GQ07: Securing Groundwater Quality in Urban and Industrial Environments (Proc. 6th International Groundwater Quality Conference held in Fremantle, Western Australia, 2–7 December 2007).

Post-Audit of the State of Hawai`i's Source Water Assessment Program

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Abstract The US 1996 Safe Drinking Water Act Amendments mandated that each state submit a source water assessment program (SWAP) that: (i) delineates the boundaries of areas providing source waters for public water systems, and (ii) identifies the origins of regulated and unregulated contaminants in the delineated area to determine the susceptibility of public water systems to such contaminants. The U.S. Geological Survey (USGS) model MODFLOW was used to determine the source capture areas for the 104 public drinking water wells located on the island of Oahu, Hawai`i. Two capture areas were defined using MODFLOW and the particle tracking code, MODPATH: a 10-year travel time zone (Zone C), and a 2-year travel time zone (Zone B). In addition to these two zones, a third area (Zone A), the "well site control zone" with a diameter of 50 meters (m) around each source, was established. Together, the three zones are referred to as Capture Zone Delineations (CZDs). Once the CZDs were established, all potentially contaminating activities (PCAs) within these zones were identified. Each PCA was assigned a score (medium, high or very high), depending on the PCAs relative potential to contaminate the underlying source water. Finally, each water source was assigned a score based on the cumulative scores of the PCAs identified within that source's CZD. In this paper, an analysis is performed that compares the susceptibility scores calculated for the groundwater supply wells on Oahu to the actual occurrence of contamination in these wells. Suggestions are made on how to improve the predictive capability of the susceptibility methodology employed in the Hawai`i SWAP.

Key words source water assessment and protection; contaminated groundwater; capture zone delineation

INTRODUCTION

Oahu is the most populated island in the State of Hawai`i and home to the State capital and largest city, Honolulu. The resident and tourist population is about 950 000 people and because much of the 586 square mile (1518 km^2) island is mountainous and covered by protected forest reserves, developed areas on Oahu are some of the most densely populated areas in the United States. Urban and industrial development on the island has been historically concentrated in Honolulu, on the coastal plain near Pearl Harbor, and at several military bases. However, the central and south-western portions of the island are currently in the process of undergoing major land use changes as a result of the cessation and replacement of large-scale plantation agriculture (sugarcane and pineapple) to suburban and diversified-crop agricultural use (Oki & Brasher, 2003).

The Honolulu Board of Water Supply (BWS) currently operates and maintains 104 water sources that combine to deliver an average of 155 million gallons of water per day. More than 90 percent of this water is obtained from the deep volcanic rock aquifers located in central Oahu and Honolulu, which has led to these systems being designated as Sole Source Drinking-Water Aquifers by the United States Environmental Protection Agency (USEPA). These basal aquifers are highly permeable and unconfined except near the coast and in urban Honolulu, where they are overlain by sedimentary confining units (Figure 1, from Oki *et al.*, 1999). The unconfined portions of these aquifers are susceptible to contamination resulting from the downward migration of chemicals applied or spilled at the land surface. In central Oahu, it has been estimated that contaminants can reach the basal water table within a few years and persist in the aquifer and unsaturated zone for several decades (Orr and Lau, 1988; Hunt, 2004). Vertical sampling of the basal aquifer in central Oahu has revealed the stratified nature of the basal lens (Voss and Wood, 1994). The uppermost water layer within the lens is 75 m to 125 m thick and consists of water recharged from local rainfall and irrigation over the past few decades. Below this upper layer is the core of the freshwater lens, 100 m to 150 m thick, containing waters with an apparent carbon-14 age of 1,800 years, which floats atop the third layer composed of saltwater that likely extends to the bottom of the aquifer. Groundwater ages were determined in these aquifer systems during the National Water-Quality Assessment (NAQWA) Program using chlorofluorocarbon and sulfur hexafluoride concentration data (Hunt, 2004). The NAQWA study found that the majority of groundwater samples collected from Central Oahu and Honolulu had apparent ages ranging from the 1950s to 1980s, which coincides with the period of the highest chemical use in agricultural chemicals (predominately fumigants and herbicides) and urban settings (predominately insecticides) (Anthony *et al.*, 2004).

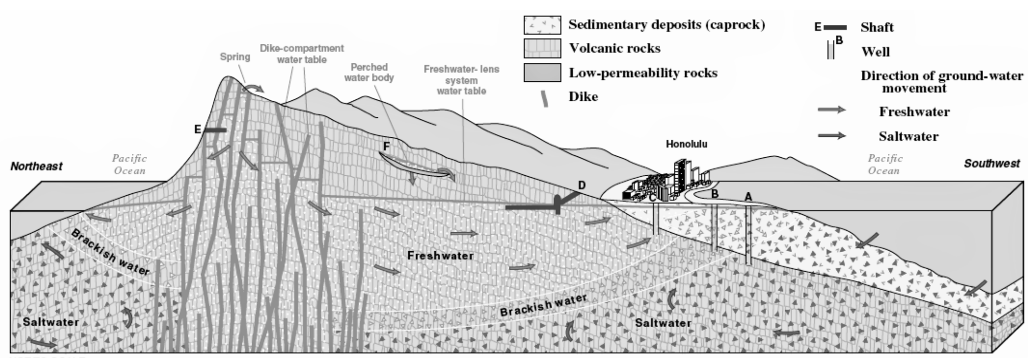

Fig. 1 Groundwater movement in Central Oahu and Honolulu aquifer systems.

Of the 90 NAQWA studies performed on major aquifer systems located throughout the United States, the detection frequencies of fumigants, solvents, insecticides and herbicides in Oahu public-supply wells were 1st, 3rd, 12th and 51st nationwide, respectively (Anthony *et al.*, 2004). The high frequency of pesticide detection is related to the high historic rates of pesticide usage in agricultural settings and the widespread use of solvents at military and civilian installations on Oahu. For instance, it has been estimated that pesticide usage in Hawai`i was roughly 10 times greater per square mile than amounts being used on the mainland during the 1960s (State of Hawaii, 1969). Historically, fumigants and herbicides accounted for the vast majority of all pesticides consumed in Hawai`i. The fumigants were predominately used by the pineapple industry (~85% of total state wide usage) for nematode control while the sugar cane industry was the major single user of herbicides in the state, accounting for about 75 percent of total herbicide usage in the State (State of Hawaii, 1969). Termite control operators (particularly in urban areas) are typically the greatest users of persistent chlorinated hydrocarbon insecticides. In the 1960s, dosages recommended for termite control in Hawai`i, up to 1500 pounds per acre, were roughly 500 to 1000 times higher per application than the amounts applied to agricultural areas. Historically, chlordane was the most widely used persistent chlorinated hydrocarbon insecticide. The mass of selected pesticides used throughout the State of Hawai`i in 1968 is summarized in Table 1.

Table 1 Total pesticide usage in State of Hawai`i in 1968.

Fumigants [60.7%]	Pounds	Herbicide [31.5%]	Pounds	Insecticides [5.5%]	Pounds	Fungicides [1.7%]	Pounds
DD (1,2-Dichloropropane)	6,050,000	Diuron	745,000	Chlordane	140,000	Dithanes	58,000
EDB (1,2 dibromomethane)	605,000	Dalapon	695,000	DDT	116,000	Copper Sulfate	56,000
DBCP (1,2-Dibromo-3-Chloropropane)	550,000	Atrazine	380,000	Dieldrin	16,000	Sulfur	50,000
Other Chemicals	159,500	Other	1,998,900	Other	398,000	Other	46,370
Total Statewide Usage (Pounds Active)	7,364,500		3,818,900		670,000		210,370

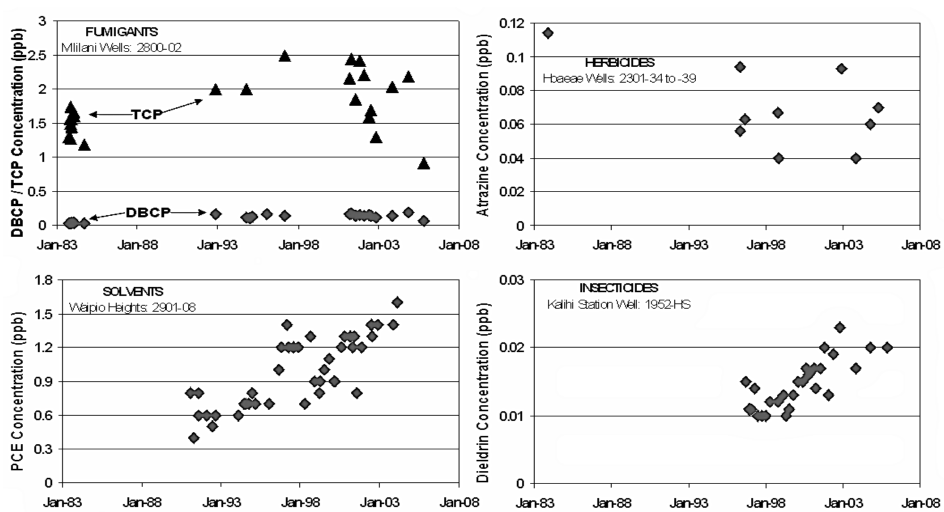

Fig. 2 Variation in pesticide and solvent concentrations in Central Oahu and Honolulu aquifer systems over the past 25 years.

It is believed that the current contamination present in Oahu's water supply wells reflects historical use of chemicals more than present use (Anthony *et al.*, 2004). The presence of numerous agricultural and pest control chemicals such as TCP (1,2,3-Trichloropropane), DPCP, and Dieldrin in the groundwater aquifers decades after their use on Oahu was discontinued is evidence of the lasting impact of former pesticide usage practices. The movement of groundwater in these basal aquifers is relatively slow (typically less than 10 feet per day (≈ 3 m day^{-1})), and many of these chemicals will likely take decades to be flushed through the aquifer systems. The State of Hawai`i Department of Health (DOH) and the BWS currently test for more than 100 different types of contaminants on an annual basis. Figure 2 shows the concentration level of fumigant, solvent, insecticide and herbicide contamination measured by DOH and BWS in various wells located in central Oahu and Honolulu over the past 25 years.

SOURCE WATER ASSESSMENT PROGRAM METHODOLOGY

The reauthorization of the Safe Drinking Water Act (SDWA) in 1996 required states to focus upon the protection of drinking water sources by development of a SWAP (USEPA, 1997). The Safe Drinking Water Branch of DOH was the lead agency for development of Hawai`i's SWAP. The University of Hawai`i's Water Resources Research Center was contracted to conduct the assessments of Oahu's 104 public drinking water sources (Whittier *et al.*, 2004). The assessment process consisted of the following elements:

- Delineation of the area around a drinking water source through which contaminants may travel to the drinking water supply;
- Inventory of activities that may lead to the release of microbiological or chemical contaminants within the delineated area; and
- Determination of the susceptibility of the drinking water source to surrounding potential contamination activities.

Delineation of capture zone

A total of three zones were delineated around each public groundwater supply system: 1) a well site control zone with a 50-meter diameter around each well site, which is intended to assess the source's vulnerability to tampering, vandalism and direct introduction of contaminants (Zone A); 2) a two-year travel time zone to delineate the area that may introduce pathogenic microorganisms directly into the water source (Zone B); and 3) a ten-year travel time zone to delineate the area from which indirect chemical contamination of a source could originate (Zone C).

The three-dimensional groundwater flow models, MODFLOW and MODPATH, were used to determine the two- and ten-year capture zone around each source, based upon the hydrogeology and pattern of groundwater withdrawal at each source (Whittier *et al.*, 2004). Two separate finite difference grid models were used to delineate the two and ten-year capture zone delineations (CZD) for wells that serve public drinking water systems on Oahu. The CZDs for wells located in Central and Leeward Oahu were delineated using a model that covered all of Oahu except the eastern end of the island (the Central and Leeward Oahu model). A second model, the Oahu model, was extended to encompass the entire island of Oahu. The Central and Leeward Oahu model consisted of 175000 cells (125643 active) arranged in 250 rows, 350 columns and two layers which were rotated thirty degrees to better conform to the orientation of the conceptual model. The Oahu model consisted of 283860 cells (203404 active) arranged in 498 rows, 285 columns and two layers.

Recharge from the USGS water budget prepared for Oahu based upon 1985-era land use on the island was added to the model (Shade & Nichols, 1996). The pumping rates used in the model were set at the allocated rates set by the State of Hawai`i Commission on Water Resource Management. Calibration was performed by adjusting the model parameters to make the model simulated hydraulic heads match the measured hydraulic heads as closely as possible. The simulated water levels were calibrated to the average water level for each well recorded in the 1999 USGS Water Year report for Hawai`i (Hill *et al.*, 2000). The primary parameter adjusted was hydraulic conductivity, but adjustments were also made to conductance of the model arcs representing streams, and to the hydraulic characteristic of the model arcs representing volcanic dikes and streams. Using this approach, a very close calibration was obtained for the basal water areas with the average error being less than 0.1 feet (Whittier *et al.*, 2004).

Inventory of potentially contaminating activities

Once the two and ten-year CZDs were determined using the MODFLOW model, all PCAs were then inventoried within these two source water assessment areas. A PCA is defined as a facility or activity that 1) stores, transmits, uses, or produces contaminants, chemicals or by-products; and 2) has the potential to release contaminants that may impact the quality of the underlying groundwater. A list of PCAs specific to Hawai`i was created and ranked according to whether they posed a very high (29 activities), high (23 activities) or medium (20 activities) contamination potential to contaminate the source water. Factors that were considered when placing a PCA into a certain category included 1) the nature of the activity, 2) chemicals associated with the activity, and 3) association with historical incidents of groundwater contamination. Table 2 provides examples of some of the more common PCAs that were inventoried during development of Hawai`i's SWAP.

Table 2 Examples of ranked potential contaminating activities inventoried.

Very High Contamination Potential	High Contamination Potential	Medium Contamination Potential
Large Quantity Hazardous Waste Generators	Automobile repair shops	Above ground storage tanks
Gas Stations	Diversified agriculture	Parking lots
Dry Cleaners	Small Quantity Hazardous Waste Generators	Parks
Leaking underground storage tanks (LUST)	Septic systems	Residential parcels
Military Installation	Sewer Lines	Storm drain discharge points
Pineapple cultivation	Golf Courses	Storm water drainage - dry wells
Sugar cane cultivation	Underground storage tanks	Transportation corridors

The initial inventory of PCAs within the CZDs was created by querying existing GIS data coverages of land use and hazardous waste release sites available from State, County and private sources. All PCAs that fell within the delineated assessment areas were integrated into a separate GIS layer created for the island of Oahu. The inventory was largely confined to existing sites, with the exception of historic sites that had already been inventoried and contained in DOH and USEPA hazardous waste contamination databases (*i.e.* LUSTs, Resource Conservation and Recovery Act (RCRA) sites, and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) sites). The location and existence of the PCAs identified during the initial electronic inventory were then verified during a follow-on field survey.

Susceptibility analysis

The susceptibility analysis determined the "relative potential" of a drinking water source to be impacted by the PCAs that were identified in the delineated capture zone during the inventory process. The purpose of the susceptibility analysis was to identify drinking water sources that were most susceptible to contamination so that preventive steps could be implemented. The scoring system shown in Figure 3 below was used to determine a total susceptibility score for each groundwater source based upon the total cumulative risk posed by the PCAs identified within that groundwater source's source water assessment protection area (*i.e.* the CZD). The total scores determined for groundwater sources on Oahu ranged from 0 to 2,119, with the highest scores typically being associated with wells located in urban settings.

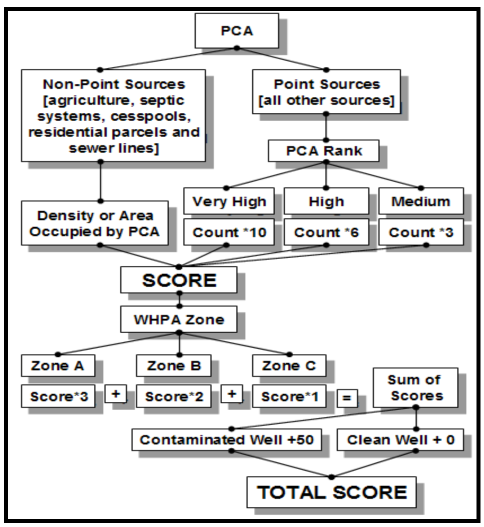

Fig. 3 Scoring system to calculate groundwater source susceptibility to contamination from PCA within delineated capture zone.

RESULTS

Figure 4 shows the two and ten-year CZD for public groundwater supply wells calculated by MODPATH as well as the location of contaminated and non-contaminated wells on Oahu.

One of the objectives of the SWAP was to provide the data required for development of a comprehensive source water protection strategy for the State of Hawai`i to ultimately prevent contaminants from entering public water supply systems. The susceptibility analysis methodology was developed to rank the relative susceptibility of the groundwater wells to contamination by analyzing the types and number of potentially contaminating activities located within the land area that overlies the extent of groundwater that contributes water to the well over a ten year time period. It is thus instructive to compare the susceptibility scores calculated during the SWAP program with the actual occurrence of contamination within the water supply wells. For the purposes of this comparison, we reduced the scores of well sources at which contamination had been detected by 50 to remove the bias towards contaminated wells built into the scoring system (*i.e.* 50 points were added to wells in which contamination has been detected in the original SWAP methodology). The correlation between the total PCA score and the occurrence of groundwater contamination is shown in Figure 5. In this figure, a single score was assigned to co-located wells which had overlapping CZDs and thus identical PCA scores.

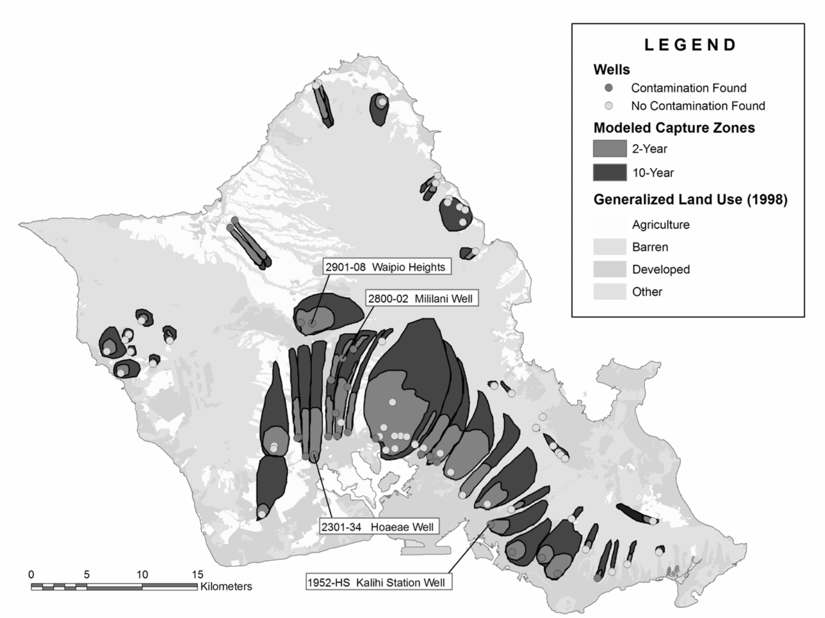

Fig. 4 Two and ten-year capture zones delineated on Oahu using MODPATH.

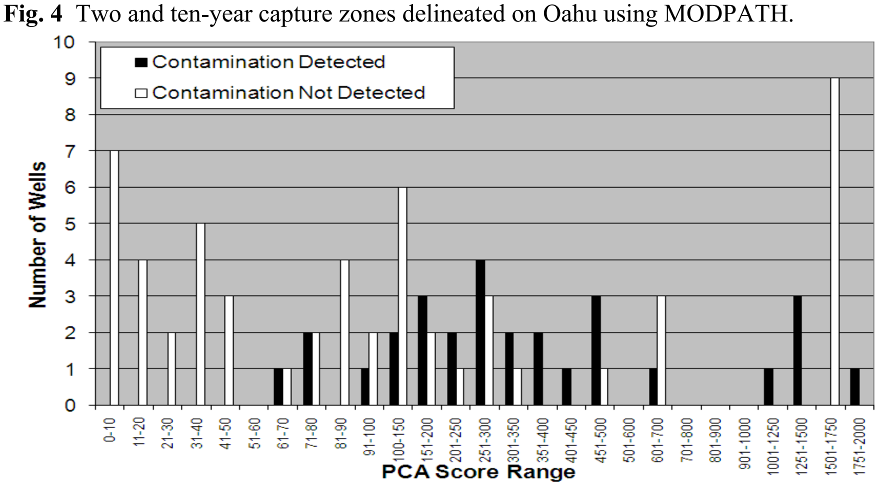

Fig. 5 Correlation between PCA score and occurrence of groundwater contamination.

DISCUSSION

Figure 5 shows that the susceptibility analysis used for the Hawai`i SWAP was not particularly predictive for determining the occurrence of groundwater contamination. The wells with very high PCA scores (>500) were typically located in urban environments with high densities of PCAs while many of the wells located in Central Oahu in the vicinity of former and current agricultural fields typically yielded total scores between 100 to 500. The predictive capability of the susceptibility analysis for Oahu could be improved somewhat if two additional factors were accounted for in the scoring analysis: 1) the mass of pesticide historically applied within the CZD and 2) the hydrogeologic setting (*i.e.* whether the CZD overlies a confined or unconfined aquifer). Figure 4 shows that virtually all of the contaminated groundwater sources on Oahu are located in central Oahu or western/central Honolulu. The central Oahu wells reflect residual contamination from the former large tracts of agricultural land in the area (sugarcane and pineapple) which received repeated applications of fumigants and herbicides over the past sixty years. These pesticides were applied over a vulnerable unconfined aquifer. Solvents and petroleum products have also been used and stored at several military installations in this area since the 1940s. The detection of these types of contaminants in central Oahu likely reflects historic releases from these installations, or other civilian sources, such as gasoline stations and automotive repair shops. In contrast to central Oahu, few organic compounds were detected in Honolulu wells despite the high urban density and the intensive use of insecticides in this area. Trace levels of the insecticides dieldrin and chlordane were detected in the Aiea to Kalihi areas of Honolulu. The absence of significant contamination in the wells located in the Honolulu area (which typically have high PCA scores due to the numerous PCAs within these wells CZDs) is due to these wells tapping confined aquifers, which afford some protection from downward migration of surface contamination.

The susceptibility analysis could be improved by adopting a fourth contamination potential category for current and former agricultural areas where the magnitude of the scores assigned for these PCAs are a function of both the area within the CZD which was in agriculture and the historic amount of pesticide applied to this area. In addition, the total score should be adjusted to reflect whether a particular well's CZD is located over a confined (decrease score) or unconfined aquifer (increase score).

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