The History of Groundwater Management and Research in Hawaii

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Abstract

This paper reviews groundwater research studies with emphasis on modeling as a tool for management of Hawaii's resources. Hawaii depends to a great extent on groundwater resources, and concern over availability of potable water has guided research regarding both water quantity and quality. Research is mainly aimed at understanding Hawaii hydrogeology, identifying aquifer parameters and modeling needs, and applying models in the management of resources. Use of models has advanced over the past ten years toward routine aquifer management, yet there is a great need to better characterize aquifer spatial data. Variability of hydrogeological conditions is a major hurdle for successful application of models. This paper also addresses legal, institutional, and economic issues pertinent to Hawaii's pressing problems regarding water allocation. Areas of critical research needs are also identified.

Hawaii Hydrogeology

Extensive coverage of Hawaii geology and hydrogeology can be found in various publications, e.g., reports by Hunt (1997) and Oki et al. (1999a). The recent book by Lau and Mink (2006) covers all aspects of hydrology in Hawaii. Figure 1 is a schematic cross section of the island of Oahu showing various hydrogeological features and different water development installations.

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As indicated in the publications listed above, disparity in aquifer types and dominance of hydrogeological variability complicate research and modeling efforts. Volcanic rock aquifers are the major subsurface water-supply systems for all populated islands of Hawaii. These aquifers are formed by layered sequences of permeable basalt. Some of these volcanic rock aquifers are overlain by coralline sediments.

Since volcanic rock aquifers are composed primarily of laterally spreading lava flows, the hydraulic conductivities are expected to be greatest along the direction of lava flows and least along the direction perpendicular to sequences of lava flows. Although volcanic rock aquifers are generally very permeable, the hydraulic conductivity values vary greatly due to the mode of emplacement of these rocks. Volcanic rocks exist in four major forms: lava flows, dikes, pyroclastic deposits, and saprolite (Oki et al., 1999a).

There are two types of lava flows: pahoehoe and aa. While the pahoehoe is smooth, the aa lava surface looks like coarse rubble. Typical sequences of lava flows contain both aa and pahoehoe flows. Void spaces in lava flows contribute to the porosity of the rocks. In the core of an aa flow, the rock can be massive with very low permeability. The flank lavas, which flew overland downslope after eruption, is characterized by high hydraulic conductivity.

Dikes are thin, near-vertical sheets of massive, low-permeability rock that intrude into existing rocks, and can extend vertically and laterally for long distances impeding the flow of groundwater. Dikes intersect at various angles and compartmentalize the more permeable rock in which groundwater can be impounded. Having lower overall porosity and permeability, dikes tend to channel groundwater flow parallel to their general trend. In most dike-intruded areas, the level of impounded water is much higher than that of the regional freshwater lens.

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Pyroclastic deposits include ash, cinder, spatter, and larger blocks. Compaction and weathering can reduce their permeability. Weathered ash beds commonly act as thin confining and perching units within lava sequences.

Saprolite is a soft, clay-rich, thoroughly weathered rock that has retained textural features of the parent rock. Exposed weathered profiles can include saprolite of thickness ranging from centimeters to several tens of meters.

Hawaii hydrogeology is also characterized by sedimentary deposits, including marine sediments in some coastal plains. These deposits, which are most common in the southern coastal areas of Oahu where they form a thick wedge over the lavas, is commonly referred to as the caprock. A second class of sediments is the alluvium filling deep-cut stream valleys. The fine-grained nature of these sediments reduces their hydraulic conductivity, causing them to act as a barrier to groundwater flow.

Hawaii Groundwater Problems

As is the case worldwide, water problems in Hawaii are related to the availability of potable freshwater and to contamination by organic or inorganic chemicals associated with land-use activities. All the main islands have large amounts of groundwater contained in volcanic rock aquifers. However, the quality of the groundwater may not be suitable for all uses.

Water-availability problems arise locally when the demand for water exceeds the supply. In some areas, water must be imported from other areas by ditches, tunnels, and pipelines to satisfy the demand. When development increases, the demand for fresh surface water and groundwater also increases, as does the potential for contamination and depletion of the water resources. To alleviate some of these problems, efforts are being made to reclaim and recycle groundwater in the state.

Contamination in some areas is caused by chemicals associated with human activities or by an increase in salt concentrations due to overpumping of well water. For example, agrochemicals, including fertilizers and pesticides, can move downward through the unsaturated zone to an aquifer and negatively affect the quality of groundwater. Other forms of contamination are due to leaching from septic-tank systems and sewer lines and due to storm runoff. Groundwater withdrawals that induce saltwater intrusion and increase mixing, especially in nearshore wells, affect water quality as well.

Deep monitoring wells used to observe changes in salinity profiles provide a means of estimating aquifer sustainable yield, which is defined as the maximum allowable total daily pumping without compromising storage and water quality. Profiles in the Honolulu area indicate that the salinity of water in the aquifer has increased over the years, indicating a steady upward movement of the transition zone (e.g., Visher and Mink, 1964; and Nichols et al., 1996).

Recharge

Accurate assessment of recharge is an essential part of groundwater management, considering that uncertainties in recharge estimates can translate into inaccurate appraisal of aquifer sustainability. For example, models, considered acceptable management tools, use recharge as one of the major input factors. Inaccurate recharge estimates will yield erroneous model results.

Efforts to estimate recharge include the work by Giambelluca (1983), Shade and Nichols (1996), Oki (2002), and Izuka et al. (2005). A typical approach to estimating recharge is based on completing a water budget of the system under study (e.g., Thornthwaite and Mather, 1955), including rainfall, surface runoff, evapotranspiration, infiltration, and soil moisture storage. Studies in Hawaii have additionally emphasized the importance of fog drip as an element of the water budget (e.g., Scholl et al., 2002a). Lack of data has promoted the use of methods that estimate fog drip as a percentage of precipitation. However, such estimates are expected to change with elevation, season, topography, and climate regime (Izuka et al., 2005). An ongoing project (Scholl et al., 2002b) includes extensive field work to examine the role of fog drip in cloud forest ecosystems at two sites in East Maui.

Modeling

Water Quantity

The study by Lau and Mink (1995) covered the history of groundwater modeling in Hawaii. Visher and Mink (1960) were the first to complete a field assessment of the transition zone near the Pearl Harbor shore of Oahu. The modeling studies by Lau (1962) and Souza and Voss (1987) benefited from the data collected by Visher and Mink. Sandbox models were used by Lau to study a nearshore aquifer to define optimal well pumping.

Mink (1981) introduced a landmark analytical solution (the robust analytical model, or RAM) that has been used by the state of Hawaii to estimate aquifer sustainable yield. With simplified assumptions in its derivation, RAM is able to calculate variations of basal aquifer head in response to pumping. In a latter study (Liu, 2005), RAM was modified by including transport processes of salt advection and dispersion. The usefulness of the modified RAM was demonstrated by applying it to an evaluation of the sustainable yield of the Pearl Harbor aquifer.

Numerical models include that developed by Meyers et al. (1974), who based theirs on the sharp-interface assumption. The model was successfully calibrated for an aquifer system in the Honolulu area. The model’s limitation, including its two-dimensional nature, caused difficulties in simulating periods of high water demand. The simulations required the use of lower values of permeability than what was expected. Liu et al. (1983) introduced an improvement through the use of a quasi-three-dimensional model for the Pearl Harbor aquifer, but it was still based on a sharp interface assumption. Essaid (1986) developed a similar model for Waialae aquifer that emphasized the importance of simulating the two-phase flow phenomenon.

Studies that dealing with mixing along the saltwater–freshwater interface include the two-dimensional, cross-sectional SUTRA model by Voss and Souza (1987) and Souza and Voss (1987). Oki et al. (1996) applied the same model to the Ewa area on Oahu and concluded that variations in hydraulic conductivity are a major control on the direction of groundwater flow and the distribution of water levels and salinity. Model results also showed that a reduction of recharge would increase salinity throughout the caprock, with the greatest change occurring in the upper limestone layer.

Modeling studies and related field work greatly advanced in the late 1990s and in the 2000s, mainly through the efforts of the Honolulu office of the United States Geological Survey (USGS). Use of numerical models as management tools has become increasingly acceptable. Models have progressed to the simulation of two-dimensional variably saturated flow and areal flow with a sharp interface between saltwater and freshwater and ultimately to fully three-dimensional density-dependent flow. Models have been mainly used in understanding the groundwater system through model conceptualization, in identifying data needs, and as management tools in a predictive framework.

Models in the USGS studies were mostly developed by that organization and are available in the public domain (USGS, 2006). They include:

- SUTRA (Voss and Provost, 2002)—A model that simulates saturated and/or unsaturated, constant-density or density-dependent groundwater flow and either single-species reactive solute transport or thermal-energy transport.

- VS2DT (Hsieh et al., 2000)—A graphical software package for simulating fluid flow and solute or energy transport in variably saturated porous media.
- SHARP (Essaid, 1990)—A quasi-three-dimensional, numerical finite-difference model to simulate freshwater flow and saltwater flow separated by a sharp interface in layered coastal aquifer systems
- AQUIFEM-SALT (Voss, 1984)—A two-dimensional (areal) finite-element code that simulates flow of confined or unconfined fresh groundwater in systems that may have a freshwater body floating on denser underlying saltwater.

Studies mainly aiming at a better understanding of Hawaii hydrogeology include those by Izuka and Gingerich (1998), who studied the southern Lihue Basin in Kauai, and Gingerich (1999a), who developed a model for the Haiku area, East Maui. The study by Gingerich (1999b) in northeast Maui was also aimed at quantifying groundwater contribution to streams. No modeling was done, but the data collected are valuable for future studies, considering the island's future water-supply needs and the importance of stream flow and its relation to aquatic life.

Aquifer management studies include those by Oki (1997) for the island of Molokai; Oki (1998) for the central Oahu area; Oki (1999) for the Kona area of the island of Hawaii; Oki et al. (1999b) for the Kaloko–Honokohau National Historical Park on the island of Hawaii; Izuka and Oki (2002) for the southern Lihue Basin, Kauai; and Oki (2002) for the Hawi area of north Kohala, Hawaii.

As emphasized by virtually all modeling studies, information to improve the understanding of the groundwater flow systems includes head monitoring and salinity distribution data. Better characterization of the subsurface, especially regarding spatial distribution of hydraulic conductivity, is also essential for future studies.

The groundwater flow models described above were limited to areal or quasi-three-dimensional models that simulate a sharp interface between freshwater and saltwater or to solute-transport models that simulate a vertical aquifer section. The model of Gingerich and Voss (2005) is based on USGS's three-dimensional solute-transport (3D SUTRA) computer code. The model was used to estimate the freshwater lens and underlying transition zone in the Pearl Harbor aquifer. Oki (2005) also used 3D SUTRA to investigate the effects of low-permeability valley-fill barriers in the Pearl Harbor area. The study is ultimately aimed at identifying suitable sustainable use of groundwater in the area through protecting water quality against saltwater intrusion.

Todd Engineers and ETIC Engineering (2005) developed a management model for a portion of the southern Oahu groundwater system to study the effects of pumping on the transition zone. The fully three-dimensional model (FEFLOW; WASY, 2002) incorporated available data over a 15-year period to address the dynamics of the transition zone. The model includes density-dependent, unsaturated–unsaturated flow that accounts for dispersion in the transition zone.

Water Quality

Water-quality problems in Hawaii include contamination by organic chemicals discovered on Oahu in 1983 (Lau and Mink, 1987). Chemicals discovered include 1,2-dibromo-3-chloropropane (DBCP) and ethylene dibromide (EDB) in the Kunia well of Del Monte Corporation in 1977 (Mink, 1982). Additionally, 1,2,3-trichloropropane (TCP) was detected in the same year. The discovery of the contaminant led to the closure of nine municipal water-supply wells that combined for a total of 13 million gallon a day. That central Oahu site was included in the National Priorities List (also know as superfund list) in 1990. The study by Lau et al. (1987, 1993) indicated that a large region of Oahu contains detectable organic contamination due to chemical use on pineapple fields. Concerns about contaminants in the unsaturated zone as documented by Lau et al. (1987) motivated Green et al. (1988) to develop a dynamic model for predicting pesticide leaching, as well as to develop a leaching index for use in ranking pesticides. Along this line, Rao et al. (1985) had previously proposed an attenuation factor as a mobility index for ranking pesticides. However, Loague et al. (1989c, 1990) indicated efficient utilization of these indices requires a better characterization of chemical retardation and transformation processes.

Annual well contamination maps for the islands are provided by the Hawaii Department of Health at its web site (HDOH, 2006). Contaminants include agrochemicals, solvents, dry-cleaning agents, and insecticides. The site lists concentrations before and after treatment, if original values exceed the maximum contaminant limits set by the federal government.

Modeling chemical transport in Hawaii’s unsaturated subsurface is complicated by the thickness of this zone and the great variability of subsurface characteristics, such as hydraulic conductivity, chemical transformations, and dispersion parameters. Potential preferential flow in the unsaturated zone exists, complicating large-scale field assessments. Overlooking preferential flow may lead to unacceptable errors in estimating travel times and the risk of contamination (e.g., Ray et al., 2004). Modeling efforts include that by Loague et al. (1989a, 1989b), who satisfactorily tested a modified version of the model PRZM but indicated the need for a better soil database that would facilitate general use of the model.

Large-scale modeling studies are limited, and much effort is directed toward small-scale or laboratory studies and prototype field studies that deal with chemical transformation in unsaturated media. Examples of laboratory studies include that by Teo et al. (2004) on screening polymers for erosion reduction and particle settling on selected Hawaii soils.

Prototype studies include an ongoing project to assess the leaching potential of five new chemicals in Hawaii soils by Dr. C. Ray of the Department of Civil and Environmental Engineering and the Water Resources Research Center. The EPA-registered chemicals include three herbicides, a fungicide, and an insecticide. The study results will be useful regarding management of agrochemicals, and they also will provide useful data for modeling purposes.

Among the few completed regional studies, Whittier et al.'s (2004) dealt with assessing both groundwater and surface-water sources in Hawaii. Groundwater sources account for about 88% of the total number of sources. The study included delineating the source-water assessment area, preparing an inventory of the potential contaminant sources within the assessment area, determining the public water system's susceptibility to contamination, and involving the public in the process. Both fixed-radius and time-of-travel (TOT) criteria were used in the delineation process. The zones based on TOT were delineated using the numerical groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) and MODPATH (Pollock, 1994). MODPATH was used to simulate the conservative advection of dissolved-phase contaminants or microbes.

The study employed horizontal flow barriers, rather than an equivalent porous media approach, in modeling the rift zones and valley fills. This method improved the simulated groundwater flow direction, capturing the anisotropy of the rift zones and preventing the overestimation of well drawdowns.

Water Reuse and Desalination

Water recycling is an important aspect of conservation that is achieved by reducing the use of precious potable water. A number of studies on the potential use of non-potable water for irrigation were completed. Early studies by Lau et al. (1975, 1980, 1989) indicated that wastewater, when properly applied on land, would not be a source of groundwater contamination. In a more recent study by Murakami and Ray (2000), secondary treated, filtered, and chlorinated effluent blended with potable water was used for turf grass irrigation at a golf course on Oahu. The study indicated possible dilution with rainwater. The study also emphasized that fecal coliforms are not suitable as indicator bacteria, due to their natural existence in tropical environments. *Clostridium perfringens*, which is present in large numbers in wastewaters, may be a better indicator bacterium since it is not found in large numbers in the natural soil environment.

Liu et al. (2002) developed and tested a prototype wind-driven reverse osmosis desalination system. The energy efficiency of the system was measured at 35%, which is comparable to the typical energy efficiency of well-operated multi-vaned windmills. Additional use of the technology for aquaculture wastewater treatment and reuse is described by Qin et al. (2005). A current project under the supervision of Dr. C. Liu of the Department of Civil and Environmental Engineering is aimed at improving the delineation system in order to overcome some of the limitations of the current system.

Historical and Institutional Background

Even before outsiders came to Hawaii in the late 18th century, development and use of the water resources was a crucial factor in the everyday lives of the inhabitants. More recently, water allocation has generated controversy against a background of profound changes in the institutional and economic framework governing water use. Do these changes improve or detract from the efficient use of the waters involved?

Traditional Hawaiians basically shared the available water as a “common property” resource, practicing an allocation rule presumably adequate for the agricultural and domestic purposes of their times. In the mid-19th century, however, immigrants began cultivating sugarcane, and at the same time, cultivation of taro, the islanders' traditional staple, underwent rapid expansion. Conflicts arose that could not be resolved within the context of traditional institutions.

These conflicts were resolved initially by alienating land and water from the monarchy to private individuals, in the "Great Mahele" of 1848. In 1879, the discovery of artesian groundwater in the southern plain of Oahu facilitated expansion of sugarcane planting. With no established legal basis for the right to exploit it, however, groundwater was treated as a common property resource. The expectable overuse, reduced pressure and flows soon became evident.

A series of commissions were created to address these problems, culminating in the creation in 1929 of the Honolulu Board of Water Supply. With broad authority to regulate water development and use on Oahu (Cox, 1981), the Board of Water Supply began metering water services, repairing or closing leaky wells, and encouraging conservation (Chang, 1981). At the same time, water rates were kept as low as possible, thus giving users no incentive to conserve.

The Waiahole Ditch

Meanwhile, sugarcane planters recognized the benefits for crop yields of irrigated, rather than rainfed, agriculture. By the late 1870s, planters on several islands had built impressive irrigation works to exploit available surface water (Wilcox, 1996). However, these sources often dried up in the summer and could not supply as much water as growers wanted. In 1913, on Oahu, sugarcane planters began work on an aqueduct to bring water from the rainy windward side of the island to the drier central and leeward parts. The aqueduct system includes 27 connected tunnels, 37 stream intakes, and four development tunnels, in addition to the main tunnel piercing the Koolau Mountains (Herschler, 1966). This early engineering feat, which came to be known as the Waiahole Ditch, added around 27 million gallons daily (Mgd) to the water supply available for irrigation in leeward parts of the island.

The ditch’s principal beneficiaries were sugarcane plantations, but over the years, numerous small farmers and cattle growers came to depend on it. Further, since some 40% of irrigation water seeps back into the aquifer, irrigation contributed substantial recharge to the Pearl Harbor aquifer, the largest source of water for urban Honolulu (C. Lao, Honolulu Board of Water Supply, personal communication, 1996).

Although it facilitated sugarcane growing in leeward Oahu, the ditch diverted water from windward farms and caused several small streams to dry up. Some people had depended on the streams for fishing, not to mention for cultural and recreational activities. The diversion also may have changed the character of parts of Kaneohe Bay by reducing inflows of freshwater from the mountain streams emptying into the bay (Kresnak, 1995). Hence a re-examination of water rights in Hawaii, stimulated by a state Supreme Court decision in 1973, gave rise to much contention over who should control ditch water.

Water Rights: Changing of the Guard

In the late 1940s, the Gay and Robinson Plantation on the island of Kauai replaced an old and leaky diversion channel with a new tunnel and, in the process, reduced water available to the neighboring McBryde Sugar Co. After a decade of fruitless negotiations, McBryde brought suit in 1959 to clarify the water right. In the 1973 decision mentioned above, “the [State Supreme] court flabbergasted everybody involved in a fight already 50 years old by declaring the water didn’t belong to either plantation, it was public property. No one expected this outcome to what seemed to be a purely private fight” (Smyser, 1989).

The State court decision was appealed to federal courts. The federal court ruled that even though the State court decision had "placed a cloud on the title of the various private owners, this inchoate and speculative cloud is insufficient to make this controversy ripe for review" (Robinson v. Ariyoshi, 887 F.2d 2215, 217 (9th Cir. 1989) vacating 676 F. Supp. 1002 (D. Haw. 1987)). By thus deciding not to decide, the door was left open for the state government to expand its control over water resources.

Among other factors, the uncertainty over the status of water rights led the 1978 Constitutional Convention to propose an amendment directing the state legislature to establish an agency to protect the state's water resources and to regulate water use. Voters approved the amendment in 1978. There followed almost a decade of studies, proposals, hearings, and arguments over what type of institutions and laws would best serve the people of the state. The resulting state water code (State Legislature of Hawaii, Act 45, 1987; Hawaii Revised Statutes, chapter 174C) has been called a masterpiece of compromise (Lau, 1988). What remains unclear, almost two decades later, is whether the compromise melded the best or the worst of competing paradigms.

Briefly, the code established a six-person Commission on Water Resource Management with power to designate water management areas wherever the quantity or quality of water resources are threatened. Within designated management areas, any water use except domestic applications requires a permit. Permits specify the water source, quantity, use, location, and other information requested by the commission. Applications for permits must establish that the proposed water use (1) can be accommodated within the capacity of the source; (2) is a reasonable and beneficial use; (3) will not cause negative third-party effects; and (4) is consistent with "the public interest" and with state and county plans. The commission must approve almost all modifications of permit terms. In short, the water code subjected water rights to close state control and, in the process, introduced substantial uncertainty for water users. It provided for restrictions on transfers of water rights and provided no incentive for rights holders to conserve.

The court decisions and the new water commission together caused a complete halt to market-induced transactions in water rights and introduced a new element of uncertainty in water users' decisions. This came at a time when substantial economic changes called for flexibility in water allocation. Oahu Sugar Company, in particular, which had been the major user of Waiahole Ditch water, decided to cease crop production in 1995, thus bringing into question the future of the 27 Mgd of water flowing through the ditch. Disposition of this water remains a matter of contention between windward and leeward interests (Earthjustice, 2006). Small farming interests would like most of the water to continue flowing through the tunnel, whereas taro farmers and native Hawaiian and environmental groups would prefer to see most of it retained on the windward side.

Uncertainty regarding water rights extends to interests on the neighbor islands as well. The Iao aquifer on Maui, for example, has experienced declining head levels and salinity increases in recent years. Its status with respect to the state Commission on Water Resource Management remains unsettled, as does the question of sources to supply Maui's growing population.

Current Institutional Research

The uncertain status of water rights and water allocation in Hawaii has engendered much research from legal, economic, and technical standpoints. It seems clear that Hawaii will sooner or later have to turn to desalinating seawater. The economic decision underlying desalination is not whether, but how soon, Hawaii must turn to this expensive means of satisfying water demand growth. First, studies have shown that demand for water is at least somewhat elastic: a 10% increase in the quantity charge for water sold to Oahu single-family residences will cut demand by about 3.5%, other things the same (Moncur, 1987). Second, accounting practices of the Honolulu Board of Water Supply (like that of most other U.S. water utilities) have led to undervaluing the resources used in providing water and thus to low quantity charges, which, in turn, have resulted in overconsumption of water (Moncur and Pollock, 1996). Finally, the Honolulu Board of Water Supply, like many other U.S. water purveyors, fails to account for the value of water in the ground (Moncur and Pollock, 1988). All these factors together suggest that a considerable slowing in the rate of growth of water demand could be achieved through demand management rather than supply enhancement.

Conventional planning suggests that some areas in Hawaii might require desalination by 2025 (Dingeman, 2003). Optimal control models combining economic analysis with simple hydrology (e.g., Kaiser et al., 2003) suggest that conservation brought about by economically efficient water pricing could push that date forward by 25 to 35 years. Moreover, water rates can be structured so as to avoid political backlash and at the same time enhance equity of the rate structure. These goals can be met by delivering an initial block of water at low or no cost, pricing higher consumption at marginal cost, and levying pumping surcharges on consumers at high elevations (Pitafi, 2005).

Concluding Remarks: Research Needs

Hawaii hydrogeology is complex. Aquifers are composed of basalts, geologic barriers, volcanic rift zones containing intersecting low-permeability vertical dikes, and valleys filled with sediment that act as barriers to flow through layered basalts. Thus Hawaii groundwater aquifers are heterogeneous at a multiplicity of scales. Traditional aquifer test analyses assume aquifer homogeneity. There is a need to develop new methodologies as well as to apply existing ones for parameter estimation. Existing methods include hydraulic tomography, which has been applied in other parts of the country (Yeh and Liu, 2000), and direct inversion of the permeability field based on the analysis of the displacement of a passive tracer (Zhan and Yortsos, 2001).

The water resources of Hawaii are being stressed by withdrawals from aquifers and by diversions from rivers and reservoirs to meet various needs. There are conflicts caused by increasing requirements to leave water in streams and rivers to meet environmental, human, and recreational needs. Limited water supplies require effective management within available sustainable supplies. There is a need to develop an integrated approach for resource management. Possible approaches include optimizing water supply operating rules under stochastic inputs (Cui and Kuczera, 2005) and integrating agricultural policies and water policies under water supply and climate uncertainty (Mejías et al., 2004). In addition, further economic research is needed to estimate values of environmental and recreational uses of water, as well as to investigate the effect of various water rate structures on growth of demand for non-residential uses.

Some Hawaii volcanic rock aquifers have low regional bulk permeability, which restricts areas of high-yielding wells and tunnels. Declining water levels and productivity in some of these wells and tunnels are expected due to overpumping. There is a need to develop geophysical methods for identifying new water sources through exploitation of low-conductivity zones. There is also a need to develop new geophysical methods to explore new water-supply aquifers.

Studies to address hydrogeochemically heterogeneous aquifers are lacking. Available methods include using partitioning tracers to optimally estimate aquifer parameters (Zhang and Graham, 2001).

Some Hawaii hydrogeological systems are characterized by a very deep unsaturated profile, consisting of soil and saprolite. The lack of information about such a zone has affected our ability to understand the impact of contamination on the saturated zone. There is a need to develop exploration methods to describe the spatial variability of this zone and its effects on chemical transformations.

The dispersion process is not well understood in fractured basalts. Recent tracer tests completed in deep wells by researchers at the Water Resources Research Center have demonstrated unusually long tailing of the breakthrough curve. There is a need to develop methods and models to describe the effects of aquifer variability on different scales of the dispersion phenomenon.

Classical scientific theory states that organic contaminants should move through basaltic aquifers without retardation due to the extremely low organic carbon content of the rock. Field observations show that organic contamination persists for decades in the source area, long after the active source of the contamination has ceased. A combination of advanced field and theoretical research is needed to address this problem.

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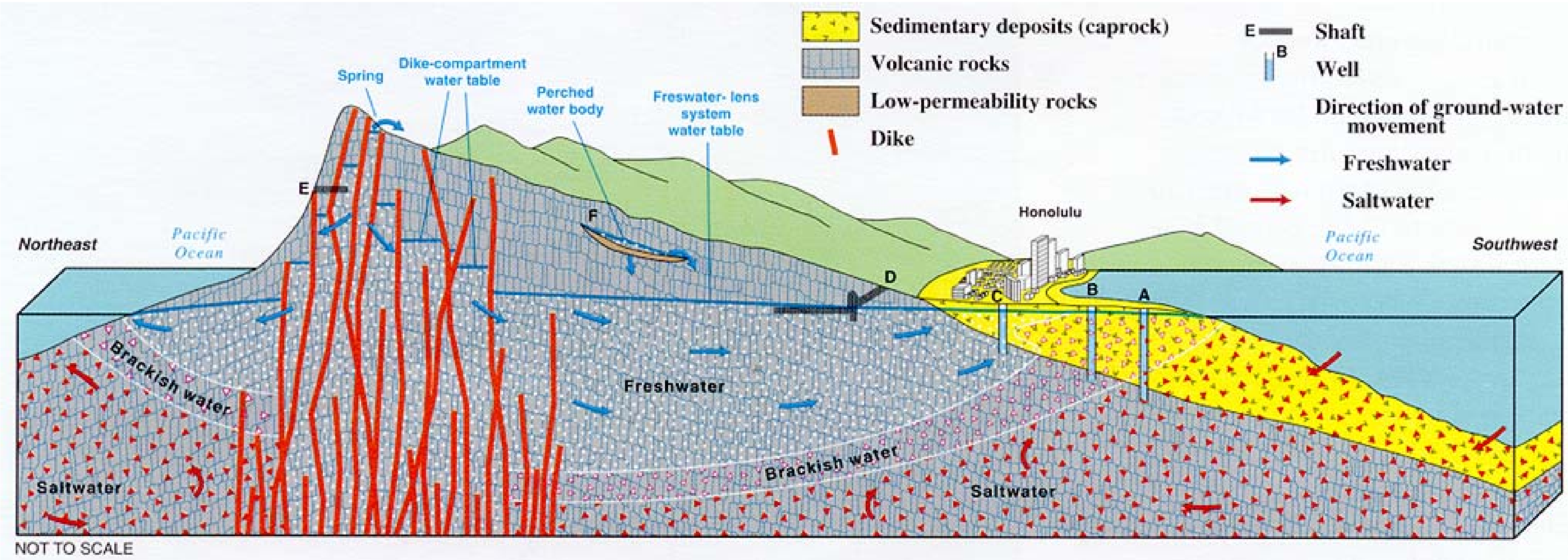

Figure 1. schematic cross section of the island of Oahu showing various hydrogeological features and different water development installations (Gingerich and Oki, 2000).