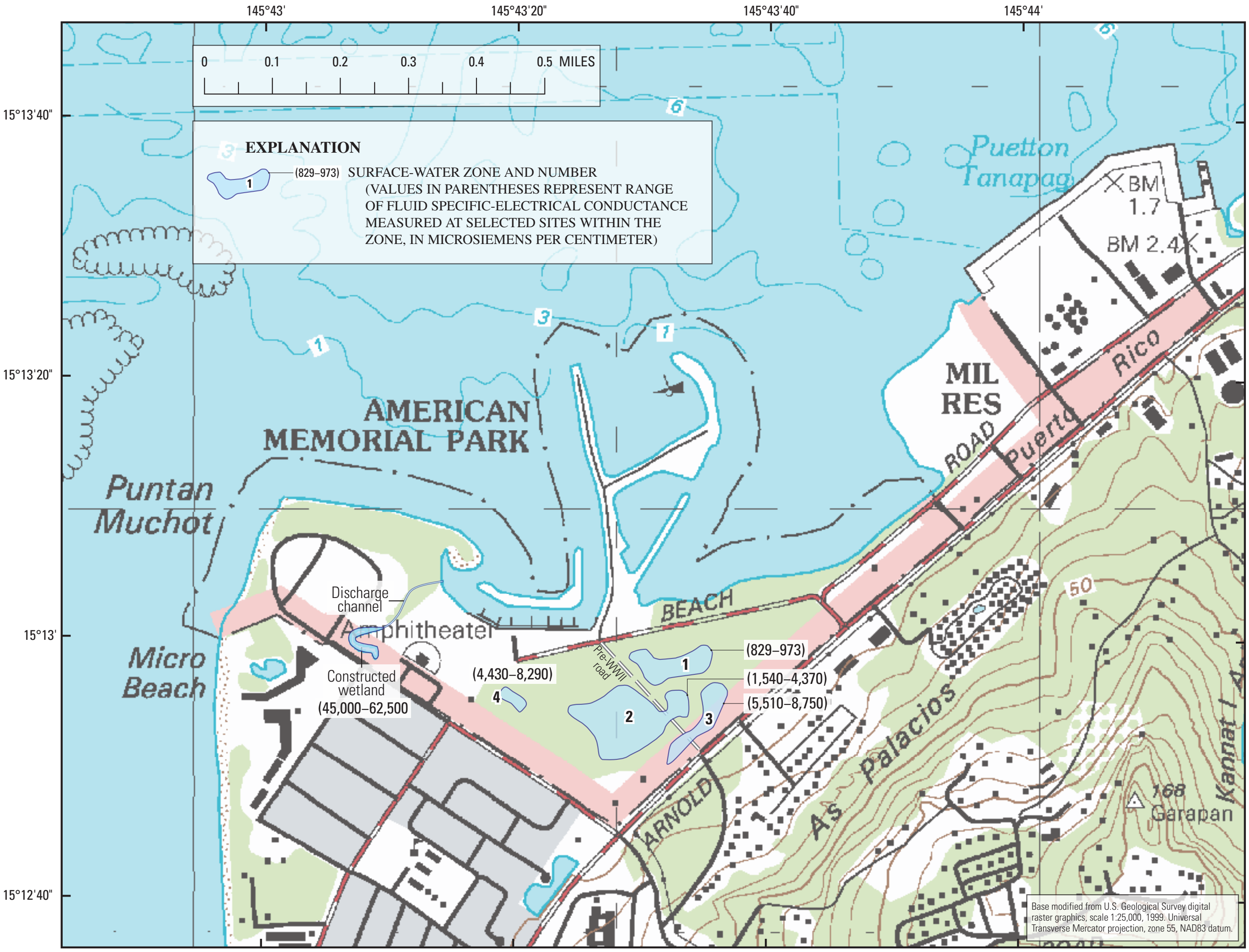

Figure 12. Four discrete zones of surface-water were observed during the reconnaissance of American Memorial Park. Conductivities measurements of surface-water within these zones indicated a general, and counterintuitive, pattern of decreasing salinity with proximity to the ocean.

approximate evapotranspiration rate of 0.21 in/d, or about 1.68 in. over an 8-day period, evapotranspiration should have elevated the salinity of all wetland surface water absent some additional input of freshwater.

Surface-water zone 4, in which ground-water-monitoring well AMP06 was centrally located, had been recognized and documented before the reconnaissance for its anomalous vegetation; a previous survey identified the vegetation within this part of the wetland as *Paspalum distichum*, a type of saltgrass, bordered by *Scirpus littoralis*, a species known as a preferred habitat by the Federally listed endangered species Marianas gallinule (*Gallinula chloropus guami*), or common moorhen (fig. 13; Tenorio, 1979; Raulerson and Rinehart, 1989). Conductivities in surface-water zone 4 ranged from 4,430 to 8,290 µS/cm; the higher value, 8,290 µS/cm, was the second-highest surface-water conductivity value measured within the natural wetland. Furthermore, unique to this surface-water zone, these measurements indicated that the salinity decreased radially outward from the approximate center of surface-water zone 4.

The conductivity of surface water in the constructed wetland ranged from 45,000 to 62,500 µS/cm, with the highest values proximal to the storm-drain inflow (into which reverse-osmosis wastewater was being discharged) and decreasing with distance from this point of inflow (fig. 14). These values exceeded nominal seawater conductivity by as much as 25 percent providing strong evidence that surface disposal of reverse-osmosis wastewater was occurring during the reconnaissance.

Figure 13. A ground-water-monitoring well (AMP06) was installed within surface-water zone 4 of the natural-wetland area of American Memorial Park. Aspects of zone 4 which were anomalous include the extensive presence of saltgrass, the dominant vegetation shown immediately surrounding the ground-water-monitoring well, and a radial pattern of outwardly decreasing surface-water salinities from the approximate center of the zone.

Figure 14. Ground-water-monitoring well AMP03 was installed near the constructed wetland (shown in the near background); in the far background is one of the hotels utilizing reverse-osmosis to obtain potable water, and releasing highly-saline wastewater into the storm-drainage system as a bi-product of the process.

Significant temporal changes in surface-water salinity were recorded in association with Supertyphoon Nabi; salinities were locally lower after the storm passed over the island on August 31, 2005. Surface-water measurements in the approximate center of surface-water zone 4 indicated that the prestorm conductivity of 8,290 µS/cm had dropped more than 57 percent to 3,530 µS/cm.

Ground-Water Salinity

Conductivities of ground-water samples from wells in the monitoring network indicated that ground-water salinity was, at the time of the reconnaissance, geographically related: conductivities were lower (801–2,490 µS/cm) in surficially dry areas, intermediate (6,090–9,180 µS/cm) in natural-wetland areas, and higher (18,250–27,700 µS/cm) in areas adjacent to the constructed wetland and its associated ocean-discharge channel (fig. 15; table 3).

The anomalously high conductivity (14,800 µS/cm) of ground water sampled from monitoring-well AMP06 may have been caused by the depth of the screened interval (midpoint) of the well relative to the rest of the ground-water-monitoring network; at 15.56 ft below sea level it was significantly deeper than the mean screened-interval depth (4.07 ft below sea level, calculated exclusive of AMP06) for the network as a whole. Alternatively, monitoring well AMP06 was unique in that little resistance to driving was encountered during piezometer installation, resulting in the greater piezometer depth at this site. This difference may represent a lithologically based (possibly karstic) preferred pathway for seawater movement into the wetland, and could also explain the higher surface-

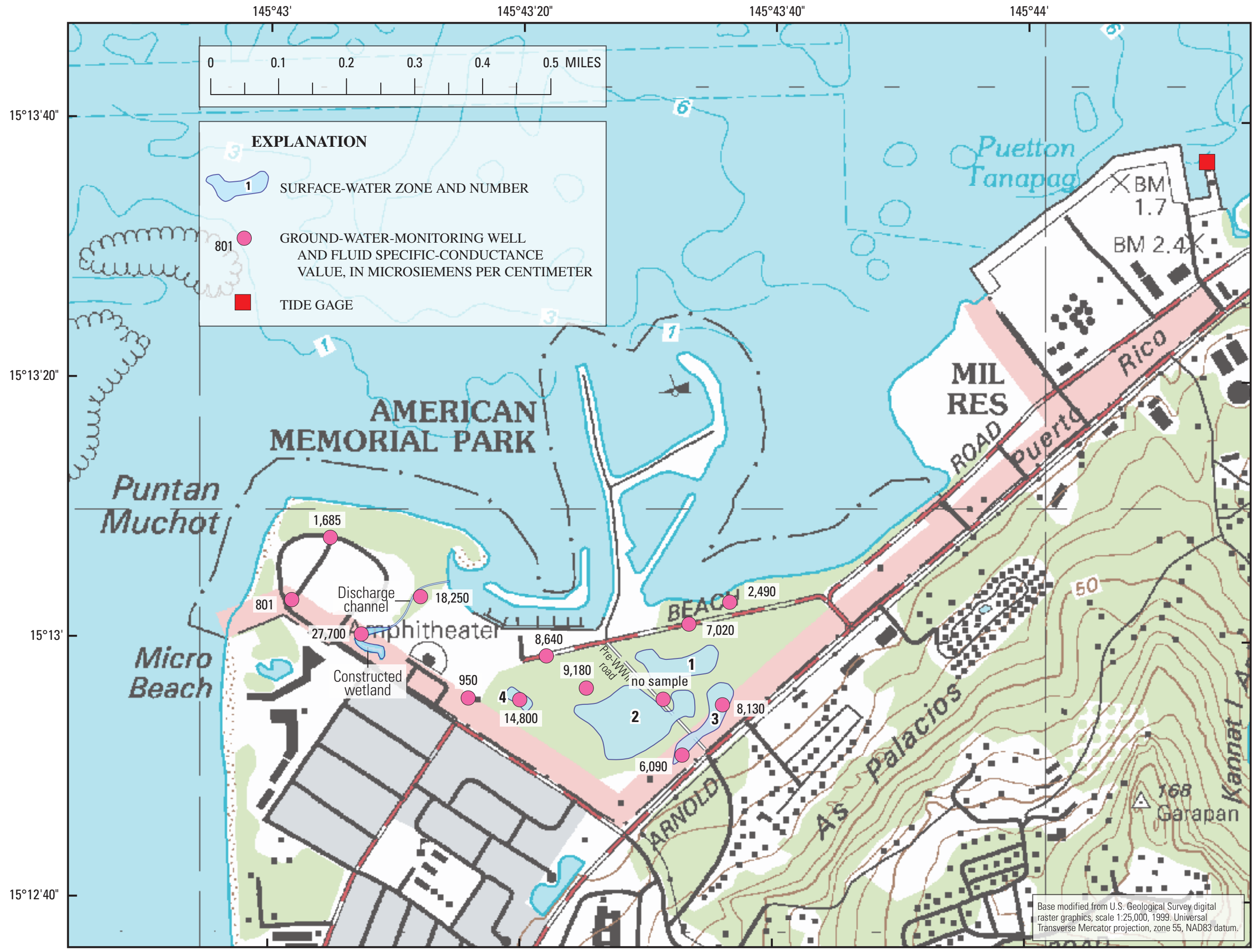

Figure 15. Conductivities of ground-water samples withdrawn from wells in the installed ground-water-monitoring network indicated that ground-water salinity was, at the time of the reconnaissance, geographically related; conductivities were lower (801–2,490 µS/cm) in surficially dry areas, intermediate (6,090–9,180 µS/cm) in natural-wetland areas, and higher (18,250–27,700 µS/cm) in areas adjacent to the constructed wetland and its associated ocean-discharge channel.

water salinities, the radially outward pattern of diminishing surface-water salinity, and the unique vegetative profile in the immediate area of ground-water-monitoring well AMP06.

Ground-Water Elevations

As previously discussed, two methods for determining ground-water elevations were used: selected installations of transducers, and synoptic water-level surveys. Data collected from the transducer installed in surface-water stilling well AMP09S reflect a varyingly declining surface-water level. (The surface-water level had previously been drastically raised by direct rainfall associated with Supertyphoon Nabi.) Once detrended, these data reflected a pattern consistent with a diurnal tidal signal. Concurrent ground-water-level data from this site are unavailable because of a failure of the transducer installed in the monitoring well (piezometer AMP09G); nonetheless, data from surface-water-stilling well AMP09S indicate that surface water may be directly connected to ground water within the natural wetland because the water level at this site varied in accordance with a tidal signal (fig. 16).

Synoptic water-level surveys were performed on September 15–17, 2005; timespans were selected to monitor the effects on ground-water levels in the natural wetland of tidal peaks and troughs (fig. 17). Data collected from the surveys were used to calculate tidal efficiencies and lag times, parameters that are commonly used to gain insight into the hydrologic properties of local subsurface strata. (Tidal efficiency is a normalized measure, commonly expressed as a fraction, relating the amplitude of ground-water-level fluctuations in

Table 3. Well purging and ground-water quality data collected on September 13 - 18, 2005.

[mL, milliliter; µS/cm @ 25°C, microsiemens per centimeter at 25°C; °C, degrees Celsius; – –, not available]

Well	Geographic location	Screened-interval elevation (midpoint) (ft)	Amount purged (mL)	Specific electrical conductance (µS/cm @ 25°C)	Temperature (°C)
Surficially dry areas					
AMP01	Western	–2.56	1,470	801	29.7
AMP02	Western	–1.83	1,355	1,685	29.1
AMP05[1]	Western	– –	2,540	950	30.9
AMP13[1]	Eastern	– –	2,170	2,490	29.0
Constructed wetland					
AMP03	Western	–4.77	2,390	27,700	29.8
AMP04	Western	–3.33	1,360	18,250	29.3
Natural wetland					
AMP06[2]	Eastern	–15.56	2,410	14,800	29.0
AMP07	Eastern	–4.16	1,515	8,640	28.7
AMP08	Eastern	–5.48	2,505	9,180	28.5
AMP09	Eastern	– –	– –	– –	– –
AMP10	Eastern	–4.13	1,580	6,090	29.8
AMP11	Eastern	–7.76	1,540	7,020	29.2
AMP12	Eastern	–2.72	1,420	8,130	30.5

[1] Configurations of preexisting monitor wells AMP05 and AMP13 are unavailable, and so midpoints are unknown.

[2] Specific electrical conductance is likely anomalously high in response to the depth of the screened interval.

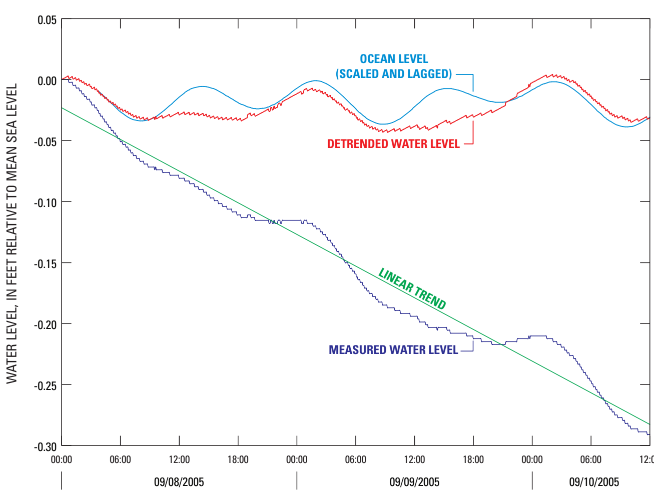

Figure 16. Surface-water elevations were recorded by a transducer-equipped surface-water-stilling well (AMP09S) installed in surface-water zone 2 of the park's natural wetland. Once detrended, these data reflect a pattern consistent with a diurnal tidal signal.

response to tidal fluctuations at the coastal boundary; the tidal efficiency at the coast is commonly set to 1.00, representing a maximum for the study area. Tidal lag is an inverse measure of the propagation of a tidal signal as it moves inland through an aquifer; the tidal lag at the coast is commonly set to 0, representing a minimum for the study area, because this is the point of origin for the signal. Tidal lag is expressed in this report as the time difference between a low or high ocean tide and the corresponding low- or high-water level measured at ground-water-monitoring sites.)

Water-level data were collected from the entire ground-water-monitoring network over a timespan that bracketed an oceanic tidal trough occurring at 12:25 Ch.s.t. September 16, 2005, thus enabling a spatial representation of ground-water level concurrent with the low tide (fig. 18). Calculated tidal lag times suggest that areal rates of hydraulic conductivity in subsurface strata may be higher in the eastern part of the park than in the western part; mean lag time in the eastern part of the park was 21 minutes versus 115 minutes in the western part (table 4).

An additional interesting pattern appears if the western part of the park is further subdivided into surficially dry areas and areas adjacent to the constructed wetland and its associ-

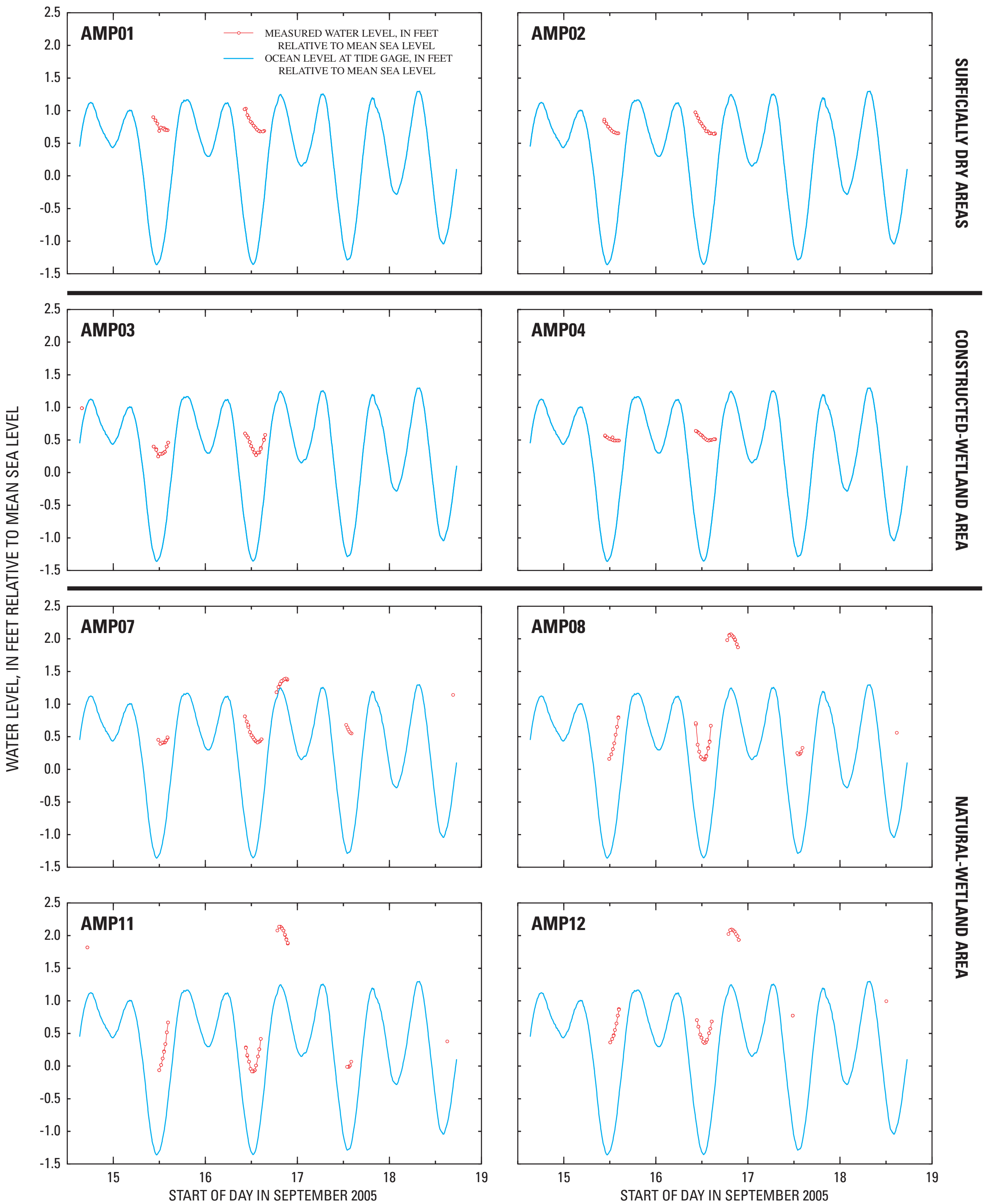

Figure 17. Synoptic water-level survey data, collected September 15–18, 2005, reflect an areal distribution of ground-water levels; the ocean's tidal signal, as it propagated through ground water, was attenuated in surficially dry areas relative to the park's natural wetland. Water levels in the western, surficially dry areas of the park were generally higher than in the eastern, natural-wetland area. Intermediate water levels and tidal-signal attenuation were observed at sites adjacent to the constructed wetland and its associated ocean-discharge channel.

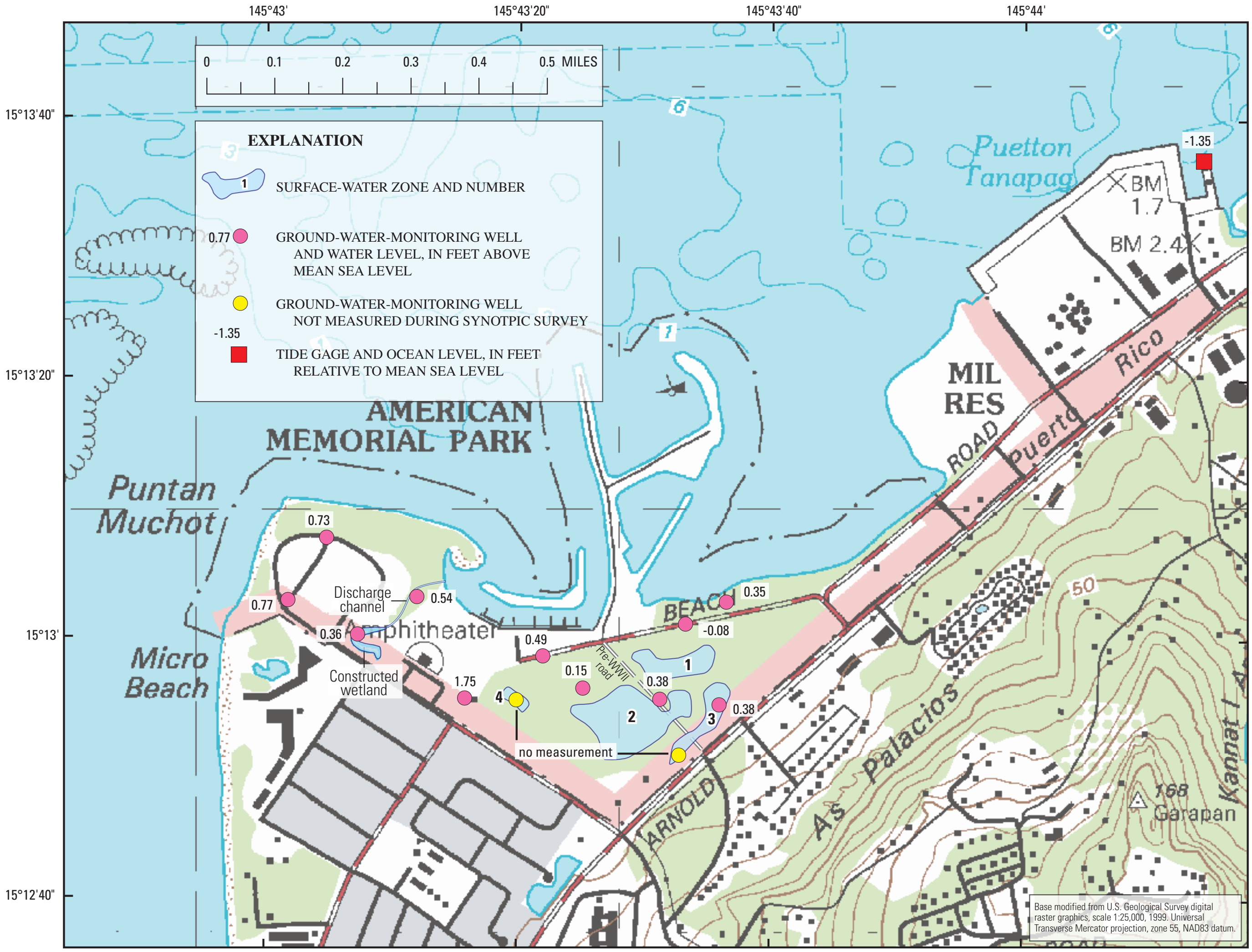

Figure 18. Low-tide ground-water levels were extracted from synoptic water-level survey data collected on the afternoon of September 16, 2005.

ated discharge channel. In this more granular breakdown, the mean lag time for ground-water-monitoring wells associated with the constructed wetland and its discharge channel (wells AMP03, AMP04) was 66 minutes versus 148 minutes for those in the surficially dry area (wells AMP01, AMP02, AMP05). This additional breakdown does not materially contribute to the more significant divergence between lag times in the eastern and western parts of the park, or to the likely areal difference in subsurface strata responsible for that divergence; however, it does indicate that within the western part of the park, the constructed-wetland discharge channel may be acting as a locally preferred pathway for ground-water flow in response to variation in ocean tides.

Water-level data were collected from wells located in the natural wetland over a timespan that bracketed an oceanic tidal peak occurring at 19:35 Ch.s.t. September 16, 2005, thus enabling a spatial representation of ground-water concurrent with the high tide (fig. 19). Similarly calculated tidal lags were consistent with those calculated from low-tide data. Calculated tidal efficiencies ranged from 0.38 to 0.85, with a mean of 0.64 (table 4).

An attempt was made to discern differences in head with depth at the ground-water-monitoring-network sites. Data do not indicate differences in head with depth at any of these sites. Possible reasons why such differences were not evident include that (1) the vertical separation between the coupled well and additional piezometer was insufficient, (2) locally high rates of hydraulic conductivity (vertical and horizontal) made head differences with depth difficult to detect, (3) an annulus immediately surrounding the well and (or) the additional piezometer was created as an artifact of the installation process, (4) the piezometer riser joints were sufficiently

Table 4. Tidal efficiencies and lag times computed from data collected on September 16, 2005.

[AMSL, above mean sea level; ft, feet; hh:mm, hour:minute; – –, not available]

Well	Low water values				High water values				Tidal efficiency
	Time (hh:mm)	Height (ft AMSL)	Offset from tide (ft)	Lag time (hh:mm)	Time (hh:mm)	Height (ft AMSL)	Offset from tide (ft)	Lag time (hh:mm)	
Tide Gage[1]	0.52	-1.36	0.00	0.00	0.82	1.25	0.00	0.00	1.00
Western wells									
AMP01[2]	0.60	0.68	2.04	0.08	– –	– –	– –	– –	– –
AMP02[2]	0.63	0.64	2.00	0.11	– –	– –	– –	– –	– –
AMP03[2]	0.55	0.27	1.63	0.03	– –	– –	– –	– –	– –
AMP04[2]	0.58	0.49	1.85	0.06	– –	– –	– –	– –	– –
AMP05[2]	0.63	1.71	3.07	0.12	– –	– –	– –	– –	– –
Mean Values	0.60	0.76	2.12	0.08	– –	– –	– –	– –	– –
Eastern wells									
AMP06	– –	– –	– –	– –	– –	– –	– –	– –	– –
AMP07[2]	0.57	0.41	1.77	0.05	0.88	1.39	0.14	0.06	0.38
AMP08[2]	0.52	0.15	1.51	0.00	0.82	2.07	0.82	0.00	0.74
AMP09[1]	0.52	0.38	1.74	0.00	0.82	2.05	0.80	0.00	0.64
AMP10	– –	– –	– –	– –	– –	– –	– –	– –	– –
AMP11[2]	0.52	-0.08	1.28	0.01	0.82	2.14	0.89	0.00	0.85
AMP12[2]	0.53	0.38	1.74	0.00	0.82	2.08	0.83	0.01	0.65
AMP13[2]	0.54	0.33	1.69	0.02	0.83	1.81	0.56	0.02	0.57
Mean Values	0.53	0.26	1.62	0.02	0.83	1.92	0.67	0.01	0.64

[1] Data are from transducers.

[2] Data are from synoptic surveys.

incoherent as to allow equilibration between surface-water and ground-water levels through leakage, or (5) some combination of these factors. Reasons 3 and 4 have been included for reasons of rigor; however, the inability to discern any differences in head with depth is most likely due to reasons 1 and 2 because the vertical and horizontal permeability rates of inplace strata probably range from hundreds to thousands of feet per day. Future efforts to constrain this critical variable will likely require deeper piezometer placement.

Hydrologic Model of American Memorial Park

A hydrologic model of American Memorial Park has been developed as a result of the efforts associated with the reconnaissance. Though determined to be connected, and therefore components of a holistic system, surface water and ground water are discussed separately in this report. Surface-water topics will include freshwater-input sources and salinity distribution. The discussion of ground water similarly includes these topics but also addresses flow mechanisms and controls and potential stressors to the park's current hydrologic regime.

Surface Water

Three major potential contributors of fresh surface water to the park, and especially to the natural-wetland area, have been identified: direct rainfall, ground-water discharge, and overland flow resulting from storms.

Direct rainfall contributes freshwater to the park; the reconnaissance was interrupted by Supertyphoon Nabi, and this input was observed and monitored. Access paths to ground-water-monitoring network sites in the wetland were flooded with standing water, in some places to depths of more than 1 ft, and large areas of the western part of the park were ponded for several days after the storm had passed.

Attempts to constrain a vertical component of the generally seaward flowing ground water were inconclusive. How-

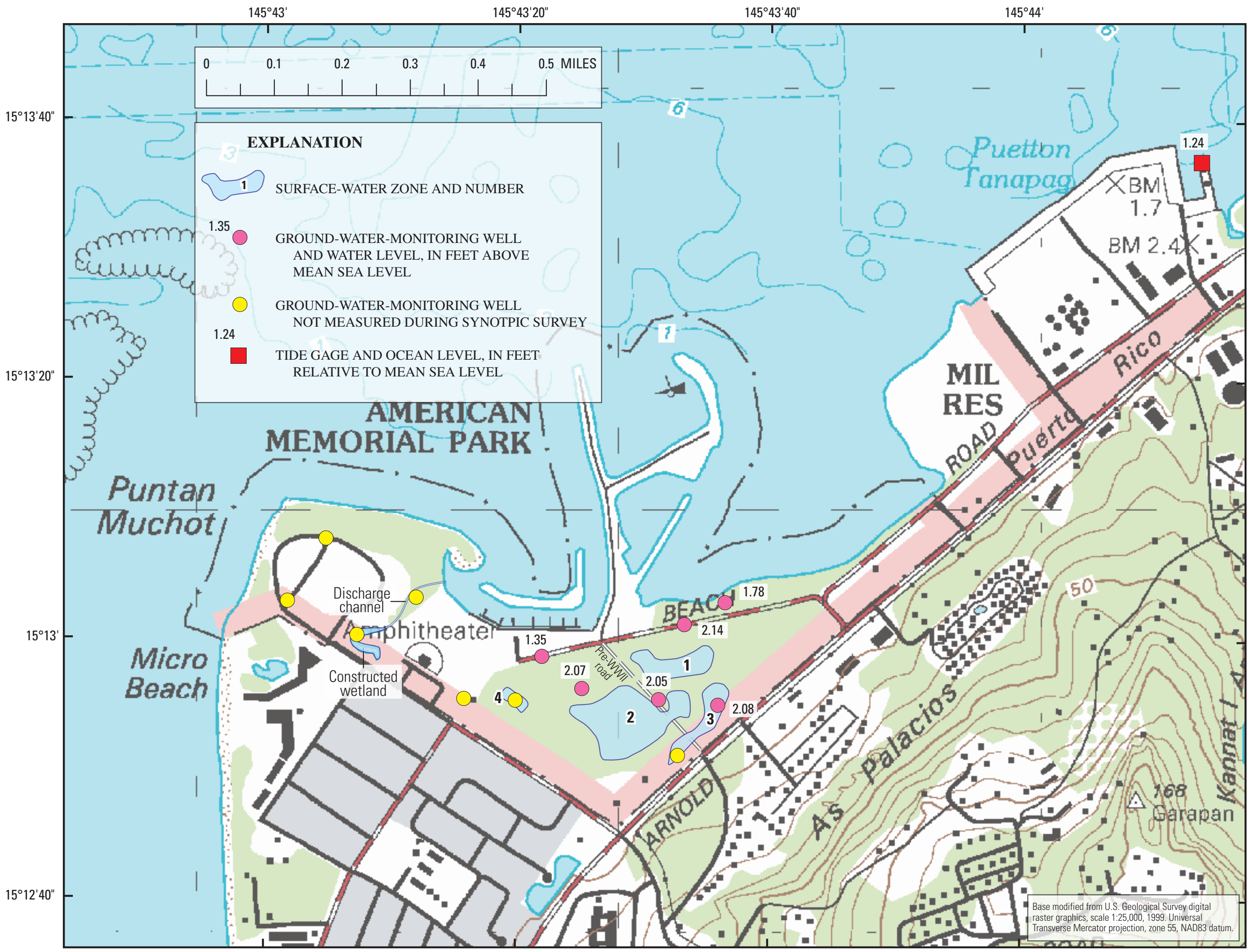

Figure 19. High-tide ground-water levels were extracted from synoptic water-level survey data collected on the evening of September 16, 2005.

ever, some sites within the natural wetland are below sea level (for example, the saltgrass area surrounding ground-water-monitoring well AMP06, fig. 13), and ground water can be expected to provide surface-water input at these sites, given that surface water and ground water are connected and that short-term inputs from direct rainfall, and associated overland flow, are insufficient to reverse the flow gradient. Pressure changes recorded by the transducer installed in surface-water-stilling well AMP09S were consistent with a pattern indicative of tidal signal. These measurements indicate that at least in some sites within the wetland, surface water and ground water may be directly connected and so, in the absence of other inputs, ground water may contribute to surface water.

The coincident occurrence of Supertyphoon Nabi during the reconnaissance enabled a denial of freshwater input from overland flow to the natural-wetland area of the park by the current configuration of roads, and associated diversion channels, to be observed and documented. Although events at the peak of the storm were not directly observed, a visit to the park within hours of the passing of the eye showed that the diversion infrastructure was successful in channeling all overland flow around the park's natural-wetland area and directly into the ocean. (Poststorm inspection of the vegetation flanking the park provided no evidence that the diversion infrastructure had failed to accommodate storm-related overland flows). This observation does not suggest, however, that there are not rainfall rates, and resulting overland-flow conditions, that could not overwhelm the capacity of this infrastructure but only that such rainfall rates and conditions were not observed during the reconnaissance in association with Supertyphoon Nabi.

Although the distribution of surface-water salinity varies spatially within the wetland, all surface-water conductivities measured during the reconnaissance fall approximately within the oligohaline range (800–8,000 µS/cm). Generally, salinity appears to decrease with proximity to the shoreline; this counterintuitive observation may result from denial of freshwater overland flow into the wetland (as described above) or indicate spatially varying discharge of fresh ground water. More data are needed to better constrain this spatially varying surface-water-salinity regime. The radially outward pattern of diminishing salinity in surface-water zone 4 (near ground-water-monitoring well AMP06) could indicate a lithologically based (possibly karstic) preferred pathway between this surface-water zone and the ocean or, more simply, between the surface water in this zone and more saline ground water at depth. The relative ease of piezometer installation here, and the subsequently measured ground-water conductivity—far greater than at any other site—would be consistent with some form of karstic pathway beneath surface-water zone 4.

Temporally, surface-water salinity varied within the wetland during the period of reconnaissance; the greatest variation coincided with the freshwater input (direct rainfall) associated with Supertyphoon Nabi. For example, the salinity in surface-water zone 4 decreased by about 57 percent (from a prestorm conductivity of 8,290 µS/cm to a poststorm conductivity of 3,530 µS/cm). Similarly wide variations over short timeframes are probably related to direct rainfall events, such as Supertyphoon Nabi; however, within the wetland, some temporal variation in surface-water salinity is probable at all times, resulting from such factors as ground-water discharge and evapotranspiration effects. Further study is needed to constrain such temporal variations, as well as to establish seasonally influenced baseline values or, more likely, ranges of values.

Ground Water

Data collected through direct measurements of ground-water levels indicate that Saipan's islandwide freshwater lens, during the period of reconnaissance, extended beneath American Memorial Park. Inputs to this lens come from three primary sources: (1) semi-immediate infiltration from direct rainfall; (2) delayed infiltration from ephemeral surface-water bodies that form as soil-infiltration rates are exceeded, owing to periods of intense rainfall and localized overland flow (as evidenced by the transducer data from surface-water-stilling well AMP09S); and (3) seaward-flowing ground water.

Semi-immediate infiltration from direct rainfall occurs in all environments at rates initially constrained by surficial perviousness and subsequently limited by vertical-hydraulic-conductivity rates. Soils in the park wetland have high infiltration and rapid percolation (permeability) rates; the U.S. Department of Agriculture (1989) characterized the dominant soil type in the wetland (Mesei variant muck) as moderately rapid with regard to permeability, with rates of about 0.6 to 2.0 in/hr. Given that rainfall occurs frequently along the western coastal plain of Saipan (Lander, 2004), direct rainfall can be expected to significantly contribute to ground water within the park.

Surface-water ponding will occur when local soil-infiltration rates are exceeded by direct rainfall, or by overland flow introduced from nearby areas where such rates have been exceeded. Although soil-infiltration rates in the wetland are moderately rapid, storm-related rainfall in the Tropics commonly exceeds these rates, resulting in localized surface-water ponding. Subsequently, this ponded water will infiltrate through the soil surface, then percolate through subsurface soils until it reaches ground water (absent being captured or diverted by other processes, such as root uptake or soil moistening). Data from the transducer installed in surface-water-stilling well AMP09S were consistent with this mechanistic description; they indicated that surface water, ponded from direct rainfall associated with Supertyphoon Nabi, slowly infiltrated through the soils underlying the wetland. That these data were consistent with a tidal-response pattern may also be evidence of direct connection between surface water and ground water, one of the primary goals of the reconnaissance (fig. 16).

Extension of the islandwide freshwater lens beneath American Memorial Park suggests a generally seaward flow of fresh ground water upgradient of the park and, therefore, a freshwater input to ground water underlying the park; however, data collected during the reconnaissance and by previous investigators are insufficient to characterize this flow's magnitude or local flowpath(s) and the effects of seasonality on these characteristics. Given that this input is likely to be the single largest contributor to fresh ground water beneath the park, especially underlying the natural wetland, additional efforts to collect and analyze ground-water data would be beneficial to understanding the hydrology of the park. A ground-water model could be constructed to facilitate this understanding, for use as a communication tool to disseminate this understanding, and as a long-term method of tracking changes to the park's hydrology.

The synoptic water-level surveys conducted during the reconnaissance indicated that the local water table varied directly with the ocean tide, generally ranging from about 0.5 to about 2 ft higher than the temporally corresponding data collected from the tide gage (table 4). Differences in elevation (offsets in water level) between the water table and the ocean were generally greater during periods of low tide and smaller during periods of high tide, and were generally greater in the western than in the eastern part of the park (figs. 18, 19).

Data collected from the synoptic water-level surveys were also used to determine tidal lags throughout the park, and tidal efficiencies in the natural-wetland area. These data indicated that hydraulic conductivities in the immediate area of the wetland were extremely high; however, lag times increased with distance from the wetland, including in wells that are seaward of the wetland. Lag times were greater still in the western part of the park. The granularity of the data, as well as the short timeframe sampled, preclude discrete spatial assessment; additional data would facilitate such assessment and be critical to construction of a ground-water model.

Further influences to ground-water flow in the park could include local faults and the reverse-osmosis injection wells. Faults on Saipan and nearby Tinian have been observed to act as areas of both higher and lower relative permeability (Carruth, 2003). Data collected in the 1980s in the Puerto Rico area (northeast of the park; see fig. 1) suggest that a major nearshore fault complex, identified by Cloud and others (1956) as the Matansa, may be acting as a zone of lower relative permeability because ground-water levels were significantly higher upgradient of the complex. Local topography suggests that this fault complex extends southwestward, immediately landward of the park's boundary-flanking road, Pale Arnold. Further study is needed to definitively determine whether this fault complex does extend into areas proximal to the park and, if so, how the fault complex may be influencing the hydrology of the park.

Subsurface disposal of reverse-osmosis wastewater by way of the injection wells could be causing a local mounding of ground water in the western part of the park. Data collected from the synoptic water-level surveys indicated that ground-water levels are highest in this area (fig. 18), and there is no evidence of any type of impounding formation (or caprock, as it is commonly referred to in Hawaiian geology) seaward of the western part of the park that could account for these raised ground-water levels. Such ground-water mounding, if it is occurring as a result of reverse-osmosis wastewater injection, could perturb ground-water flow throughout the park, including in the Federally listed natural-wetland area.

In addition to identifying the freshwater lens underlying the park, the spatial distribution of ground-water salinity suggests an enhanced ground-water connection with the nearby ocean in the immediate area of the natural wetland and, possibly, in a strip underlying and flanking the constructed wetland's discharge channel to the ocean. Habitat may be strongly influenced, even controlled, by ground-water salinity, especially in areas with a strong ground-water/surface-water connection, such as the natural wetland appears to represent. The reconnaissance was not intended to address biotic regimes, only the hydrology of the park. However, given the influence of hydrology on habitat, a cooperative effort to further constrain the quantity and quality of surface water and ground water, and the potentially adverse effects of environmental changes on the park's biota, might be prudent.

Additional Data and Analysis Needs

The habitat associated with the 27-acre estuarine system is primarily a reflection of areal surface-water distribution and salinity. The areal distribution of surface water varies on an hourly to daily basis with regard to storms, on a seasonal basis as a reflection of rainfall and the upward discharge of ground water, and on a multiyear to multidecadal basis owing to long-term cyclical patterns (for example, El Niño) or global changes in climate and sea level. The reconnaissance study addressed the hourly to daily temporal variation, but characterization of longer-term variation requires additional data and analysis. The reconnaissance study was not intended to comprehensively map the areal distribution of surface water within the wetland or to characterize how that distribution could vary with changing conditions.

Equally important as areal distribution is the salinity of the surface water within the estuarine system. Surface-water conductivities measured during the reconnaissance fell predominantly into the oligohaline category of salinity. Given that some types of vegetation within the wetland are critically sensitive to specific ranges of salinity (for example, mangroves can tolerate higher salinities than can casuarinas), a spatial baseline needs to be established, along with an enhanced understanding of what factors are contributing to the range of salinities measured throughout the wetland. Measuring localized differences in head with depth could provide insight into the vertical flow of ground water and, by extension, the spatial pattern of salinity within the wetland and adjacent areas.

Similarly, an enhanced spatial and temporal dataset of ground-water quality with regard to salinity, including profiles of the brackish-water transition zone (zone of freshwater/saltwater mixing), would augment understanding of the hydrology of American Memorial Park. Given the increasing urbanization near the park and probable commensurate increases in freshwater withdrawal and wastewater injection, establishment of baseline conditions would enable short-term changes and long-term trends to be identified that could affect the park's critical habitats. With regard to the western part of the park, it may already be too late to establish a historical baseline; however, recent correspondence with the CNMI Department of Environmental Quality has indicated that local hotels have yet to fully transition from surface disposal of reverse-osmosis wastewater to subsurface injection (Brian Bearden, CNMI Department of Environmental Quality, written commun., 2006). To better constrain ground-water salinity, clustered piezometers of differing depths could be installed at selected sites within the park.

The effects of subsurface disposal of reverse-osmosis wastewater on the hydrology of the park could be significant. If ground-water mounding occurs as a result of subsurface injection then ground-water flow within the park will likely be changed. The reconnaissance study was not intended to characterize ground-water flow in the western part of the park; however, additional efforts should address the potential effects such an injection mechanism could introduce, recognizing that their influence may be parkwide. This reconnaissance study was not intended to characterize ground-water flow in the western part of the park; however, additional efforts should address the potential effects of such injection techniques, recognizing that the effects may be parkwide.

The road flanking the southeast boundary of the park, Pale Arnold, is currently preventing overland flow from entering the wetland. At present, water is being diverted around the park in a series of surface drains and conduits. The effect of this diversion on the wetland could be studied to determine its significance to the hydrology and, by extension, the critical habitat of the park.

Numerous fault complexes bisect Saipan parallel to the island's long axis. Cloud and others (1956) suggested that one of these fault complexes, the Matansa, is responsible for the significant change in relief proximal to, and in alignment with, the southeast boundary of the park (fig. 2). Data collected in the Puerto Rico area, about 1 mi from the park, suggest that this fault complex may be acting as a locally low permeability barrier to the generally seaward flow of fresh ground water, resulting in higher ground-water levels upgradient of the fault complex. Given that the local discharge of seaward-flowing ground water may be significant to maintaining the wetland's brackish salinity, and that the fault complex may be acting as a ground-water-flow control, an improved understanding of the effects of this fault complex on the hydrology of the park could be informative.

Summary and Conclusions

American Memorial Park on the Island of Saipan, CNMI, represents a significant local asset with its varied mix of historical, recreational, and natural-resource features, which include a 28-acre Protected Natural Area Zone and a 27-acre estuarine system. These natural-resource features provide critical habitat for various migratory and resident waterfowl, including two Federally listed endangered species: the Marianas gallinule (*Gallinula chloropus guami*) and the nightingale reed warbler (*Acrocephalus luscinia*). Estuarine systems have become rare within the CNMI, and so the park's estuarine system has been identified as a Mitigation Policy Resource Category 2 site by the U.S. Fish and Wildlife Service, the only such Federally protected area within the CNMI possessing viable populations of these endangered species.

In recognition of the park's critical habitat, and the integral relation between this habitat and the local hydrologic regime, a need to enhance the understanding of the hydrology of American Memorial Park was identified. To address this need, a reconnaissance study of the park was undertaken during August and September 2005. The goals of the study were (1) to describe the occurrence and salinity of surface and ground water within American Memorial Park; (2) to present a conceptual model of the hydrology of the park area, with emphasis on the 27-acre estuarine system; and (3) to identify additional data needed to further develop this model and address continuing information gaps.

With regard to surface water, three possible freshwater inputs to the park's natural wetland were identified: direct rainfall, seaward-flowing ground water, and overland flow. Direct rainfall is likely an important source of freshwater to the wetland. Evapotranspiration is probably occurring at a rate of about 0.21 in/d, a rate that will frequently be exceeded by direct rainfall, both seasonally and per storm; infiltration of direct rainfall in excess of this evapotranspiration rate would represent a freshwater input to the wetland. The seaward flow of ground water is likely to be a source of freshwater to the wetland because ground water commonly expresses an upward vertical component in the nearshore environment; however, attempts to constrain this vertical flow component were unsuccessful, likely owing to the relatively high rates of hydraulic conductivity. Overland flow upgradient from the park could contribute a significant input of water during periods of intense rainfall, but perimeter-flanking roads and infrastructure currently act as a barrier to such surface inflows.

Specific electrical conductance, or conductivity, was measured within the four discrete bodies, or zones, of observed surface water in the park's natural wetland. These surface-water measurements yielded conductivities that typically ranged from 1,540 to 4,370 μS/cm (surface-water zone 2), although conductivities as low as 829 μS/cm (surface-water zone 1) and as high as 8,750 μS/cm (surface-water zone 3) were recorded. As a result of these measurements, the natural-wetland area meets the definition criteria of an estuarine system that is dominantly oligohaline: (1) its salinity is ocean derived, (2) its salinity is primarily within the conductivity range 800–8,000 μS/cm, and (3) it is tidally flooded at times, although this flooding may be extremely infrequent, occurring only during large tropical cyclones and their associated storm surges, or by a tsunami. Counterintuitively, these natural-wetland surface-water conductivities indicated a general trend of increasing salinity with distance from the ocean, possibly resulting from the denial of overland freshwater flows, owing to the previously discussed road and related infrastructure barrier. Further study is needed to understand this apparent anomaly.

Surface-water zone 4, containing ground-water-monitoring-well AMP06, was unique in that salinity decreased radially outward from a central, near-sea-level area vegetated by saltgrass. Conductivities measured later in the reconnaissance within this surface-water zone, after the passing of Supertyphoon Nabi and the associated addition of significant freshwater input to the wetland in the form of direct rainfall, indicated that surface-water salinity had decreased by about 57 percent, a significant temporal variation in surface-water salinity. These changes may represent the norm rather than the exception, given Saipan's position within the formative region for the northwestern Pacific tropical-cyclone basin.

Surface-water conductivity was also measured in the constructed wetland. A phaseout of surface disposal of reverse-osmosis wastewater had been planned in favor of subsurface disposal by way of injection wells; however, the reconnaissance coincided with this planned transition, and so both surface (by way of storm drains) and subsurface (by way of injection wells) disposal of reverse-osmosis wastewater may have been occurring concurrently. Conductivities of surface water in the constructed wetland exceeded nominal seawater levels by as much as 25 percent, ranging from 45,000 to 62,500 μS/cm, with the highest values recorded near the storm drains discharging directly into the constructed wetland. These data indicate that surface disposal of reverse-osmosis wastewater was occurring during the reconnaissance. Analysis of water-level data collected from wells located downgradient from the injection wells was inconclusive in identifying any ground-water mounding as a result of subsurface injection; however, if such mounding is occurring, or does occur in the future, it will modify ground-water flow within the park. Further study is needed to constrain the affects of subsurface wastewater disposal.

Previous investigations of Saipan's ground-water resources have determined that a freshwater lens underlies most of the island, including the western coastal plain on which American Memorial Park lies. Data collected by way of the ground-water-monitoring network installed as part of the reconnaissance identified the presence of fresh ground water underlying the park and indicated that surface water is directly connected to ground water in the natural wetland because the water levels of both varied directly with the tide. This fresh ground water is likely continuous with the islandwide freshwater lens identified by previous investigations; however, this reconnaissance study was not intended to determine such continuity.

Conductivities of ground-water samples collected from wells in the monitoring network indicated that ground-water salinity was, at the time of the reconnaissance, geographically related: conductivities were lower (801–2,490 µS/cm) in surficially dry areas, intermediate (6,090–9,180 µS/cm) in natural-wetland areas, and higher (18,250–27,700 µS/cm) in areas adjacent to the constructed wetland and its associated ocean-discharge channel.

Synoptic water-level surveys, conducted to enhance understanding of the spatial expression of the water table, were scheduled to overlap with peak and trough tidal signals to enable limited characterization of local hydrologic properties. The water-level surveys indicated that ground-water levels were directly influenced by ocean tides because tidal fluctuations were reflected in ground-water levels. The surveys also indicated that, at any given time, ground-water levels were higher than ocean-water levels; this offset in water level was greater at low than at high tide, and greater in the western than in the eastern part of the park. Tidal lags calculated for the entire park, and tidal efficiencies calculated for the natural-wetland area, suggest that areal rates of hydraulic conductivity in subsurface strata may be higher in the eastern than in the western part of the park: mean lag time in the eastern part of the park was 21 minutes versus 115 minutes in the western part. Tidal efficiencies in the eastern part of the park ranged from 0.38 to 0.85, with a mean of 0.64.

Additional data are needed to develop a better understanding of the hydrology of American Memorial Park. Installation of additional monitoring wells would be needed to constrain ground-water flow through the park, including the vertical component of flow, which would be evidenced by differences in head with depth. Additional ground-water measurements (water level and salinity) in the western part of the park, in coordination with varying amounts of subsurface reverse-osmosis wastewater disposal from nearby facilities, could lend insight into the effects of such disposal practices on ground-water flow within the park. Ground-water measurements (water level and salinity) bracketing faults that are proximal to, parallel to, and upgradient from the southeast boundary of the park can lead to improved understanding of the potential effects of these faults on the local hydrology. Understanding of the potential negative effects of perimeter-flanking roads and associated infrastructure on freshwater flow, both surface and subsurface, could be improved by installing an enhanced monitoring-well network, and by monitoring surface flows that are currently and artificially being diverted around the park to the ocean.

Modeling local and islandwide hydrologic characteristics could assist in identifying short- and long-term hydrologic trends that could adversely affect the park and its critical habitats. Development of a water-budget model on a larger, possibly island, scale could enhance understanding of upgradient influences on the local hydrologic regime in the park. Development of a numerical model, on a park scale, to address coupled surface-water/ground-water flow and solute transport could enhance understanding of local processes, enable implementation of response-specific (adaptive) management practices, and serve as a visual-communication tool to inform interested parties of changes to the park's hydrologic characteristics, including critical habitats, resulting from both local (for example, proposed urban development projects, such as the subsurface disposal of reverse-osmosis wastewater by way of injection wells) and farfield (for example, anthropogenic climate and (or) sea-level changes) influences.

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