Dye Trace of Groundwater Flow from Guam International Airport and Harmon Sink to Agana Bay and Tumon Bay, Guam

By

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Our sincerest appreciation also goes to Mr. Rick Wood, Manager of the WERI Water Laboratory for his patience and persistence in training and assisting author Moran in the spectrofluorimetry.

ABSTRACT

The Harmon Sink, which lies near the west coast of central Guam, is one of the striking surface features of the Northern Guam Lens Aquifer, a highly permeable carbonate island karst aquifer in uplifted Cenozoic limestone. Surrounded by the island's densest industrial and urban areas, the sink collects storm water from a surrounding industrial park and from the adjacent airport to the southeast. In recent years, it has also received large discharges of sewage from failing lift stations. The island's premier tourist district is located in the nearby coastal zone, in Agana Bay 2 to 4 km west, and in Tumon Bay 1 to 3 km north. There has been concern that contaminants entering the sink or airport may be carried to these bays by groundwater discharging in the coastal zone. A dye trace was therefore conducted to help characterize groundwater transport from the sink and the airport to the adjacent coastal zone. Dye receptors were placed at seeps and springs in each bay and in sampling wells installed 150 m down gradient from each injection point. The results of the dye trace are consistent with a highly permeable triple porosity system:

1. Dye injected at the surface in a dry streamway along the axis of the sink was detected on the fourth day after injection at sites in Agana Bay 2500 m west-southwest. Dye injected at the water table from a well on the airport about a kilometer south of the Harmon Sink injection point, was detected on the sixth day after injection at sites in Agana Bay 2150 m west. The general direction of transport to Agana Bay from each site is nearly perpendicular to the regional hydraulic gradient but consistent with mapped regional fracture orientation.

2. Dye from the Harmon Sink injection was detected on the 17th day after injection at sites in Tumon Bay 1400 m northwest. Dye from the airport injection was detected on the eighth day after injection at sites in Tumon Bay 1400 m north-northwest. The transport rate to Tumon Bay was thus very rapid, though slower than transport to Agana Bay. The general direction of transport to Tumon Bay from each site is consistent with the regional hydraulic gradient.

3. Dye from the Harmon Sink injection was detected in the sampling well 150 m down gradient four days after the injection (with daily sampling). Dye from the airport injection was also detected in the sampling well 150 m down gradient when the well was sampled for the first time on the fourth day following injection.

From these observations, we hypothesize that the fastest transport (to Agana Bay) was controlled by relatively open, regional-scale fracture pathways. The rapid, but intermediate transport rate (to Tumon Bay) may be controlled by gradient-driven flow, probably through enhanced secondary pathways in the general direction of the gradient. Local flow (from injection points to nearby sampling wells) is apparently controlled by gradient-driven diffuse flow through the aquifer matrix.

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INTRODUCTION

There is public concern that contaminants originating from the heavily industrialized and commercialized Guam International Airport and the adjacent Harmon Sink (Fig. 1) may discharge into Tumon Bay or East Agana Bay, which are the principal tourist and recreational districts of Guam. This report describes a dye trace study conducted to determine whether surface water that infiltrates in Harmon Sink or enters the water table beneath the airport discharges into these bays, and if so, precisely where it discharges and how rapidly it water-borne contaminants may be transported.

The area of interest is part of the Northern Guam Lens Aquifer (NGLA), an island karst aquifer (cf. Mylroie and Vacher, 1999) composed of very permeable Cenozoic limestone, in which water not only infiltrates rapidly and percolates downward through the bedrock matrix as diffuse flow, but can also travel to the water table much more rapidly as concentrated vadose fast flow from closed depressions, or sinks (Jocson et al., 2002). Numerous small sinks are located on the airport surface. However, most of the runoff from the airport is diverted to the Harmon Sink, which is one of the largest and most well known sinks in northern Guam.

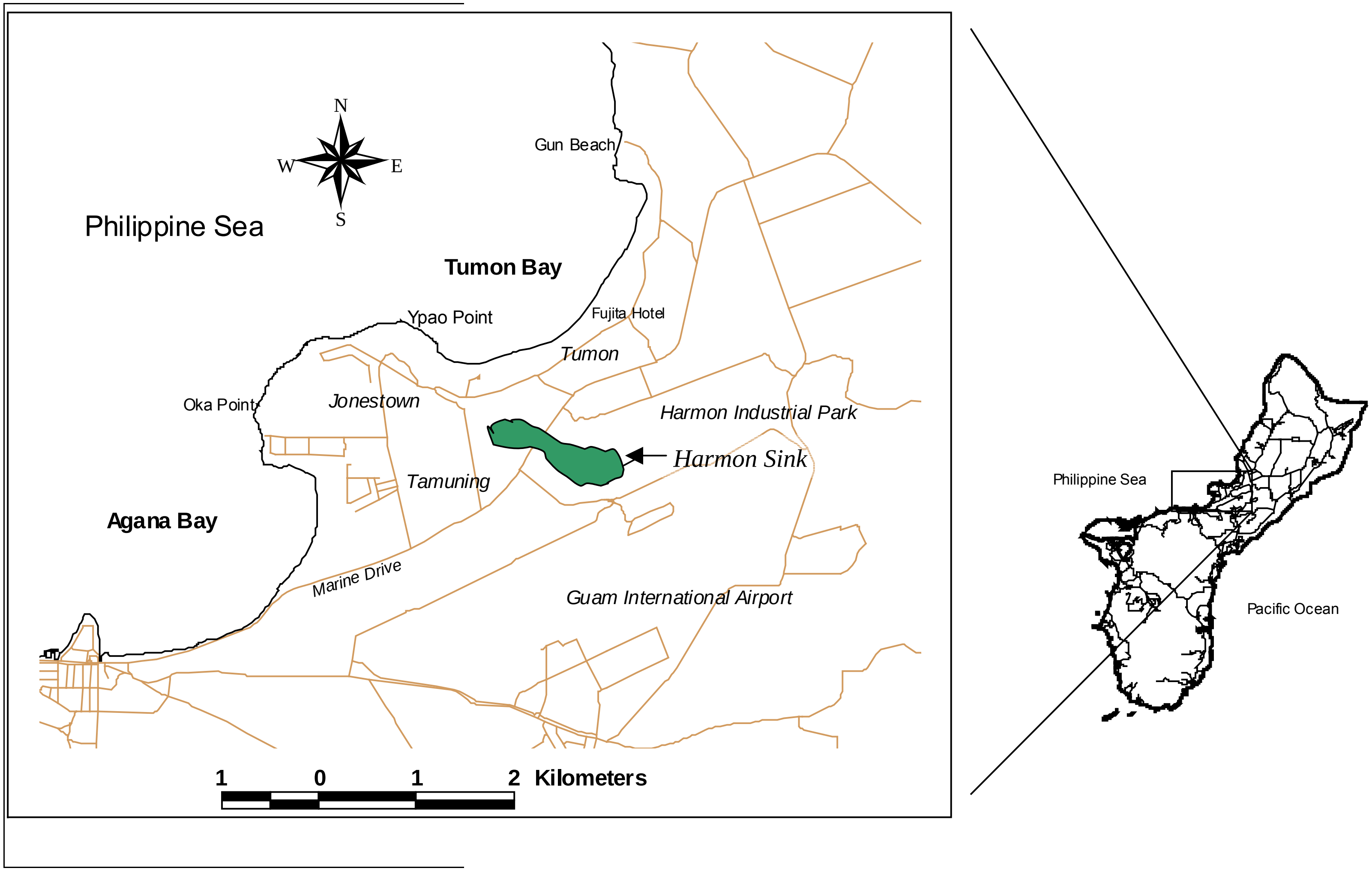

Figure 1. Research area showing Agana Bay, Tumon Bay, Harmon Sink, Guam International Airport, and key landmarks.

Climate and Hydrogeology of Guam

Climate

Guam's climate is tropical wet-dry with a mean annual maximum temperature of 30.5º C and a mean annual minimum temperature of 24.5º C (National Weather Service Forecast Office, Tiyan, Guam, www.prh.noaa.gov/guam). The wet season extends from June through November, and the dry season from December through May (Fig. 2). Precipitation measured at the National Weather Service (NWS) station at the airport averages 2.2 m yr^{-1} with the mean monthly precipitation ranging from 7 cm in February to greater than 36 cm during September. Monthly precipitation during the study period is shown in Figure 3. Twenty-four cm of rain fell on the research area during the 2 weeks of 6-20 September 2000, prior to the dye injections (20 and 22 September 2000) (Fig. 4).

Hydrogeology

The southern half of Guam is dominated by deeply dissected volcanic uplands, while the northern half is a plateau composed primarily of two uplifted limestone units: the Mariana Limestone and the Barrigada Limestone (Tracey, et al. 1964). The Mariana Limestone is a barrier and fringing reef deposit, which comprises the ramparts and cliffs of the northern plateau. Stratigraphically beneath the Mariana Limestone is the Barrigada Limestone, a unit of deeper water lagoonal origin, which comprises the core of the NGLA. The plateau slopes gently to the southeast, and is cut by numerous normal faults. Hydrologic pathways in young limestones such as the NGLA are complex. Vacher and Mylroie (2002) have presented evidence that in addition to matrix and fracture porosity, aquifers in young limestones exhibit important secondary porosity consisting of touching-vug channels and dissolution-enhanced passageways that lace through the less porous, but nevertheless very permeable matrix.

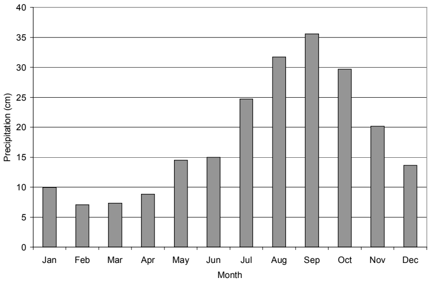

Figure 2. Precipitation Summary (1956-2000) recorded at the Airport National Weather Service Station, Tiyan, Guam.

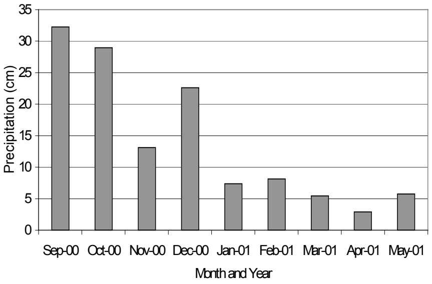

Figure 3. Monthly total rainfall recorded at the Airport National Weather Service Station for the period of this study.

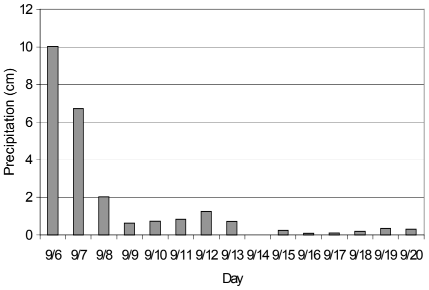

Figure 4. Precipitation for the 2 week period prior to the September 20 injection.

Related Previous Research

An early study entitled "The Geology of Middle Guam," was performed soon after World War II for the Department of the Navy by Pacific Island Engineers (PIE, 1950). The United States Geological Survey subsequently conducted comprehensive studies of the geology and hydrology of Guam (Cloud, 1951; Emery, 1962; Ward and Brookhart, 1962; Tracey, et al., 1964). Mink (1976) conducted the first in-depth study of the groundwater yield potential of the NGLA. Mink and Lau (1977) evaluated the age of phreatic groundwater by tritium analysis and reported that the oldest groundwater sampled in the NGLA was about five years or younger.

Mink also directed a comprehensive study of the aquifer for Barrett, Harris and Associates in association with Camp, Dresser & McKee, under contract to the Guam Environmental Protection Agency. This report (CDM, 1982), locally known as the Northern Guam Lens Study (NGLS), is still used by local regulators as the baseline study from which to estimate aquifer potential. Mink and Vacher (1997) published a summary paper that highlights the results of the NGLS and subsequent studies.

Groundwater discharge has been documented at various times and places along the coast of northern Guam since the 1960's. Estimates of discharge rates, water chemistry, and water quality have been performed by Emery (1962); Ward et al (1965); Mink (1976); Zolan (1982); Matson (1993); Jenson et al. (1997); Ogden (1998); and Jocson et al. (2002). Matson (1993) conducted a study of discharge and the seasonal chemical content of groundwater discharge along the coast of Guam. Taborosi (1999) made the most recent inventory of coastal springs and seeps, building on the work of Jocson (1998).

Previous studies have shown that groundwater in the aquifer moves readily through the aquifer matrix by diffuse, gradient-driven flow. Most notably, a hydrogeological study (CLEAN, 1995, 1998) conducted for the Navy to support remediation of an area that is now part of the civilian airport, showed that groundwater beneath the airport moves towards Agana and Tumon Bays. Groundwater velocities measured by a flow meter near the northern boundary of the property in MW-03 were 1-3 m/d.

In November 1992, Andersen Air Force Base conducted a dye trace to identify suitable locations for monitoring wells around a landfill closure (AAFBER, 1995; Barner, 1995, 1997). Fluorescein was injected at the middle of the vadose section, some 75 meters below the surface and 60 meters above the water table. Rhodamine WT was injected at the water table. Conditions were extremely wet: some 150 cm of rainfall had been recorded in the preceding three months, including 97 cm in August, near the end of which Typhoon Omar passed directly over the island, and 38 cm in October, during which Typhoon Brian passed nearby. During November, 33 cm more were recorded, including 13 cm on 18 November, with the nearby passage of Typhoon Hunt two days before dye injection. The day of the injection, 20 November, saw 2.5 cm of rainfall. Another 5 cm was recorded on 23 November, three days after the injection, as Typhoon Gay passed by the island. During the first post-injection sampling round, conducted on 23 November, dye receptors from 4 wells ranging from 0.4 to 1.1 km from the injection point showed fluorescent peaks in the fluorescein range of 20-83% above maximum background fluorescence. Notably, samples taken from wells at intermediate locations showed negative results. Barner (personal communication, 1999) interpreted the elevated fluorescence at the 4 wells as positive results based on the uniform timing of the elevated fluorescence in the 4 wells, the remarkably low background fluorescence he observed on Guam, and the fact that no similar peaks were observed at any of the 71 sampling points during the subsequent 31 sampling rounds over the next 14 months. Moreover, the generally wet prior conditions and heavy rainfalls immediately before and after dye injection would have been conducive to maximum transport rates. Calculated minimum mean linear transport rates for the fluorescein were 90-240 m/d (300-790 ft/d). The Rhodamine WT injected in the phreatic zone was detected over a year later at points along the coast to the north, and in the meantime at intermediate points, from which were calculated mean linear travel times of 6-11 m/d (20-36 ft/d). The timing and distribution of detections of the Rhodamine were consistent with dominantly diffuse flow controlled by the local hydraulic gradient. Apparent paths of the fluorescein, on the other hand, were about 90 degrees to the direction of the Rhodamine, and consistent with one of the principal fracture orientations of the island. Based on these results Barner proposed a dual-porosity model for the aquifer….

In another dye trace, conducted on the navy housing area at South Finegayan (OHM, 1995), 5 km north of the study area for this project, dye was injected in an area surrounded by 8 monitoring wells that were placed strategically based on the hydraulic gradient of the area. No dye was detected in any of the wells, even after 170 days, indicating that if the dye had moved it must have followed a discrete conduit of some sort. In a follow-on study, dye was injected into a banana hole 200 m southeast of the original site. The injection was primed and chased with 250 m^3 of water to simulate a large storm event. The dye detected 4 hours later in water samples collected from springs on Tanguisson Beach, 2000 m away. Average linear velocity was thus some 12000 m/d (OHM, 1999).

MATERIALS AND METHODS

Two separate dye injections were made, at sites about 1000 m apart (Fig. 6). The first was a water-table injection of eosine on September 20, 2000, into a monitoring well previously installed on the cliff line of the Airport Housing Area on East Sunset Blvd. The second was a surface injection of fluorescein on September 22, 2000, in Harmon Sink into a pit in a dry streamway along the axis of the sink, and near the end of the Airport open drainage culvert.

Survey of Potential Sampling Sites

Prior to injection, we conducted a detailed survey of the springs and seeps discharging into Agana and Tumon Bay. Many of these have been noted in earlier reports, and most of them were documented and given field names by Jocson (1998), according to the nearest easily recognizable landmark, in most cases major hotels and condominiums. We have followed this practice and retained the names assigned by Jocson, except where the names of the landmarks have changed. Where the landmark was renamed we have assigned the new name to the spring or seep. Locations and names are shown in Fig. 6. GPS-derived latitude and longitude of the collection sites are shown in Appendix A. The results of the survey are described below, in order of occurrence along the coast from the south-westernmost site in Agana Bay to the northeast end of Tumon Bay.

Agana Bay Coastal Spring Survey

Agana Bay is generally west-southwest to west of the injection sites. Alupang Beach Club Stream (Fig. 5) flows into the south end of East Agana Bay near the Alupang Beach Club, forming an erosional channel maintaining a small sand delta on the beach. By some reports the stream was thought to be perennial. We observed, however that flow ceased during the 2001 dry season, on March 23, 2001. (See Fig. 3 for monthly total rainfall record.) Eight hundred meters to the northeast of the Alupang Beach Club Stream in East Agana Bay is Dungca's Stream (Fig. 7). While this stream exhibited very low flow during the dry season of 2001, it never completely stopped. The head of neither stream is exposed; their origins have apparently been covered or altered by development.

Figure 5. Alupang Beach Club Stream discharging through the beach into East Agana Bay.

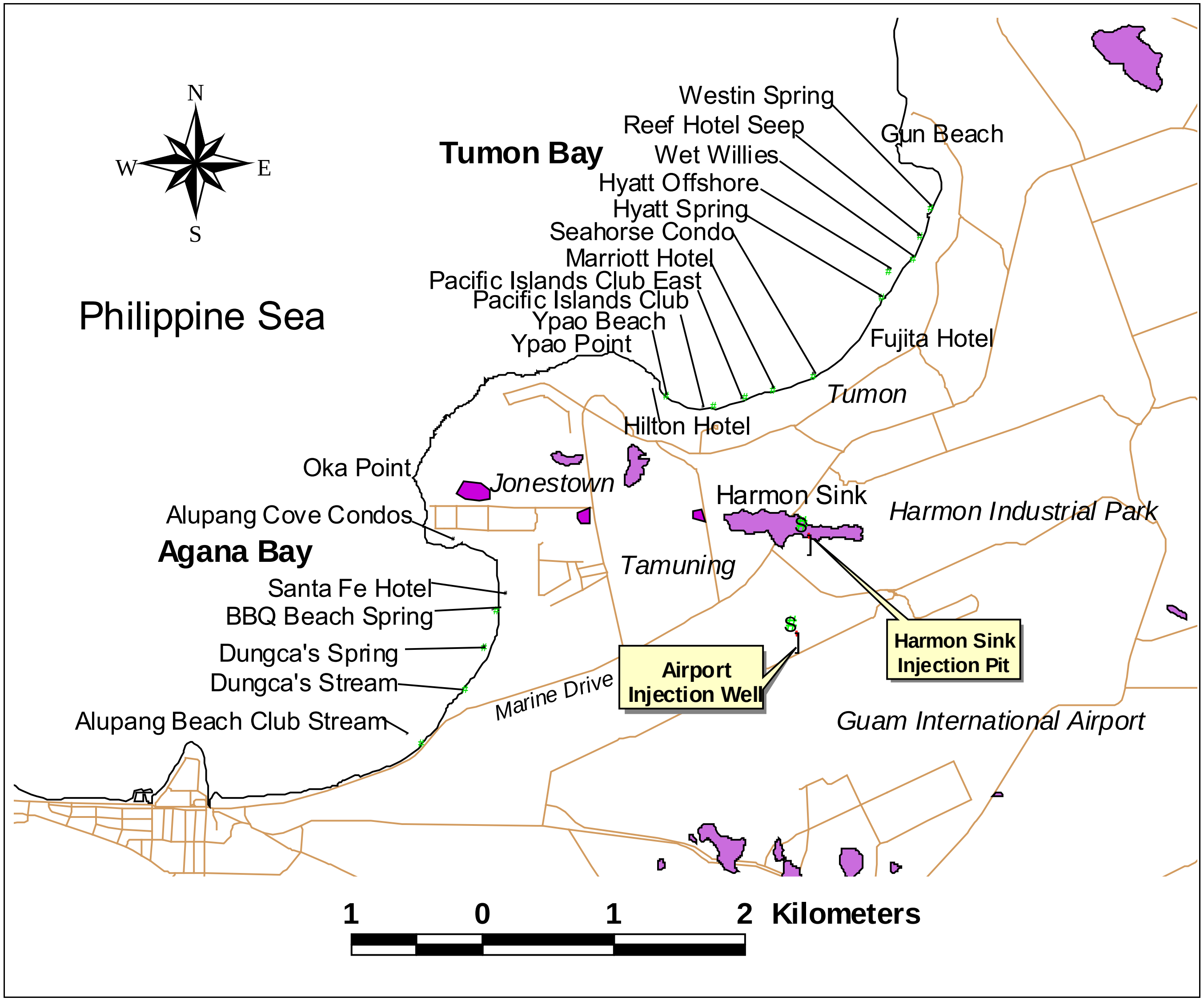

Figure 6: Geographical map showing injection locations and coastal sampling locations.

Between Dungca's Stream and the Santa Fe Hotel to the north are several intertidal and subtidal springs. By far the largest subtidal spring is Dungca's Spring (Fig. 8), which based on comparison with other springs documented by Jocson (1998) probably discharges several 1000 m^3/d. Intertidal seep fields are prevalent all along the beach in both bays. In Agana Bay, they begin on the south side of the Santa Fe Hotel, and extend northwest for 600 meters along the beach to the Alupang Cove Condominium. Several small intertidal springs with observable flow are located in the area from Alupat Island to Oka Point (Fig. 6), with a subtidal spring on Oka Point at the intersection of the cliffs and the reef edge.

Only one subtidal spring was located between Oka Point and the Hilton Hotel. The spring lies slightly to the east of the mid-point between Oka Point and the Hilton Hotel. The point of discharge could not be located because it is behind a large boulder, which causes the flow to disperse over a large area. This, together with the spring's remote location, made it poorly suited as a sampling point for the purposes of this study.

Tumon Bay Coastal Spring Survey

Tumon Bay extends to the northeast from Ypao Point. Beginning southeast of Ypao Point an intertidal seep field extends about 100 meters from the Hilton Hotel property to the pavilion at Ypao Beach. At low tide, seep flow is exposed on beach rock and runs in medium-sized rivulets (10 cm across) to sea level. Jocson (1998) estimated this seep to discharge 7.6 x 10^3 m^3/d.

From the Ypao Beach to the Pacific Islands Club beach, 500 meters eastward, there is little to no flow. Only an outcrop of Mariana Limestone breaks the otherwise continuous sand of the beach. Eastward from the Pacific Islands Club, intertidal seeps are almost continuous for 470 meters to the Marriott Hotel (formerly Pacific Star Hotel). Directly in front of the Marriott Hotel are several intertidal springs with flow estimated by Jocson (1998) to be 1.9 x 10^3 m^3/d (Fig. 9). Intertidal seeps are the dominant discharge style for the next 600 meters from the Marriott Hotel northeast to the Fujita Hotel.

East of the Fujita Hotel is an intertidal beach spring with flow estimated by Jocson (1998) to be 5.7 x 10^3 m^3/d. An almost continuous intertidal beach seep exists for 200 meters from the Fujita Hotel northeast along the beach to the southwestern side of the Hyatt Hotel. A PVC pipe pushed into one of the springs exhibited water flow with at least 6 cm of head (Fig. 10). Dispersed fresh water discharge is also widespread on the reef platform, extending 150 m from the beach to the reef flat behind the modern algal ridge. Fresh water can be seen discharging from small conical mounds of sand, some of which are whiter than the surrounding sand. Excavation of sand near the mounds typically exposes reef flat pavement with fissures and openings through which the fresh water discharges. Additionally, slicks of fresh water from large subtidal springs are easy to see when the surf is calm and there is a slight wind across the surface (Fig. 11).

Between the Hyatt Hotel and the Outrigger Hotel, 225 m to the northeast, there is an intertidal spring known locally as Wet Willies Spring (named by Jocson, 1998, for a beach bar that occupied the site) with flow estimated to be 5.7 x 10^3 m^3/d. Twenty-five meters to the northeast is an intertidal beach spring that forms a channel up to 3 m across and 20 cm deep, with a sand delta extending 20 m seaward from the beach (Fig. 12). Another intertidal spring with flow estimated to be 7.6 x 10^3 m^3 /d (Jocson, 1998) is located 450 m northeast of the Outrigger Hotel, in the front of the Westin Hotel. There are several other subtidal springs that discharge through the reef pavement further north toward the Okura Hotel. However, these springs were decided to be less significant than the Westin spring and were not sampled.

Figure 7. Dungca's Stream discharging through the beach in East Agana Bay.

Figure 8. Dungca's Spring is an intertidal spring that discharges into East Agana Bay.

Figure 9. Intertidal beach spring located on the Marriott Hotel beach (formerly Pacific Star Hotel).

Figure 10. Fresh water flowing from PVC pipe pushed into the substrate in front of the Outrigger Hotel

Figure 11. Fresh water slicks from a subtidal spring, with a depth of 1.5 meters, in front of Hyatt Hotel. (Hilton Hotel is in the background).

Figure 12. Flow from intertidal beach spring in front of the Outrigger Hotel. (Marriott Hotel in the background).

Geologic Survey of the Research Area

In addition to selecting sampling sites along the coast, we also checked and corroborated previous maps of the sinks and faults lying between the sampling area and the injection sites (PIE, 1950; Tracey et al., 1964; Siegrist et al., unpublished.). The features verified from these previous maps are compiled in Fig. 13.

The dominant structural feature of the area is the Campanaya Fault, first mapped by PIE, which trends 100˚ from Oka Point. Several sinks, including Harmon Sink, lie along its axis. An unnamed fault mapped by Siegrist trends 130˚ from the Guam Memorial Hospital, north of Oka Point, curving eastward to join the Campanaya Fault along the axis of Harmon Sink, which extends about 1200 meters with a maximum width of about 200 meters. Marine Drive now bisects the sink across an artificial embankment built to support the road. The embankment blocks east-to-west surface flow in the sink, including sewage discharged from the Mamajanao sewage lift station located within the sink..

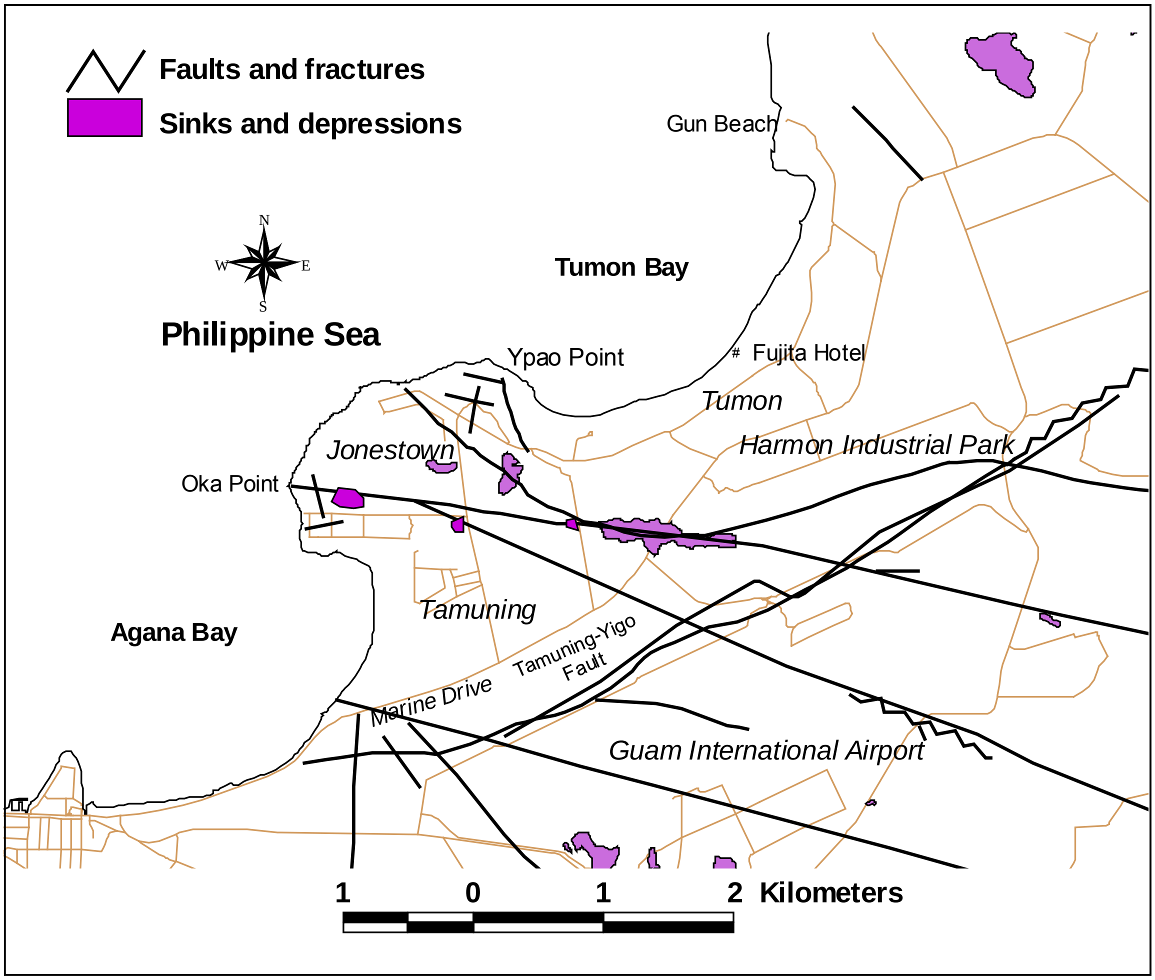

Figure 13. Significant geologic features of the study area (Tracey, 1964; PIE, 1950; Siegrist, unpublished).

Selection of Monitoring Sites

Coastal monitoring sites were selected (Fig. 6) to provide extensive coverage in each bay and to sample the most significant volume discharges. Ten sampling locations (sites 1 through 10, Appendix A and Fig. 6) were selected in Tumon Bay, and four sampling locations (sites 11 through 14, Appendix A and Fig. 6) were selected in Agana Bay.

The first injection site (labeled "Airport Injection Well" Fig. 14) was selected to simulate migration of contaminants entering phreatic groundwater beneath the Airport. The second injection site (labeled "Harmon Sink Injection Pit") was selected to simulate migration of contaminants in surface water discharged into the sink. In addition to the coastal sampling sites shown in Fig. 6, two sampling wells were installed 150 m down-gradient of each injection site. Water table contours mapped by Ogden Environmental and Energy Services Company, Inc. (1998) for a groundwater remediation project on the former naval air station (1998) were used as a basis for inferring regional hydraulic gradient.

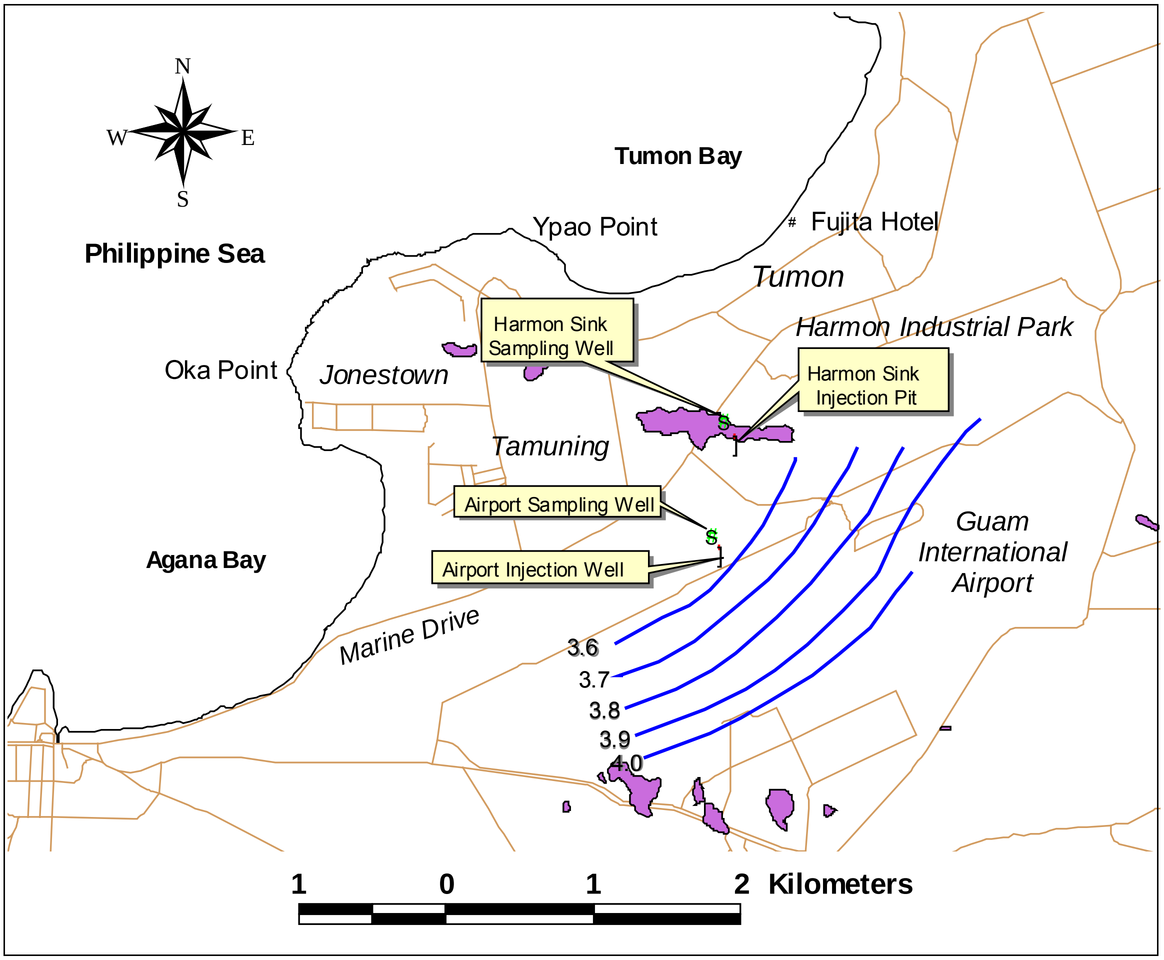

Figure 14. Location of injection points and sampling wells in relation to hydraulic gradient (Ogden 1998).

Background Fluorescence of Natural Waters

Background fluorescence sampling was performed at the 14 Tumon and Agana Bay sampling locations (Appendix A and Fig. 6), following field and laboratory procedures recommended by

Aley (1999), to identify background levels from natural sources so that reliable benchmarks could be established for the detection of injected dye. Qualitative background levels were recorded from activated charcoal receptors left at each of the 14 sites for 24 hours, 3 days, and 4 days, respectively, for a total of 42 samples.

Selection of Tracer Dyes

Eosine and fluorescein and were selected—for the Airport and Harmon Sink injections, respectively—based on their fluorescent intensity, ability to adsorb to the receptors, and the ease with which they could be eluted from the receptors. In addition, both have a high resistance to adsorption to organic and inorganic materials and are detectable at very low concentrations (Aley, 1999).

Eosine also is a complex water-soluble dye that exhibits peak fluorescence in the yellow-orange range of the visible spectrum. When it is exposed to its maximum excitation wavelength of 515 nm, it emits visible light at 539 nm, and its intensity is directly proportional to the concentration of dye. Eosine is detectable in elutant down to 0.050 ppb.

Fluorescein is a complex water-soluble dye that exhibits peak fluorescence in the yellow-green range of the visible spectrum. When it is exposed to its maximum excitation wavelength of 481 nm, it emits visible light at 519 nm, and its intensity is directly proportional to the concentration of dye. Fluorescein is detectable in elutant down to 0.025 ppb.

Quantities and Injection of Dye

On 20 September 2000, at 2:00 p.m., the Airport injection well was primed with 800 liters of water was used to flush and lubricate the well. Eosine dye solution with a specific gravity of 1.0040 was then injected through a hose at 20 Lmin^{-1}. Afterwards, an additional 1600 liters of chase water was added. A total of 5.2 Kg of eosine dye was injected.

On 22 September 2000, at 10:00 a.m., the Harmon Sink injection pit was primed with 9500 liters. Fluorescein dye solution with a specific gravity of 1.0060 was then injected at 20 Lmin^{-1}, while simultaneously adding water at 500 L min^{-1} (Fig. 15). Afterwards, an additional 28,000 liters of chase water was flushed into the injection pit to facilitate the movement of dye through the vadose zone. A total of 37,500 liters of water was used for this injection. A total of 12 Kg of fluorescein dye was injected.

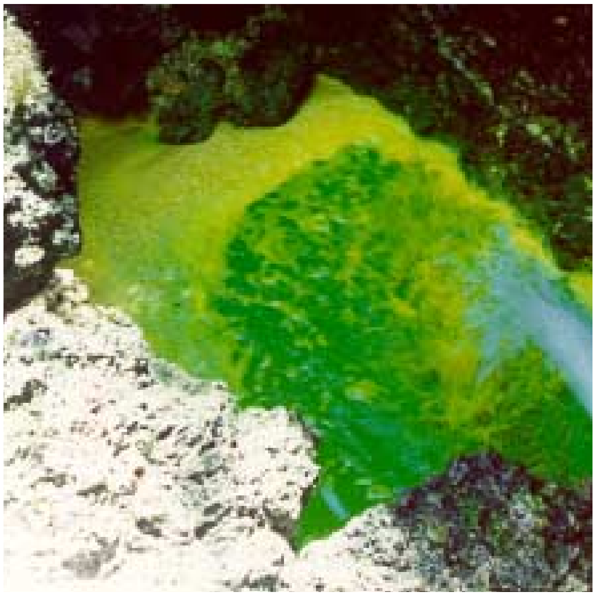

Figure 15. Injection of fluorescein dye into the Harmon Sink injection pit.

Dye Receptors at Sampling Sites

Dye receptors were composed of granulated activated charcoal sealed in a nylon mesh bag. The receptors in Agana Bay, Tumon Bay, and the sampling wells were collected daily at each site for the first twenty days (with the exception of the first three days at the Airport sampling well), every other day for the next thirty days, and weekly over the subsequent five months. Grab samples, used to determine quantifiable levels of dye were collected from each site at the time of receptor replacement and were stored in 9-mL glass vials. Both the receptors and the vials were stored together in resealable plastic bags. Field blanks were included in the collection container for the receptors that were being replaced. Blanks were analyzed to determine if any contamination had occurred during the replacement process. To protect against photochemical decay, each sample was wrapped in aluminum foil immediately after collection.

Receptor Placement Plan

The receptors were attached to 20 cm x 20 cm x 3 cm blocks of concrete and placed in the area of the stream or spring having the highest flow rate. The blocks were secured to concrete pilings or buried in the middle of the streams. The receptors were then attached to the underside of the block to minimize photodegradation. In areas such as streams and large springs, the concrete blocks were placed in the area of direct high-volume discharge and covered with sand and other material to prevent detection and tampering or pilfering.

Sampling Wells

Well receptors were placed in the sampling wells to collect samples from 1.5 meters below the water table (w.t. – 1.5 m) and 15 meters below the water table (w.t. – 15 m). The drilling logs showed the water level in the Harmon Sink Sampling Well to be 20.64 meters below ground surface at 1315 on 5 September 2000 (HLA 2000) and the water level of the Airport Sampling Well to be 46 meters below ground surface at 0930 on 8 September 2000. Unfortunately, the precise elevation of each site is not known, and cadastral surveys were not performed to determine ground elevations from which to compute water table elevations. Water table contours previously mapped for the area by Ogden (1998) were therefore used to estimate the local hydraulic gradient (Figs. 13 and 14).

Lab Procedures

Receptors were dried in an oven at 60º C for 48 hours. Each receptor was opened and the charcoal was poured into a 50 mL plastic vial to be weighed. An eluent solution (to remove dye from charcoal) was made of 70% 2-propanol concentration added to distilled water at a ratio of 7:3 per unit volume. Potassium hydroxide pellets were added to supersaturate the solution forming a supersaturated layer on the bottom of the container. The supersaturated layer was separated from the eluent and not used for elution. This raised the pH of the eluent, further facilitating the removal of dye from the charcoal. The samples were then eluted for one hour with 30 ml of eluent per sample. While the samples were being eluted, eluent or distilled water blanks were placed into a Shimadzu 1501 spectrofluorophotometer to calibrate it to the designated fixed excitation wavelength. The processed samples were then pipetted into 4 mL cuvettes and analyzed. This procedure was repeated for both dyes being tested, and the fluorescence levels were recorded. Fluorescence values were normalized to concentration of dye per gram of charcoal to compensate for the varying amounts of charcoal eluted.

Criteria for Positive Detection of Dye

Based on a review of previous dye trace studies performed on Guam, (AAFBER 1995; Ogden 1996; and O.H.M. 1998), the following conservative detection criteria were adopted to minimize uncertainty in the interpretation of positive results: (1) the intensity of the emission fluorescence must be at least two standard deviations above background fluorescence levels established prior to the dye injection; (2) the sample must exhibit peak emission wavelengths within 2 nanometers (nm) of the maximum peak emission wavelengths established with the dye standards; and (3) the results of a spectrum scan must reveal narrow, symmetrical spectrum peaks consistent with the dye being tested. Background interference typically exhibits low, broad, asymmetrical peaks (Aley, 1999).

RESULTS

Harmon Sink Surface Pit Injection

Harmon Sink Sampling Well

The Harmon Sink sampling well, 155 meters to the northwest of the injection point, was sampled daily immediately following the injection. Fluorescence observed on days 2 and 3 did not meet the spectral criteria for positive detection. The first positive detection occurred on the fourth day after injection (Fig. 16). Positive detections persisted for the next two days, but returned to background levels after day six. Subsequent positive detections of fluorescein were made in the well on days 24 and 37, and from days 91 through 164. Unfortunately, the well was inaccessible from days 12 to 24 and 39 to 91 because the site was inundated with raw sewage from the Mamajanao sewage pump station. After day 112 there was a persistent increase in concentration, spanning an order of magnitude, until day 155. When the final sample for this study was taken on day 164, the concentration was an order of magnitude below the previous maximum. Concentrations observed in the upper l (w.t – 1.5 m) and lower (w.t. – 15 m) sampling levels of the well were usually similar, with only a few significant exceptions.

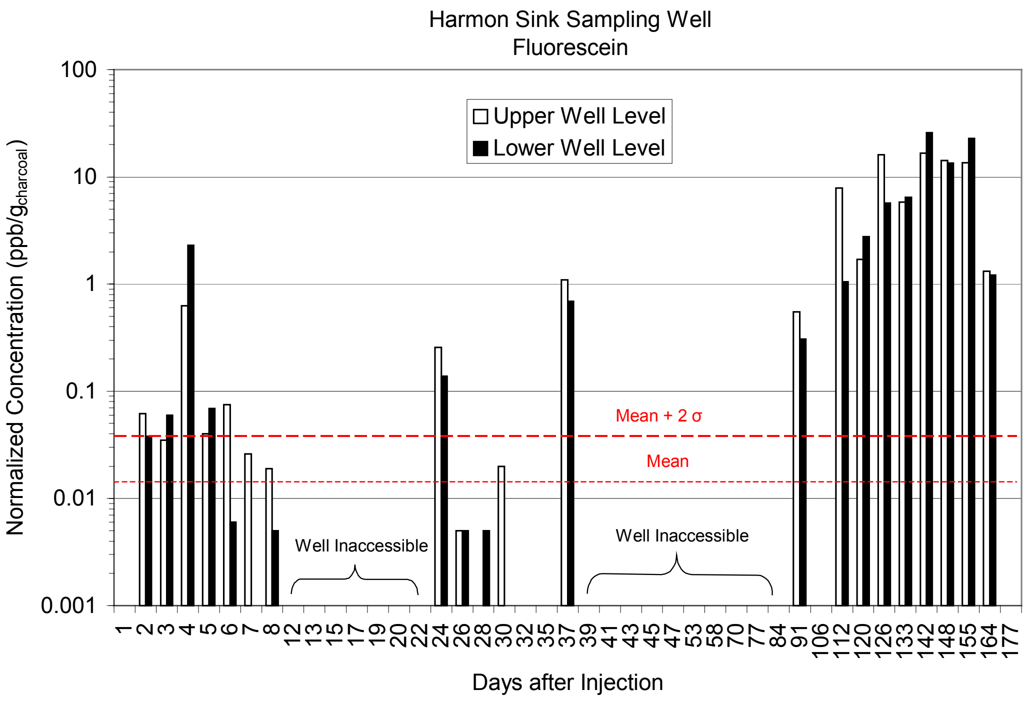

Figure 16. Log_{10} of concentrations of fluorescein dye in Harmon Sink sampling well located 155 m northwest of the injection point. Concentrations measured on days 2 and 3 were interpreted as false positives, based on spectral criteria (see text).

Agana Bay

Fluorescein from the Harmon Sink surface injection was detected at Dungca’s Stream (Figs. 6 & 17), 2500 meters west-southwest of the injection point, on days 4 and 6. Fluorescence observed on days 1 and 164 did not meet the spectral criteria for positive detections, and were thus interpreted as false positives. No dye was detected at Dungca’s Stream for the remainder of the study.

Fluorescein from the Harmon Sink surface injection was detected at Dungca’s Spring (Figs. 6 & 17), 2580 m west-southwest of the injection point, on days 4, 5 and 6. Fluorescence observed on days 1 and 106 did not meet the spectral criteria for positive detections. No dye was detected at Dungca’s Stream for the remainder of the study.

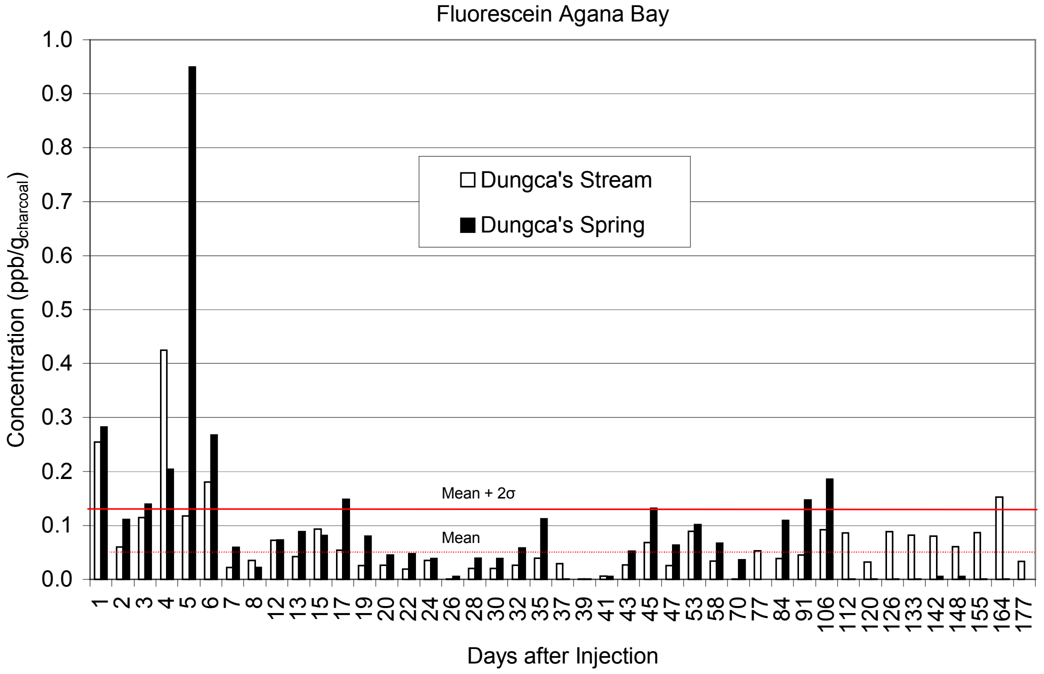

Figure 17. Linear concentrations of fluorescein dye in Agana Bay at Dungca's Stream and Dungca’s Spring. Concentrations measured on days 1 and 164 were interpreted as false positives, based on spectral criteria (see text).

Tumon Bay

Fluorescein was detected in Tumon Bay on day 17 at Ypao Beach, 1600 m from the injection point, and PIC Beach seep, 1200 m from the injection point (Fig. 6 & 18). Fluorescence observed on days 1, 3, 4 and 12 did not meet the spectral criteria for positive detections and were thus interpreted as false positives. No dye was detected at these sites for the remainder of the study.

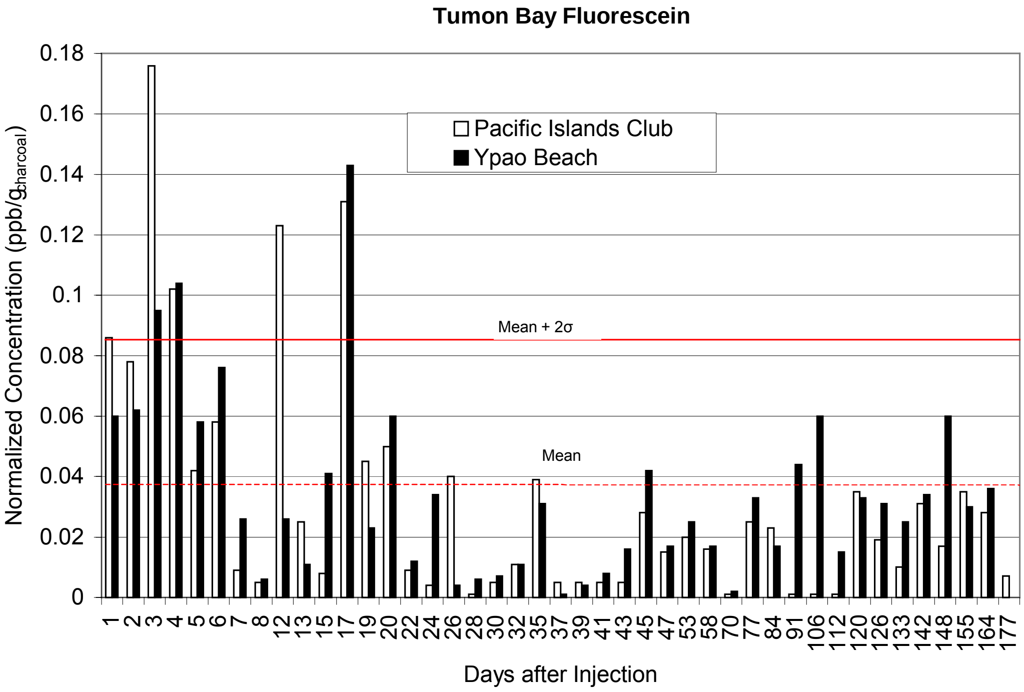

Figure 18. Linear concentrations of fluorescein dye at Ypao Beach and Pacific Islands Club Beach in Tumon Bay. Concentrations measured on days 1, 3, 4 and 12 were interpreted as false positives, based on spectral criteria (see text).

Airport Water Table Injection

Airport Sampling Well

The injection at the Airport Sampling Well was done by a separate contractor to the Airport, who began the injection while the authors were still preparing to take background samples. Background analysis of the groundwater was therefore not performed on the well. The subsequent pattern and extremely high fluorescence observed in samples taken from the well, however, left no doubt about the presence of dye in the well from the third week of sampling and thereafter; by day 60, the white plastic electrical ties used to secure the receptors to the retrieval line were stained red when recovered from the well.

On the fourth day after injection, dye was detected in the Airport Sampling Well, 150 m to the north of the injection site. Day 4 saw the first round of collections at this site, so the actual arrival time of dye could have been anytime from day 1 through day 4. Samples collected from days 10 through 25 contained no dye. The concentrations of dye eluted from the receptors then increased logarithmically, over 4 orders of magnitude, from day 25 through day 169 (Fig. 19).

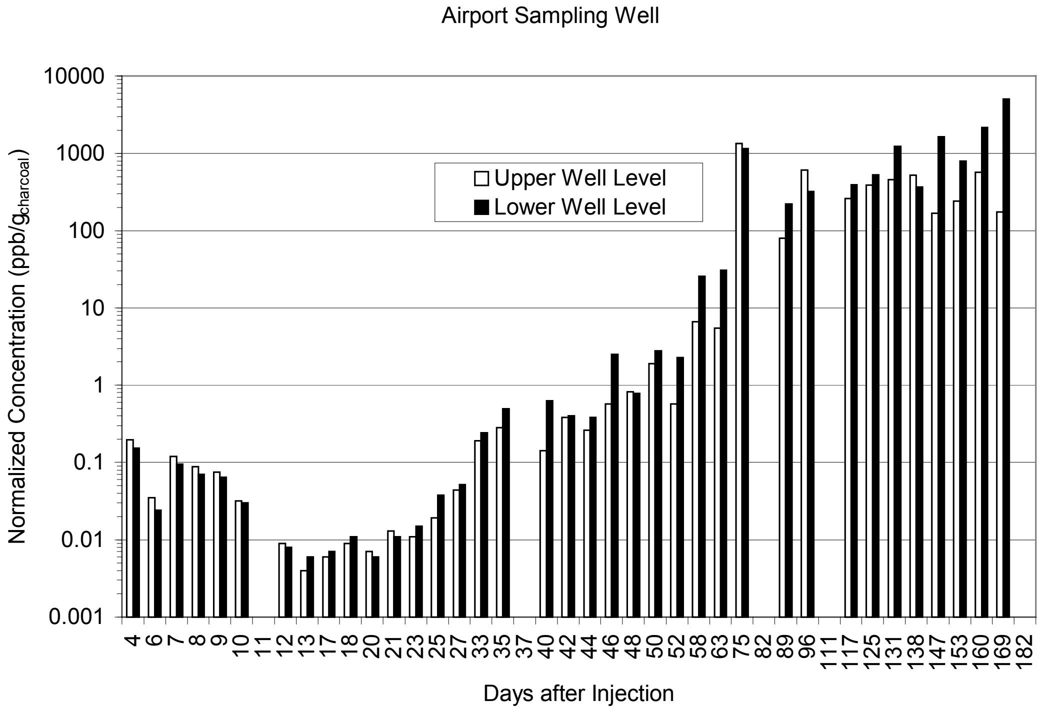

Figure 19. Log_{10} concentrations of eosine dye in Airport Sampling Well.

Agana Bay

Eosine from the Airport water table injection was detected in Agana Bay at Dungca’s Spring and Barbeque Beach Spring (Figs. 6 & 20), 2,200 m to the west-southwest, on the 6th day after injection. Both sites tested positive on days 6 through 27, with the marginal exception at Dungca’s Spring on day 12. Fluorescence observed on days 12, 50, 96, 111 and 147 did not meet the spectral criteria for positive detections. There were no positive detections of dye at either site after day 27.

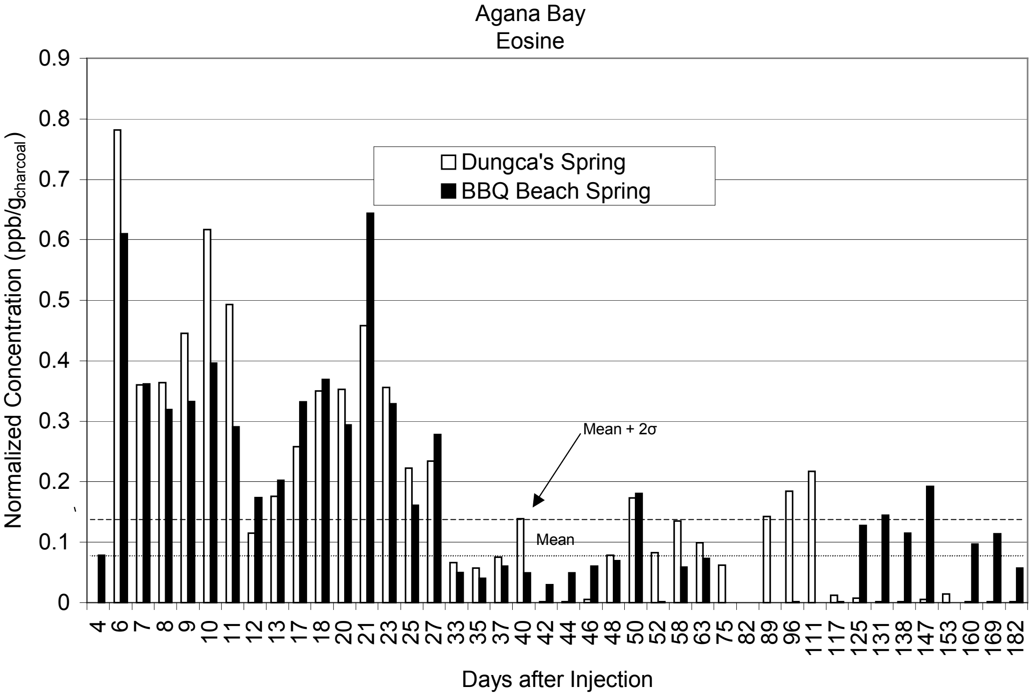

Figure 20. Linear concentrations of eosine dye in Agana Bay at Dungca’s Spring and Barbeque Beach Spring. Concentrations measured on days 12, 50, 96, 111 and 147 were interpreted as false positives, based on spectral criteria (see text).

Tumon Bay

Eosine was detected in Tumon Bay, 1,400 meters to the north of the Airport Injection Well, at Pacific Islands Club beach, on days 8, 17, and 21 (Fig. 6 & Fig. 21). These detections met all three established criteria. Fluorescence observed on days 6, 7, and 9 did not meet the spectral criteria for positive detections. There were no positive detections of dye at either site after day 21 for the remainder of this study.

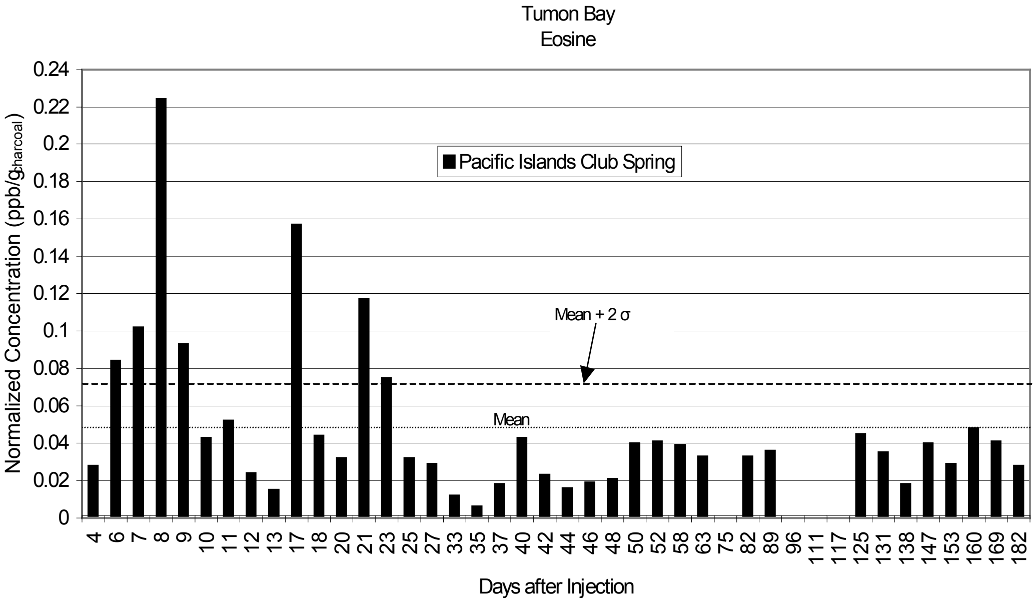

Figure 21. Linear concentrations of eosine dye at Pacific Islands Club Beach in Tumon Bay. Concentrations measured on days 6, 7 and 9 were interpreted as false positives, based on spectral criteria (see text).

DISCUSSION

Harmon Sink Surface Injection

Discharge locations and arrival times for the fluorescein injected in Harmon Sink are summarized in Fig. 22 and Table 1.

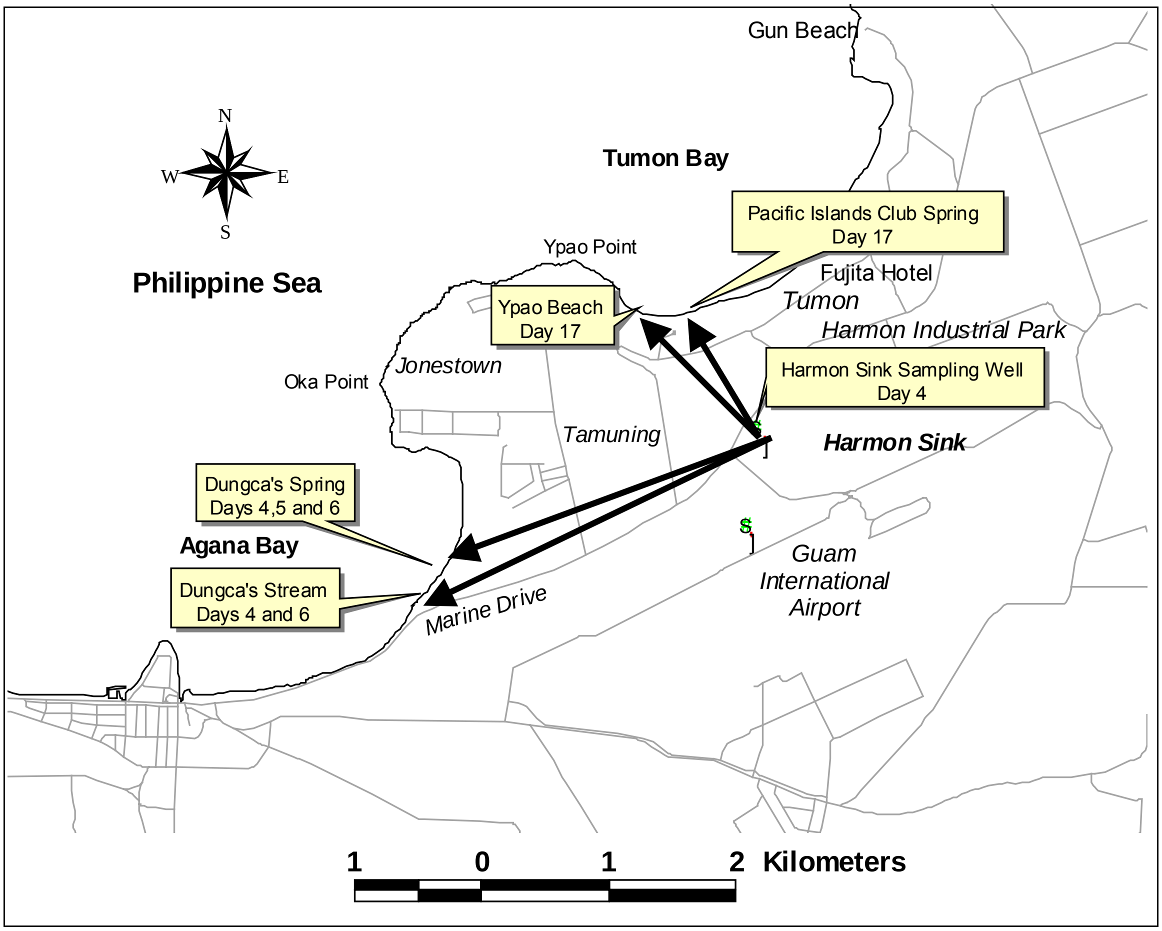

Figure 22. Discharge locations and arrival dates of fluorescein in Agana and Tumon Bays originating from Harmon Sink injection.

Harmon Sink Sampling Well

The calculated apparent minimum straight-line transport velocity for the initial detection of fluorescein in the Harmon Sink Sampling well was 40 m/d (Table 1). The pattern of positive detections on the three consecutive days from days 4 through 6, with dissipation thereafter, suggests that some portion of the dye found its way into a relatively open vadose pathway that extended to the water table near the well. Subsequent persistent increases in concentrations observed following day 91 (Fig. 16) are consistent with movement of the main mass of dye to the north, along the hydraulic gradient mapped by Ogden (1998) (Fig. 13). The positive detections on days 24 and 37 suggest that the main mass arrived much earlier than day 91, but as mentioned above, regular sampling was precluded from days 12 to 24 and 37 to 91 because of sewage discharges into the sink. The order-of-magnitude increase in the dye concentration following day 91, however, suggests an actively moving, but still fairly compact dye mass had intercepted the well by this time.

Table 1. Calculated apparent straight-line transport rates of fluorescein.

Sample location	Straight line distance from Harmon Sink injection point	First day detected	Minimum straight-line transport rates
Dungca’s Stream	2,500 m	4	625 m/d
Dungca’s Spring	2,580 m	4	645 m/d
Harmon Sink Sampling Well	155 m	4	38 m/d
Pacific Islands Club Seep	1200 m	17	70 m/d
Ypao Beach Spring	1600 m	17	94 m/d

Agana Bay

The calculated apparent minimum straight-line transport velocity of the fluorescein detected in Dungca’s Stream and Dungca’s Spring (Figs. 6 and 17) on the fourth day after injection is 625 m/d (Table 1). The flow direction (Fig. 22) is nearly perpendicular to the mapped hydraulic gradient (Ogden, 1998) of the area (Fig. 14), but consistent with regional fracture orientation (Fig. 13). This behavior is similar to that observed during the 1992 Andersen Air Force Base dye trace (AAFBER, 1995), in which a dye injected into the vadose zone was detected in monitoring sites along routes consistent with the regional fracture orientation, and traveled with apparent rates of 400-580 m/d. The pattern of fractures and faults in our study area (Fig. 13) shows a general east-to-west trend, which could provide pathways consistent with rapid transport from the injection point to Agana Bay. It is noteworthy that the Radio Barrigada Fault (Fig 13) terminates near Dungca’s Stream and Dungca’s Spring. Fracture flow would thus explain both the rapid transport observed as well as the transport direction.

Tumon Bay

Fluorescein was detected simultaneously on day 17 the Pacific Islands Club Seep and Ypao Beach Spring (Figs. 6 & 18). The respective apparent minimum straight-line velocities are 70 and 94 m/d. Since sampling was being performed daily, the day of detection is the actual day of arrival. These detections on day 17 could be discharge of the same dye mass that had previously passed through the Harmon Sink Sampling Well on day 4. The northward path to Tumon Bay is nearly perpendicular to the regional fracture orientation, but is consistent with the regional hydraulic gradient. A plausible explanation for the relatively rapid flow in this direction, in spite of it being nearly perpendicular to regional fracture orientation, is flow along dissolution-enhanced secondary pathways, perhaps following the model suggested by Vacher and Mylroie (2002). The simultaneous arrival at these two separate discharge points suggests that the dye may have followed a dominant path for most of the way, diverging into separate paths as it approached the coast.

Airport Water Table Injection

Discharge locations and arrival times of eosine dye originating from the Airport Injection Well are shown on Fig. 23 and Table 2. The dye was injected only 3 meters above the water table in the injection well; therefore, dye is unlikely to have moved laterally through the vadose zone for any significant distance.

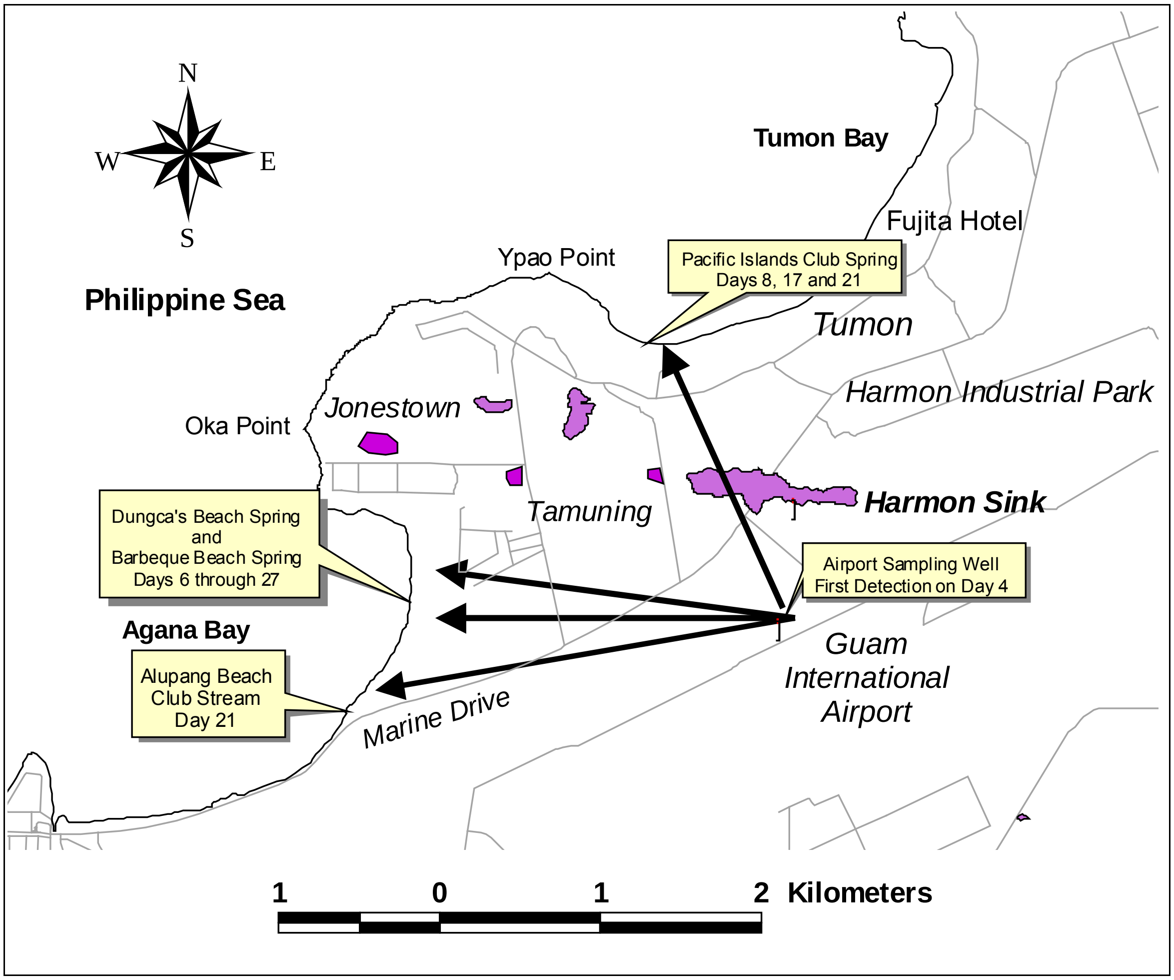

Figure 23. Discharge locations of eosine dye into Agana and Tumon Bays originating from the Airport water table injection.

Table 2. Calculated, apparent straight-line transport rates of eosine.

Sample location	Straight line distance from Harmon Sink injection point	First day detected	Minimum straight-line transport rates
Dungca's Spring	2,175 m	6	360 m/d
Barbeque Beach	2,140 m	6	356 m/d
Airport Sampling Well (Initial Pulse)	150 m	4	38 m/d
Airport Sampling Well (Second pulse of dye)	150 m	27	5 m/d
Pacific Islands Club Beach	1400 m	8	175 m/d

Airport Sampling Well

The minimum apparent straight-line velocity of eosine detected in the Airport Sampling Well on the fourth day after injection is 38 m/d (Fig. 19, Table 2). Because the well was sampled for the first time only on day 4, this is a minimum velocity. The actual velocity could be even higher. The combination of the relatively short duration of the dye in the well and the abrupt decrease in concentration after day 9, suggests that the dye mass found its way into a discrete, relatively open pathway, by which it passed quickly by the sampling well.

The arrival of a second, longer-lived series of detections beginning on day 27 and exhibiting concentrations that increased over 4 orders of magnitude through the end of the observation period suggests that the main mass of dye arrived during the third week following the injection. The calculated minimum straight-line velocity for the occurrence of the first detection on day 27 is 5 m/d. This is consistent with the transport rates of 1-3 m/d calculated for the groundwater beneath the Airport by Ogden (1998). The additional consistency of the transport direction with hydraulic gradient calculated for the Airport by Ogden (1998) suggests that the transport of the main mass of dye from the injection point to the sampling well was by classic darcian flow through the porous bedrock matrix. Such movement is also consistent with the theoretical dual-porosity model of Vacher and Mylroie (2002) for karst in young limestone aquifers.

Agana Bay

The minimum straight-line velocity for the arrival of eosine at Dungca's Spring and Barbeque Beach Spring in Agana Bay beginning on the sixth day after injection (Fig. 20, Table 2) is 360 m/d. The dye moved rapidly west, in a general direction nearly perpendicular to the regional hydraulic gradient. The fact that detections were continual for 21 days is noteworthy. Dye could be converging on these discharge points through multiple routes along an interconnected network, so that arrival times vary while appearing to be continuous. Alternatively, a significant mass of dye may have been held in at some point along the route and released more or less continually through some sort of hydrologic "bottleneck." A third alternative is that the transport rate might be controlled by the timing and amount of recent rainfall. These alternatives are not mutually exclusive. Testing of them will require focused follow-on studies. At this point, however, it can be noted that the geologic map of the area (Fig. 13), when overlain on the map showing the flow direction of the dyes (Fig. 24), shows a pattern of intersecting faults and fractures in this area that could explain the rapid transport towards Dungca's Stream and Barbeque Beach Spring. The 2400 liters of primer and chase water were probably not sufficient to mobilize flow through the fractures, but it is plausible that such flow could have been driven by the 24 cm of rainfall that arrived during the 2 week period prior to injection (Fig. 4).

Tumon Bay

The minimum straight-line transport velocity of eosine to the Pacific Islands Club Beach in Tumon Bay (Fig. 24, Table 2) on days 8, 17, and 21 ranges from 67 m/d for the arrival on day 21 to 175 m/d. for the arrival on day 8. These arrival times are similar to those of the fluorescein from Harmon Sink. Flow direction is consistent with the regional hydraulic gradient, but the rapid and apparently separate arrival times suggest flow along multiple pathways.

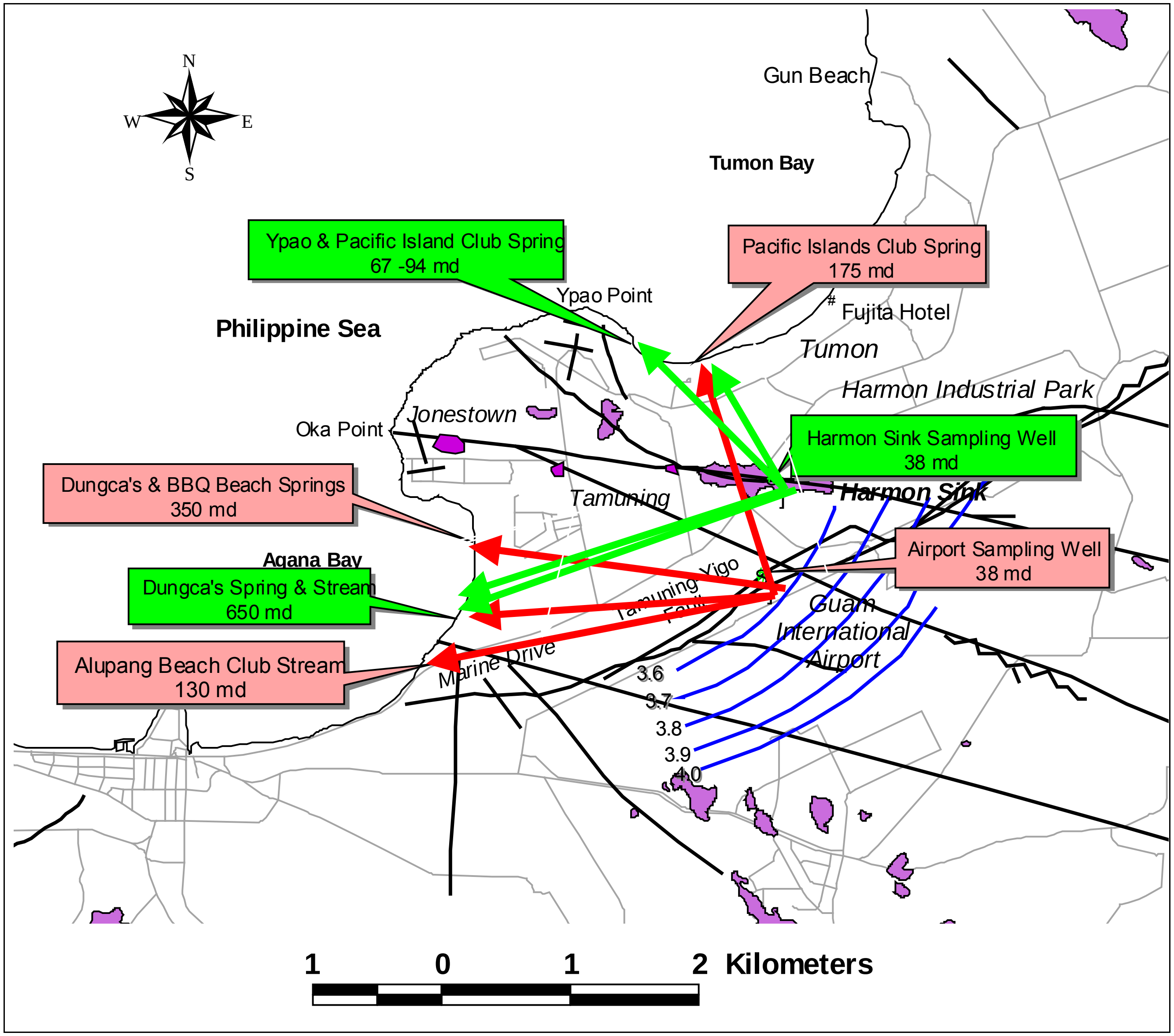

Figure 24. Dye trace results superimposed on hydrogeologic features (Tracey, 1964; PIE, 1950; Siegrist, npublished) and the hydraulic gradient (Ogden, 1998).

CONCLUSIONS

Aquifer porosity

The observations of this dye trace are consistent with theoretical multiple porosity models for karst aquifers (e.g., White, 1999; Worthington, 1999; Vacher and Mylroie, 2002). Fracture control is suggested by the rapid arrival of dye in Agana Bay from both injections along directions nearly perpendicular to the regional hydraulic gradient but consistent to the regional fracture orientation. The apparent transport rates (350-650 m/d) are also similar to those attributed to fracture flow in the 1992 AAFB dye trace (400-580 m/d). The subsequent arrival of dye in Tumon Bay, with apparent linear transport rates ranging from 80 to 175 m/d may reflect flow through multiple, partially interconnected dissolution-enhanced pathways developed in direction of the hydraulic gradient, as proposed by Vacher and Mylroie (2002). Conductivity associated with such features would certainly exceed that of the matrix but would probably be less that that associated with fractures. Finally, transport rates for the of the main dye masses from the injection points to the nearby sampling wells (1-5 m/d) is consistent with gradient-driven diffuse flow through finer matrix porosity.

Implications for contaminant transport

The observations of rapid dye transport to the coast indicate that initial pulses of contaminants released into the water table at the airport or into Harmon Sink could discharge into the recreational waters of Agana and Tumon Bays in a matter of days. On the other hand, contaminants carried by slow diffuse flow through the bedrock matrix may discharge continuously over several month or years. The implications for coastal water quality would depend on the type of contaminant, the concentration, residence time in the aquifer, and residence time in the coastal waters.

Recommendations for follow-on study

Further studies should include:

1. A careful study should be made of background fluorescence in the waters from Agana Bay to north of Double Reef. This would provide a baseline for future studies and negate the need for duplication of efforts in this regard.
2. A dye trace should be performed near the Harmon Annex, where there are frequent large-volume sewage overflows into a local sink, to determine the flow rates and direction from this area. If this study and the previous studies performed are any indication, Tumon Bay could experience contaminant flow from this region of the aquifer. It would also provide needed information on the source of freshwater discharge along the eastern end of Tumon Bay.
3. Testing of dyes should be performed in a laboratory setting with proper controls in place to determine dye characteristics pertinent to a complete understanding of their physical limitations. The characteristics of photochemical decay, effective rates of adsorption to activated charcoal, detection limits in distilled water, groundwater, salt-water, brackish water, and the effectiveness of varying eluents in each of these conditions should be examined. Additionally, the rate of absorption/adsorption to limestone substrates should be examined.
4. A dye injection should be designed, performed, and modeled to more precisely determine the location of the hydrologic divide that apparently exists in the area between Agana Bay and Tumon Bay. From this data, a more precise model of the potentiometric surface could be designed that could help in identifying sources of contaminants entering the aquifer in this region.

5. Fracture orientation appears to play a role in the rapid transport of dye to the coastal discharge points. By putting a dye into one of these features and monitoring it, we would have a better understanding of the role that fractures play in dye transport.
6. An array of shallow monitoring wells placed in beach deposits in Agana Bay and Tumon Bay should be installed. These would provide relatively inexpensive and accessible points in which we could monitor flow of dyes and contaminants in these two areas. Data from these findings could provide a basis from which to develop and implement sound environmental policies with regard to our recreational waters.
7. Bacterial levels in discharging spring waters that enter into Agana Bay should be monitored to determine the influence of contaminants entering from these sources.
8. A comprehensive survey of discharge styles and volumes that exist between the beach and the shallow fore-reef area of both Tumon and Agana Bays.

GLOSSARY

Adsorption. The attraction and adhesion of a layer of ions from an aqueous solution to the solid mineral surfaces with which it is in contact.

Advection. The process by which solutes are transported by the motion of flowing ground water.

Aquifer. Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.

Average Linear Velocity. The rate of movement of fluid particles through porous media along a line from one point to another.

Discharge. The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.

Dispersion. The phenomenon by which solute in flowing ground water is mixed with uncontaminated water and becomes reduced in concentration. Dispersion is caused by both differences in the velocity that the water travels at the pore level and differences in the rate at which water travels through different strata in the flow path.

Dissolution. The change of matter from a solid state to a liquid state by combination with a liquid.

Epikarst. A relatively thick portion of bedrock that extends from the base of the soil zone and is characterized by extreme fracturing and enhanced solution. It is separated from the phreatic zone by an inactive, relatively waterless interval of bedrock that is locally breached by vadose percolation. Significant water storage and transport are known to occur in this zone. Synonym for subcutaneous zone.

Homogenous. Pertaining to a substance having identical characteristics everywhere.

Hydraulic Gradient. The change in static head per unit of distance in a given direction.

Hydraulic conductivity. Coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

Isotropic. The condition in which hydraulic properties of the aquifer are equal in all directions.

Karst. The type of geologic terrain underlain by carbonate rocks where significant solution of the rock has occurrence due to flowing ground water.

Phreatic. The portion of the aquifer below the water table.

Permeability. The ability of a medium to transmit a fluid through a porous medium.

Sinkhole (sink). A shallow place or depression where drainage collects.

Slick. Something that is smooth or slippery; A smooth spot on the water.

Talus slope. A collection of disintegrated rock material forming a slope at the base of a cliff or steep incline.

Vadose zone. The zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Also called zone of aeration and unsaturated zone.

Water table. The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells.

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APPENDIX A

AGANA LOCATIONS	**NORTH LAT**	**EAST LON**
Alupang Beach Club Stream	13.4807°N	144.7678°E
Dungca’s Stream	13.4856°N	144.7721°E
Dungca’s Spring	13.4877°N	144.7722°E
BBQ Beach Spring	13.4889°N	144.7726°E
TUMON LOCATIONS		
Ypao Beach	13.5040°N	144.7850°E
Pacific Islands Club	13.5034°N	144.7900°E
Pacific Islands Club East	13.5037°N	144.7910°E
Marriott Hotel	13.5042°N	144.7927°E
Seahorse Condo	13.5044°N	144.7938°E
Hyatt Spring	13.5120°N	144.8010°E
Hyatt Offshore	13.5132°N	144.8016°E
Wet Willies	13.5137°N	144.8023°E
Reef Hotel Seep	13.5157°N	144.8029°E
Westin Spring	13.5171°N	144.8036°E
SAMPLING WELLS		
Airport Upper Level (w.t. – 1.5 m)	13.4880°N	144.7920°E
Airport Lower Level (w.t. – 15 m)		
Harmon Sink Upper Level (w.t. – 1.5 m)	13.4954°N	144.7944°E
Harmon Sink Lower Level (w.t. – 15 m)		