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MANAGEMENT RESPONSES TO GROUNDWATER QUALITY VIOLATIONS ON GUAM: 1996-2007

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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 ~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 US 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 US Safe Drinking Water Act requirements. This report summarizes and compares the groundwater data-sets for two discrete time intervals: 1996-2001 and 2002-2007 for chemicals, and 1997(8)-2002 and 2003-2007 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 afterwards have significantly reduced the incidence of *Escherichia coli* contamination in recent years.

**KEY TERMS:** Guam; groundwater monitoring; chemical and microbiological contaminants.

## INTRODUCTION

Guam (13°28'N, 144°45'E) is a small volcanic island that lies in the tropical western Pacific ~2000 km due east of the Philippines. It is about 30 miles long, 4 to 9 miles wide and covers an area of approximately 212 square miles. 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, while 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 ~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 this time frame, 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 two microbiological contaminants to meet the requirements of the National Primary Drinking Water Regulations (NPDWR) and the Guam Primary Safe Drinking Water Requirements (GPSDWR). Sampling for chemical analysis is conducted in accordance with the USEPA Standardized Monitoring Framework (SMF) introduced in

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1991 and implemented nationwide in 1993 (Federal Register, 1991). The SMF is divided into 9-year monitoring cycles, e.g., 1993-2001, 2002-2010 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 non regulated contaminants during the first monitoring period of each cycle. Monitoring frequencies during the second and third monitoring periods are dependent upon the 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 above, in order 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 *E. coli*, respectively. Currently, GWA draws water from ~125 production wells although not all are up and running in any one year. Water from these wells 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.

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 $\geq$ 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 $\geq$ MCL: further sampling conducted on a quarterly basis until levels $<$ MCL for period determined by Guam EPA
Inorganic Chemicals	as above	Triannually	If levels $\geq$ MCL: further sampling conducted on a quarterly basis until levels $<$ MCL for three consecutive quarters
Nitrate	as above	Annually	If levels $\geq$ 50% MCL: further sampling conducted on a quarterly basis until levels $<$ 50% MCL for three consecutive quarters
Nitrite	as above	Triannually	If levels $\geq$ 50% MCL: further sampling conducted on a quarterly basis until levels $<$ 50% MCL for three consecutive quarters

## RESULTS AND DISCUSSION

### Chemical Contaminants

The total numbers of wells showing positive detections for all regulated and non regulated chemicals over the 1996-2007 sampling period are shown in Table 2, together with the total number of hits plus the range and median concentration found for each contaminant respectively. Of the 24 regulated chemicals detected, five occurred in one or more wells at levels  $\geq$ 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-set summaries for these contaminants over the 1996-2002 and 2003-2007 sampling intervals are presented in Table 3, along with the total number of  $\geq$ 50%MCL and  $\geq$ MCL exceedences recorded over each period.

While GWA pays close attention to any well yielding contaminant levels  $\geq$ 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 of less than 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 twelve consecutive non-detects are reported, after

US EPA ARCHIVE DOCUMENT

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

Table 2: Chemicals Detected at Least Once in One or More of GWA's Drinking Water Production Wells: 1996-2007

Synthetic Organic Chemicals					Volatile Organic Chemicals					Inorganic Chemicals							
	Total		Concentration (µg/L)				Total		Concentration (µg/L)				Total		Concentration (µg/L) <sup>a</sup>		
	Wells	Hits	Range	Median	MCL <sup>b</sup>		Wells	Hits	Range	Median	MCL <sup>b</sup>		Wells	Hits	Range	Median	MCL <sup>b</sup>
<b>REGULATED</b>					<b>REGULATED</b>					<b>REGULATED</b>							
<i>Pesticides</i>					<i>Solvents</i>					<i>Metals</i>							
Chlordane	63	599	0.02 - 3.4	0.23	2.0	Carbon tetrachloride	4	17	0.5 - 2.9	0.7	5	Antimony	2	4	1.0 - 3.8	1.6	6
Dibromochloropropane	1	1	0.01	-	0.2	Dichloromethane	4	4	0.6 - 2.2	1.7	5	Arsenic	21	25	1.0 - 14.0	1.5	10
Endrin	31	151	0.01 - 0.3	0.01	2.0	Perchloroethylene	11	115	0.2 - 7.7	1.3	5	Barium	22	63	2.0 - 66	3.5	2000
Ethylene Dibromide	1	7	0.01 - 0.12	0.11	0.05	Trichloroethylene	12	193	0.05 - 4.8	0.9	5	Chromium	119	273	0.2 - 27	4.1	100
Heptachlor	3	3	0.01 - 0.02	0.01	0.4	<i>THMs</i>					Copper <sup>c</sup>	48	57	0.75 - 25	3.5	1300 <sup>d</sup>	
Heptachlor Epoxide	24	61	0.01 - 0.05	0.01	0.2	Total THMs	59	526	0.5 - 57.4	1.8	80 <sup>d</sup>	Lead <sup>e</sup>	33	39	0.4 - 4.5	0.78	15 <sup>d</sup>
<i>Herbicides</i>					<b>UNREGULATED</b>					<i>Others</i>							
Atrazine	3	10	0.05 - 0.07	0.06	3.0	<i>Solvents</i>					Fluoride	49	98	0.05 - 0.40	0.10	4	
Dalapon	3	3	6.5 - 9.5	7.8	200	Bromomethane	2	2	0.6 - 0.7	0.7	-	Nitrate-N	124	754	0.1 - 5.0	2.5	10
Picloram	8	32	0.1 - 0.9	0.4	500	Chloromethane	1	1	3.1	-	-	<b>UNREGULATED</b>					
2,4-D	2	2	0.1 - 0.5	0.3	70	Dibromomethane	2	2	0.7 - 1.6	1.2	-	<i>Others</i>					
<i>Phthalate Esters</i>					<i>THMs</i>					<b>UNREGULATED</b>							
Di(ethylhexyl)-adipate	1	1	3.2	-	400	Bromoform	34	66	0.5 - 34.0	1.6	-	<i>Others</i>					
Di(ethylhexyl)-phthalate	20	23	0.6 - 2.8	0.9	6.0	Bromodichloromethane	33	88	0.5 - 12.0	1.3	-	Sulfate	118	285	2.1 - 270	9.4	-
<b>UNREGULATED</b>					<i>THMs</i>												
<i>Pesticides</i>					<i>THMs</i>												
Aldrin	4	7	0.01 - 0.01	0.01	-	Bromoform	34	66	0.5 - 34.0	1.6	-						
Dieldrin	88	875	0.01 - 1.6	0.05	-	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	-						

<sup>a</sup>Concentrations for fluoride, nitrate-N and sulfate as mg/L; <sup>b</sup>MCL = Maximum Contaminant Level, an enforceable standard prescribed under the NPDWR for regulated contaminants only

<sup>c</sup>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 include here for reference purposes only; <sup>d</sup>Action Level in distribution system only

Of the five contaminants of concern referred to above, 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 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.

Table 3: Chemicals of Concern in GWA's Drinking Water Production Wells: 1996-2007

Contaminant	Sampling Interval	Total		Concentration (µg/L) <sup>a</sup>		Quarterly Exceedences	
		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 <sup>a</sup>	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

<sup>a</sup>data for Nitrate-N as mg/L

The hitherto unknown presence of EDB in well F-8, a high production well in the north of the island (Fig. 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

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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 was 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 one cannot fault GWA for their conservative approach towards the cautious 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  $\mu\text{g/L}$ . 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). Additionally, 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.

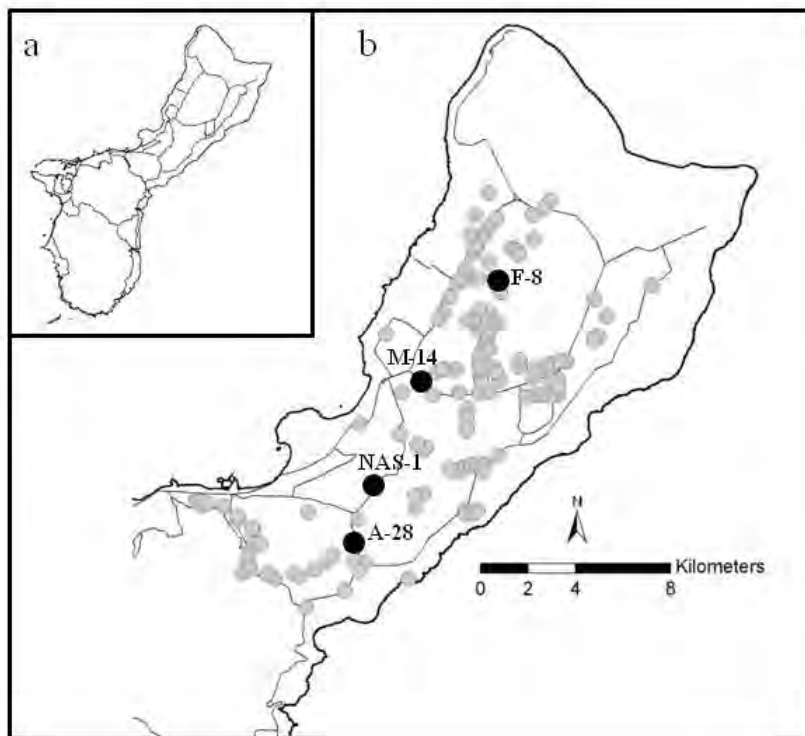


Figure 1: Map of Guam (inset a) and northern half of the island (b) showing location of GWA's production wells. The larger black filled circles represent wells with MCL violations. These are referred to in the text by their alphanumeric designations.

The case history described above draws some interesting parallels with a prior TCE problem in well NAS-1 in central Guam (Fig.1). The well previously belonged to the US 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 US 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; Gabarini 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 several wells yielded MCL exceedences over this 12 year period, the only MCL violation occurred in M-14

(Fig. 1) in September 2004, and the well was taken off-line shortly thereafter. Since 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 one kilometer 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 in order 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. While 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 (Fig. 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 demonstrates 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 nearby neighboring wells also 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 1997-2007 and for *E. coli* from 1998-2007. The findings for both organisms are presented for two discrete sampling intervals: up to and including 2002, and from 2003 onwards. 2003 was the year that 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% (Federal Register, 2006).

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

Bacteria	Sampling Interval	Wells			Samples		
		Total	Contaminated <sup>a</sup>	%	Total	Contaminated	%
Total Coliforms	1997 - 2002	110	95	89	2273	451	20
	2003 - 2007	113	101	89	1886	386	20
<i>Escherichia coli</i>	1998 - 2002	110	35	32	1886	70	3.7
	2003 - 2007	113	13	12	1886	28	1.5

<sup>a</sup>Wells categorized as contaminated yielded one or more microbial hits over the appropriate sampling interval

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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 1-38 for total coliforms, and 1-14 for *E. coli*. Median data-set values were 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 would likely 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 onwards. 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-June quarter, which typically represents the end of the dry season.

#### Concluding Remarks

While 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 over 10,000 septic tanks are currently positioned over the aquifer, along with numerous cesspools and outhouses (Benny Cruz, Water Resources Management Program Director, GEPA, pers. com.). 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, 2006). The question begs, however, as to whether this standard can be maintained during severe storm conditions, the likes of which, has not been seen on Guam since Typhoon Pongsona passed over the island in December 2002.

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