Ground Water Monitoring&Remediation

Groundwater Monitoring on Guam: Management Responses to Recent Water Quality Violations

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Abstract

Guam has one of the finest limestone aquifers in the world. Located in the northern half of the island, this vital underground resource supplies the local community with about 80% of its drinking water needs. The majority of the island's approximately 180,000 inhabitants live in the northern half of the island where significant economic growth and urban development have occurred over the last 30 years. The U.S. military has also occupied large tracts of land in this region for the past 60 years. The risks of groundwater contamination are, therefore, very real considering the population density in northern Guam and the rapid recharge rates to the underlying aquifer. Since April 1996, Guam Waterworks Authority (GWA) has regularly monitored the island's drinking water resources for chemical and biological contaminants in accordance with the U.S. Safe Drinking Water Act requirements. This report summarizes and compares the groundwater data sets for two discrete time intervals: 1996 through 2001 and 2002 through 2007 for chemicals, and 1997(8) through 2002 and 2003 through 2007 for bacteria. Adaptive management strategies that evolved to deal with contaminant violations over this time frame are critically discussed. Overall, 95% of all GWA's drinking water production wells were considered to be in relatively good shape from a chemical standpoint. Identified chemicals of concern were chlordane, ethylene dibromide, perchloroethylene, trichloroethylene, and nitrate. The microbiological integrity of Guam's groundwater was, by comparison, less impressive prior to 2003 because of numerous wastewater spills, leaks, and overflows. Improved management practices introduced shortly afterward have significantly reduced the incidence of *Escherichia coli* contamination in recent years.

Introduction

Guam (13°28'N, 144°45'E) is a small island that lies in the tropical western Pacific approximately 2000 km due east of the Philippines. It is about 50-km long, 6- to 14-km wide and covers an area of approximately 550 square km. The geology and corresponding topography divides the island into two distinct regions that determine the nature of the predominant water resources within each. Steep volcanic hills and well-defined river valleys cut through highly weathered volcanic soils in the southern half of the island, whereas a highly porous limestone plateau, derived from ancient coral reefs, covers the basement volcanics in the north. The natural aquifer that has evolved within this latter structure provides approximately 80% of island residents (~180,000 people) with their daily drinking water requirements. The remaining 20% of the population rely almost exclusively upon surface waters obtained from the south.

Although Guam regulators and water resource managers have collectively monitored the chemical and biological integrity of the island's groundwater since the late 1970s, efforts were largely sporadic and data sets incomplete until April 1996, when sufficient funds were set aside for the comprehensive monitoring program that is currently in place. This paper summarizes and compares the chemical and microbiological data sets for two approximately equal sampling intervals over the period 1996 through 2007, and briefly discusses remediation and adaptive management strategies where appropriate.

Materials and Methods

The Guam Waterworks Authority (GWA) monitors Guam's groundwater resources for 67 regulated chemicals, 32 unregulated chemicals, and 2 microbiological contaminants to meet the requirements of the National Primary Drinking Water Regulations (NPDWR) and the Guam

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Primary Safe Drinking Water Requirements (GPSDWR). Sampling for chemical analyses is conducted in accordance with the USEPA Standardized Monitoring Framework (SMF) introduced in 1991 and implemented nationwide in 1993 (USEPA 2004). The SMF is divided into 9-year monitoring cycles, for example, 1993 to 2001, 2002 to 2010, etc. Each cycle is further divided into three 3-year monitoring periods. All GWA production wells are required to be monitored for all regulated and nonregulated contaminants during the first monitoring period of each cycle. Monitoring frequencies during the second and third monitoring periods are dependent upon contaminant and levels previously encountered as summarized in Table 1.

Funding constraints prevented GWA from initiating the chemical monitoring program until 1996. As a consequence, the agency adopted a slightly modified approach to that outlined earlier to complete all sampling requirements of the first SMF cycle by December 2001. Quarterly monitoring of all groundwater wells for the two microbiological contaminants began in 1997 and 1998 for total coliforms and *Escherichia coli,* respectively. Currently, GWA draws water from approximately 125 production wells, although not all are up and running in any 1 year. Water from these wells (~45MGD) feed into a blended distribution system and is piped directly to consumers. Thus, chlorination and any clean-up process takes place solely at the well head.

Results and Discussion

Chemical Contaminants

The total numbers of wells showing positive detections for specific regulated and nonregulated chemicals over the 1996 through 2007 sampling period are shown in Table 2. Also listed is the total number of times each contaminant was detected (hits), plus the concentration range and median value for each. Of the 24 regulated chemicals detected, five occurred in one or more wells at levels ≥50% of the maximum contaminant level (MCL) and were considered contaminants of concern. These were chlordane, ethylene dibromide (EDB), perchloroethylene (PCE), trichloroethylene (TCE), and nitrate. Data summaries for these contaminants over the 1996 through 2002 and 2003 through 2007 sampling intervals are presented in Table 3, along with the total number of ≥50% MCL and ≥MCL exceedences recorded for each period.

Although GWA pays close attention to any well yielding contaminant levels ≥50% MCL, the monitoring frequency continues at quarterly intervals until the yearly running average exceeds MCL, when the impacted well is immediately shut down. Initially, there was no established policy to determine what happens next, and as a consequence, costly, ineffective, or unnecessary corrective measures were sometimes implemented. Lessons learned from these early experiences subsequently evolved into the adaptive management strategy that currently prevails, whereby wells in violation and taken off-line, continue to be monitored on a monthly basis until 12 consecutive values <50% MCL are obtained. At this point, the well may be brought back on-line with the approval of the Guam Environmental Protection Agency (GEPA). Monitoring is continued on a monthly basis for the life of the well, or until such time as 12 consecutive nondetects are reported, after which, quarterly monitoring may be resumed with GEPA approval. This policy is independent of any remediation strategy implemented. In situations where there is no long-term improvement in contamination,

Table 1
Standardized Monitoring Framework for Chemical Analyses of Groundwater

Contaminant	Sampling Point	Required Monitoring Frequency	Frequency Increase Trigger
Synthetic Organic Chemicals	After treatment entry point to the distribution	Four consecutive quarters initially, then two quarters in one year of each compliance period for the remainder of the cycle	If levels ≥Maximum Contaminant Level (MCL): further sampling conducted on a quarterly basis until levels <MCL for period determined by Guam EPA
Volatile Organic Chemicals	as above	Four consecutive quarters initially, then annually for the compliance period, then once per compliance period for the remainder of the cycle	If levels ≥MCL: further sampling conducted on a quarterly basis until levels <MCL for period determined by Guam EPA
Inorganic Chemicals	as above	Triannually	If levels ≥MCL: further sampling conducted on a quarterly basis until levels <MCL for three consecutive quarters
Nitrate	as above	Annually	If levels ≥50% MCL: further sampling conducted on a quarterly basis until levels <50% MCL for three consecutive quarters
Nitrite	as above	Triannually	If levels ≥50% MCL: further sampling conducted on a quarterly basis until levels <50% MCL for three consecutive quarters

Table 2

Chemicals Detected at Least Once in One or More of GWA's Drinking Water Production Wells

Synthetic Organic Chemicals	Total		Concentration (µg/L)		
	Wells	Hits	Range	Median	MCL[2]
Regulated					
Pesticides					
Chlordane	64	599	0.02–3.4	0.23	2
Dibromochloropropane	1	1	0.01	—	0.2
Endrin	31	151	0.01–0.3	0.01	2
Ethylene dibromide	1	7	0.01–0.12	0.11	0.05
Heptachlor	3	3	0.01–0.02	0.01	0.4
Heptachlor epoxide	24	61	0.01–0.05	0.01	0.2
Herbicides					
Atrazine	3	10	0.05–0.07	0.06	3.0
Dalapon	3	3	6.5–9.5	7.8	200
Picloram	8	32	0.1–0.9	0.4	500
2,4-D	2	2	0.1–0.5	0.3	70
Pthalate Esters					
Di(ethylhexyl)-adipate	1	1	3.2	—	400
Di(ethylhexyl)-phthalate	20	23	0.6–2.8	0.9	6
Unregulated					
Pesticides					
Aldrin	4	7	0.01–0.01	0.01	—
Dieldrin	88	875	0.01–1.6	0.05	—

Volatile Organic Chemicals	Total		Concentration (µg/L)		
	Wells	Hits	Range	Median	MCL[2]
Regulated					
Solvents					
Carbon tetrachloride	4	17	0.5–2.9	0.7	5
Dichloromethane	4	4	0.6–2.2	1.7	5
Perchloroethylene	11	115	0.2–7.7	1.3	5
Trichloroethylene	12	193	0.05–4.8	0.9	5
THMs					
Total THMs	59	526	0.5–57.4	1.8	80[4]
Unregulated					
Solvents					
Bromomethane	2	2	0.6–0.7	0.7	—
Chloromethane	1	1	3.1	—	—
Dibromomethane	2	2	0.7–1.6	1.2	—
THMs					
Bromoform	34	66	0.5–34.0	1.6	—
Bromodichloromethane	33	88	0.5–12.0	1.3	—
Chlorodibromomethane	32	51	0.5–21.0	0.9	—
Chloroform	44	420	0.5–18.3	1.4	—

Inorganic Chemicals	Total		Concentration (µg/L)[1]		
	Wells	Hits	Range	Median	MCL[2]
Regulated					
Metals					
Antimony	2	4	1.0–3.8	1.6	6
Arsenic	21	25	1.0–14.0	1.5	10
Barium	22	63	2.0–66.0	3.5	2000
Chromium	119	273	0.2–27.0	4.1	100
Copper[3]	48	57	0.75–25.0	3.5	1300[4]
Lead[3]	33	39	0.4–4.5	0.78	15[4]
Mercury	2	2	0.29–0.75	0.52	2
Nickel	41	46	5.0–22.0	6	100
Selenium	1	1	14.0	—	50
Others					
Fluoride	49	98	0.05–0.40	0.10	4
Nitrate-N	124	754	0.1–5.0	2.5	10
Unregulated					
Others					
Sulfate	118	285	2.1–270	9.4	—

[1]Concentrations for fluoride, nitrate-N, and sulfate as mg/L. [2]MCL = maximum contaminant level, an enforcable standard prescribed under the NPDWR for regulated contaminants only. [3]Lead and copper analyses of source water are not required under the NPDWR and GPSDWR, however, levels of both elements were determined in well water samples collected in 2005 and 2006 and are included here for reference purposes only. [4]Action Level in distribution system only.

the impacted well may be either remediated, or capped and abandoned, depending upon its importance to the distribution system.

Of the five contaminants of concern referred to earlier, MCL violations were recorded for chlordane (pesticide), EDB (soil fumigant and gasoline anti-knock ingredient), and PCE (industrial solvent) only, with single wells being affected in each case (Table 3). Adaptive management strategies implemented by GWA in response to these violations are described below in the chronological order in which they occurred. The location of each well referred to in the text is shown in Figure 1.

The hitherto unknown presence of EDB in well F-8, a high production well in the north of the island (Figure 1) precipitated the very first MCL violation that GWA has ever had to deal with. The initial water sample taken from this well in May 1996 yielded an EDB value of 0.12 µg/L (more than twice MCL). Monthly samples taken thereafter were similarly high resulting in the well being taken off-line 5 months later with no further monitoring after February 1997. In the absence of nearby wells to make up for production losses to the distribution system in this part of the island, the remediation plan adopted by GWA was to install a granulated activated charcoal (GAC) filter at the well head as quickly as possible (total cost ~$200,000). This was completed in April 1999 and the well brought back on-line soon after.

Ironically, EDB has not been detected in unfiltered F-8 source water since monitoring resumed. In retrospect, this adaptive management strategy was perhaps not the most cost-effective choice in light of EDB's rapid disappearance, although GWA appears to have adopted a conservative approach toward the protection of public health. Nevertheless, clues that the chemical was rapidly attenuating prior to the GAC installation were available from the last two 1997 samples that returned low levels of 0.03 µg/L. Had monitoring continued for another 6 months, a clearer picture would almost certainly have emerged given the compound's relatively high mobility in soil (log Koc: 1.8; Rogers and McFarlane 1981). In addition, the fact that F-8 was the only EDB contaminated well on Guam clearly indicated the limited extent of the contamination and was another important clue that was missed.

The case history described earlier draws some interesting parallels with a prior TCE problem in well NAS-1 in central Guam (Figure 1). The well previously belonged to the U.S. Navy, who transferred ownership to the government of Guam in 1995. Because the well had a history of MCL violations for TCE and had been shut down for a number of years, a condition of transfer set by GWA was that it be fitted with a GAC filter at the U.S. Navy's expense ($1.2 million). This was eventually agreed to and the well was brought back on-line in July 1998. Although this industrial solvent continues to be detected in unfiltered source water, no further MCL violations have occurred to date, which suggest that levels are attenuating in this part of the aquifer. This seems a reasonable assumption given that TCE is relatively mobile in soils (log Koc: 2.0-2.6; Garbarini and Lion 1986). It could also explain the notable decline in the number of TCE impacted wells on Guam in recent years (Table 3).

The widespread occurrence and increasing presence of chlordane in Guam's aquifer is, potentially, the most serious chemical contamination problem that GWA will have to deal with in the future. This pesticide was popularly used as a termiticide in the construction business on Guam until it was banned by USEPA in 1983. Although chlordane has a high sorption affinity for organic material, and is not readily leached from soil (log Koc: 3.49-4.64; Lyman 1982) information gathered to date suggests it is slowly migrating down through the soil profile into the aquifer with each successive wet season. Between 1996 and 2001, for example, chlordane was detected in 30 wells compared with 58 by the fourth quarter of 2007. Although samples from several wells yielded values >50% MCL over this 12-year period, the only MCL violation occurred

Table 3
Chemicals of Concern in GWA's Drinking Water Production Wells

		Total		Concentration (µg/L)[1]		Quarterly Exceedences	
Contaminant	Sampling Interval	Hits	Wells	Range	Median	≥50% MCL	≥MCL
Chlordane	1996–2001	283	30	0.07–1.9	0.24	18 (1 well)	0
	2002–2007	316	58 (34 additional)	0.02–3.4	0.23	15 (5 wells)	3 (1 well)
Ethylene dibromide (EDB)	1996–2001	10	1	0.01–0.12	0.1	2	6 (1 well)
	2002–2007	0	0	all <0.01	<0.01	0	0
Perchloroethylene (PCE)	1996–2001	53	4	0.2–7.7	2.0	18 (2 wells)	3 (2 wells)
	2002–2007	62	10 (7 additional)	0.5–7.3	1.0	8 (2 wells)	3 (1 well)
Trichloroethylene (TCE)	1996–2001	114	12	0.5–4.7	0.9	4 (2 wells)	0
	2002–2007	79	5 (0 additional)	0.5–4.8	0.8	7(1 well)	0
Nitrate-N[1]	1996–2001	165	105	0.3–4.5	2.3	0	0
	2002–2007	588	122 (19 additional)	0.1–5.0	2.6	1	0

[1]Data for Nitrate-N as mg/L.

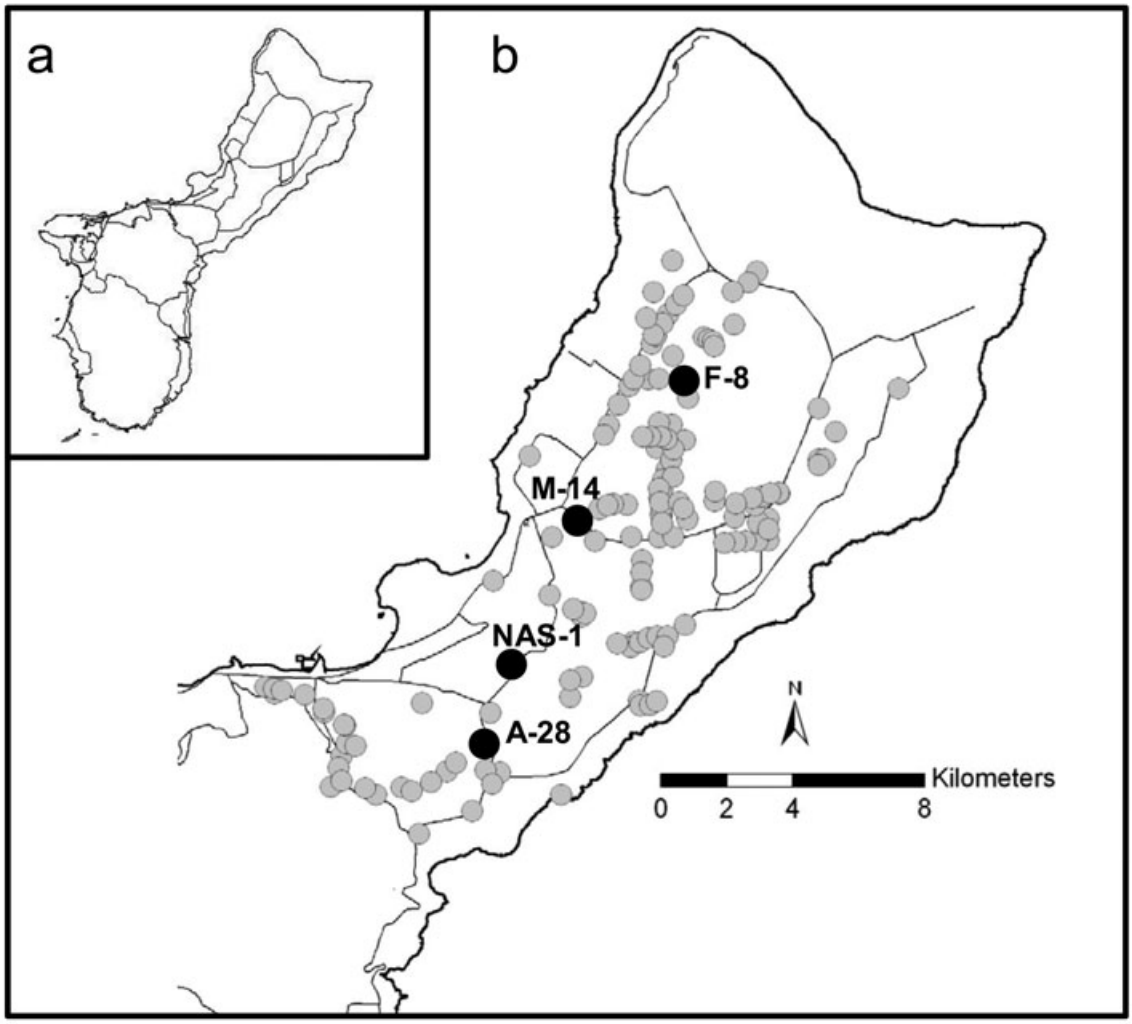

Figure 1. Map of Guam (inset a) and northern half of the island (b) showing location of GWA's production wells. The larger black filled circles represent wells with MCL violations. These are referred to in the text by their alphanumeric designations.

in M-14 (Figure 1) in September 2004, and the well was taken off-line shortly thereafter. Because the presence of nearby wells offset the impact on overall production rates in this part of the system, GWA opted to continue monitoring M-14 indefinitely on a monthly basis, rather than invest money immediately in another GAC filter. This "wait and see" strategy was probably not the best decision that could have been made under the circumstances. The fact that chlordane is so widely distributed throughout the aquifer and turning up in more and more wells over time, is a clear indication that problems associated with this highly persistent and slow moving chemical will probably get worse before they get better. More importantly, shutting down M-14 could redirect the chemical plume to nearby wells, which is exactly what appears to have happened in a down gradient sister well located less than 1 km away. Chlordane levels of 0.14 μg/L were recorded in this well at the time M-14 was taken off-line and steadily increased to exceed 50% MCL (1.10 μg/L) by July 2007. Perhaps, it would have been wiser to relocate the F-8 GAC filter to M-14, at least for the time being. In the longer term, however, it may be necessary to expedite GWA's future plans to convert the entire distribution system into a transmission system to lower clean-up costs associated with this contaminant given that additional chlordane impacted wells are likely to be taken off-line in the future.

Although PCE is not widespread throughout Guam's aquifer, it seems to be turning up in more and more wells as time goes by (Table 3). By December 2007, 11 GWA wells had shown detectable levels of PCE at one time or another since 1996. Although the levels recorded were generally low, three wells yielded quarterly MCL exceedences on one or more occasions over this time frame, and one of these, well A-28 (Figure 1), was shut down in January 2006, following an MCL violation. The first quantifiable levels of PCE in A-28 were detected in November 2003. Eight months later, the first quarterly MCL exceedence was recorded, and by January 2006 the well was taken off-line. The incident clearly shows how rapidly changes in the chemical integrity of groundwater can occur in karst limestone systems. So far, the source of PCE contamination in A-28 remains a mystery, but the mere fact that it happened within a relatively short space of time, despite the chemical being only slightly mobile in soil (log Koc: 2.2-2.7; Seip et al. 1986; Zytner et al. 1989), suggests it is located nearby. The absence of detectable PCE contamination in neighboring wells also

Table 4
Microbiological Summary Before and After Implementation of Improved Management Practices in 2003

		Wells			Samples		
Bacteria	**Sampling Interval**	**Total[1]**	**Contaminated[2]**	**%**	**Total**	**Contaminated**	**%**
Total coliforms	1997–2002	110	95	89	2273	451	20
	2003–2007	113	101	89	1886	386	20
Escherichia coli	1998–2002	110	35	32	1886	70	3.7
	2003–2007	113	13	12	1886	28	1.5

[1]Total number of wells sampled per sampling interval.
[2]Wells categorized as contaminated yielded one or more microbial hits over the appropriate sampling interval.

suggests the source of this chemical is highly localized, and the volume released relatively small.

GWA has yet to decide upon a suitable remediation plan for well A-28, but it seems likely that it will be capped and abandoned, in view of its relatively high chloride content (McDonald and Jenson 2003), and because all nearby wells appear to be unaffected by the contamination. Certainly, the removal of this low capacity well from the distribution system will have minimal impact on local production rates, and should additional capacity ever be required, the most likely scenario would be for GWA to commission the drilling of another well in the area.

Microbiological Contaminants

Table 4 summarizes the quarterly microbiological data sets collected for total coliforms from 1997 to 2007 and for *E. coli* from 1998 to 2007. The findings for both organisms are presented for two discrete sampling intervals: up to and including 2002, and from 2003 onward. In 2003, GWA greatly improved its management capability and implemented training requirements that significantly increased the number of certified operators at its wastewater treatment plants. Better generators, pumps and motors were installed and the disinfection system was improved. As a result of all these changes, sewage spills and overflows from sewage pump stations were reduced by 90%. These improvements were clearly mirrored by the sharp drop in *E. coli* contaminated wells from 32% of all wells monitored prior to 2003 to 12% five years later. This was indeed a commendable effort by GWA management and one worthy of note, particularly in light of the corresponding national average which currently stands at around 26% (USEPA 2006a).

Interestingly, the number of wells impacted by total coliforms remained proportionately similar over the entire study period. The fact that total coliforms can survive indefinitely in biofilms that form naturally within wells and can be dislodged during the pumping process probably accounted for this anomaly. Overall, 111 wells yielded total coliform hits at one time or another during the study period, compared with 36 wells for *E. coli.* The total number of quarterly hits for any given well ranged from 1 to 38 for total coliforms and 1 to 14 for *E. coli* with median values of 6 and 1 for each organism, respectively. The highest incidence of total coliform hits was generally confined to the older "A" series wells where biofilms are likely to be more substantial. On average, wells testing positive for total coliforms, tested positive for *E. coli* 28% of the time before 2003, and 8% of the time from 2003 onward. There was no readily identifiable relationship between rainfall and well contamination for either organism over the study period; however, *E. coli* hits were significantly lower ($P < 0.05$) during the April to June quarter, which typically represents the end of the dry season.

Conclusions

Although Guam's groundwater is currently in reasonable condition from a chemical standpoint, the distribution and abundance of chlordane within the well field is increasing and, in all probability, will continue to do so for several years to come. Another potentially problematic chemical of the future is nitrate. Although this naturally occurring chemical is typically high in limestone aquifers (Matson 1993), the records indicate that levels in certain drinking water wells on Guam have increased significantly over time (McDonald 2002). This is hardly surprising given the fact that more than 10,000 septic tanks are currently positioned over the aquifer, along with numerous cesspools and outhouses (B. Cruz, personal communication, 2009). In the past, GWA has been more concerned with microbial contributions from these facilities, given the shallow soils in which many are located. Remarkably, this has not yet been shown to be a problem. In fact, from a microbial standpoint, Guam's drinking water is now considered to be the safest it has been in decades (USEPA 2006b). Maintaining this standard during severe tropical storm conditions probably ranks among GWA's greatest challenges. On such occasions, major flooding and interrupted power supplies can result in sewage overflows and surface water quality changes that are rapidly transmitted to the aquifer. The notable improvement in microbiological integrity of Guam's groundwater since 2003 may thus be due in part to the fact that such a storm has not been seen on Guam since Typhoon Pongsona passed over the island in December 2002.

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Biographical Sketches

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