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March, 1985

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Uses and Abuses of Wastewater Injection Wells in Hawaii¹

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ABSTRACT: During the past two decades in Hawaii, more than 500 injection wells for the disposal of domestic sewage wastewater have been constructed and operated. Thus far, contamination of potable groundwater supplies has not been a problem. Many of the injection wells, however, have not performed as designed, and aquifer clogging and reduced injection capacity have produced numerous well failures resulting in public health, legal, and financial problems. Factors most commonly responsible for the well problems have been unfavorable hydrogeology, underdesign of injection well capacity, poor effluent quality, and lack of injection well maintenance. Detailed study of clogging mechanisms in the immediate vicinity of injection wells suggests that binding of pore spaces by nitrogen gas is the most important cause of aquifer clogging. Other clogging mechanisms also operating are filtration of solid particles and growth of microorganisms.

THE HAWAIIAN ISLANDS ARE principally dependent on groundwater for potable water supplies. Consequently, the disposal of liquid wastes into the subsurface is of great concern. The principal mode of groundwater occurrence is the basal (or Ghyben-Herzberg) lens of fresh water overlying and displacing the denser saline water. The basal groundwater body is generally thickest and freshest where recharge (i.e., rainfall) is greatest, which is generally in the interior portions of the islands. Along the coastal margins of the islands, groundwater bodies are generally thinner and more saline. The predominant aquifers are highly permeable basaltic lava flows. However, in the coastal portions of the older islands, especially Oahu and Kauai, less permeable marine and alluvial sediments, commonly referred to as caprock, often occur and may confine fresh basal water beneath them. The caprock materials may also contain some fresh groundwater, but more commonly contain brackish water.

Because the Hawaiian Islands are surrounded by the Pacific Ocean and the vast majority of the population lives in the coastal region, disposal of municipal wastewaters has been achieved mainly by ocean outfalls in the urban sewered areas and by cesspools in the rural unsewered regions. During the last two decades, however, numerous hotels, apartments, and condominiums have been constructed in outlying unsewered areas, generally along the coast. These new facilities have produced volumes of sewage that for the most part are too great for cesspool disposal, but too small for economic ocean outfall disposal. As a result, the use of injection wells for subsurface disposal has proliferated, often with less than satisfactory results (Figures 1 and 2).

HAWAIIAN INJECTION WELLS

At present there are more than 250 injection facilities that utilize over 500 injection wells in the state. These wells are used for a variety of industrial and domestic wastes, but the majority are for the disposal of treated sewage effluent. Figure 3 shows the generalized location of injection well facilities in the State of Hawaii.

Most wells are privately owned and operated and are characterized by shallow depth

¹ Manuscript accepted 1 November 1984.

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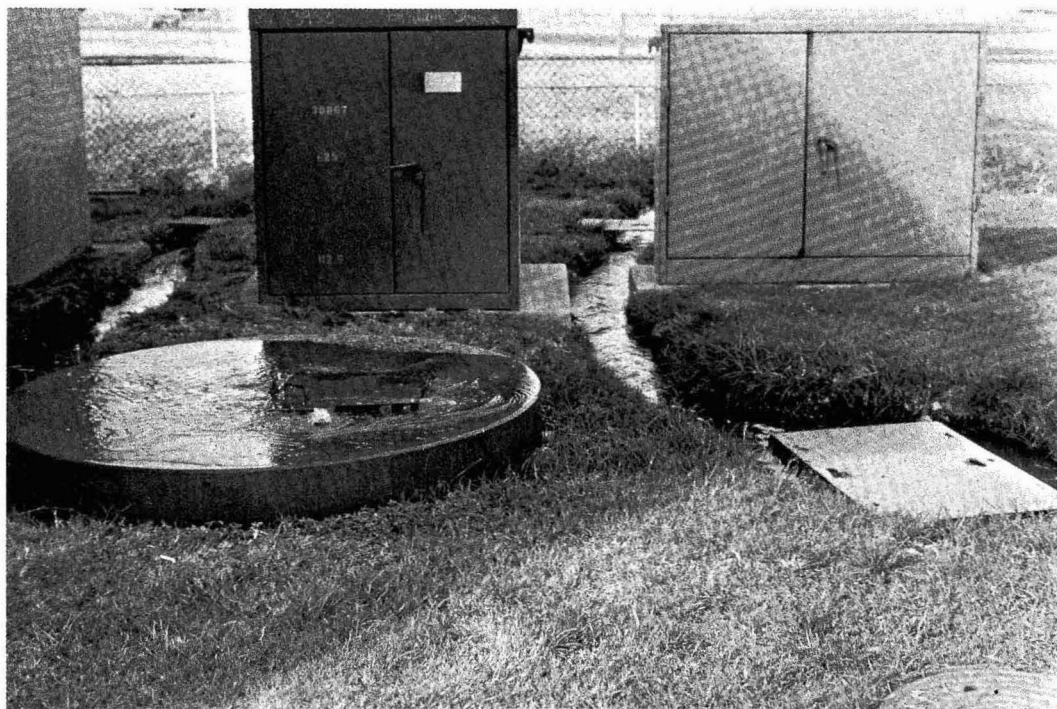


FIGURE 1. Overflow of sewage effluent from clogged injection wells, Ewa Beach, Oahu.

(usually less than 30 m), small diameter (0.10 m being the most common), and injection rates of only a few hundred liters per minute. In addition, there are several municipal injection well facilities on Oahu and Maui. The wells at these facilities are generally deeper and larger than the private installations, and typically inject several hundred thousand to a few million liters per day of wastewater.

Most of the injection wells in Hawaii, especially those for disposal of treated sewage effluent, are located in the coastal region where the receiving waters are brackish or completely saline. In this environment the groundwater table usually lies only a few meters below the ground surface; therefore, water table fluctuations resulting from ocean tides and storms and seasonal changes in groundwater recharge often significantly affect injection well performance. The receiving formations are generally sedimentary caprock materials, but in some regions, especially on Hawaii Island, the receiving formations are lava flows. Figures 4A and 4B show a hydro-

geologic cross section and a plan view of wastewater injection into a typical coastal aquifer environment.

INJECTION WELL PROBLEMS

Wastewater injection poses two distinctly different types of potential problems in the Hawaiian environment. If the injectant migrates too far from the injection wells without sufficient dilution by the resident groundwater, contamination of potable groundwater supplies and the shallow nearshore coastal waters may result. Contamination of fresh groundwater bodies by injected wastewater has been investigated in detail by Peterson, Williams, and Wheatcraft (1978) and Wheatcraft and Peterson (1979), and is not known to be a significant problem at the present time. Fortunately, because virtually all wastewater injection is restricted to coastal areas where the groundwater is generally brackish or saline, freshwater aquifers have not been



FIGURE 2. Compressed air used to unclog injection well, Ewa Beach, Oahu.

threatened. The Honolulu Board of Water Supply (1982) and the Hawaii State Department of Health (1984) have set stringent controls on the placement of injection wells (Figure 5). Wastewater injection is generally allowed only in those areas where the chlo-

ride content in the groundwater exceeds 5000 mg/liter. Furthermore, in areas where basaltic aquifers containing potable water underlie sedimentary caprock, injection into the caprock is permitted only where at least 15 m of nonpermeable material separates the

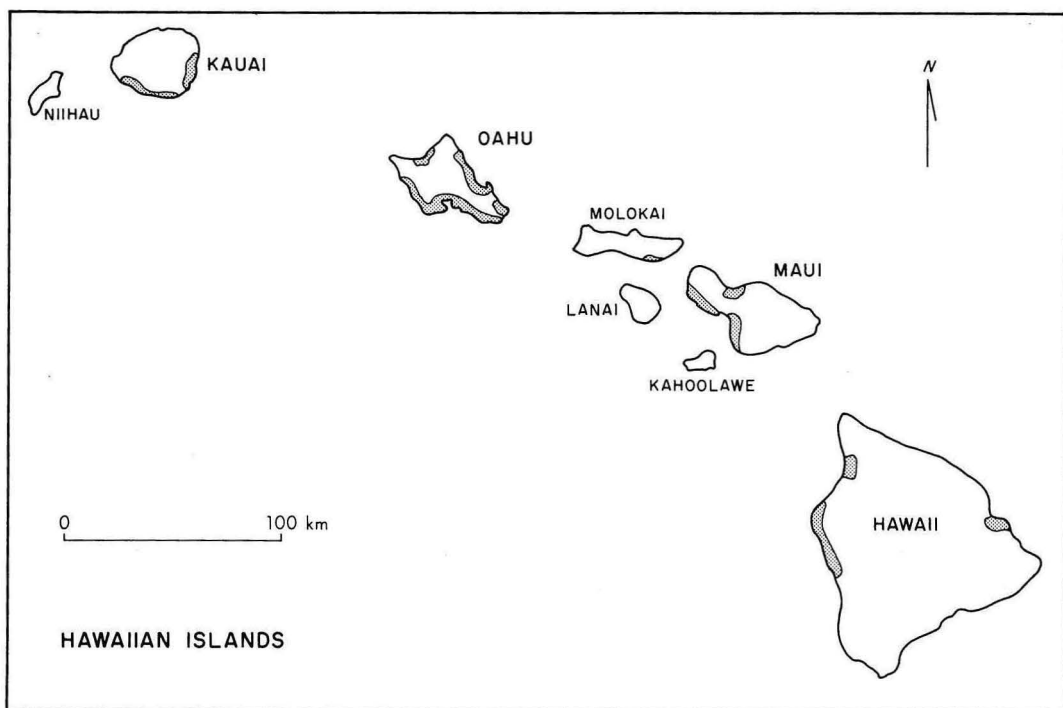


FIGURE 3. Generalized location of injection well facilities (stippled areas) on the islands of Kauai, Oahu, Molokai, Maui, and Hawaii.

potable groundwater from the bottom of the injection wells.

The extent of shallow coastal-water contamination is more problematic. Wastewater injected into coastal aquifers only a few tens or hundreds of meters from the shore must discharge, virtually undiluted, directly into the coastal waters (Figure 4*A, B*). The effects of coastal discharge are primarily a function of how deep and how disperse the discharge is, with deeper and more disperse discharge having less impact on shallow nearshore waters. In areas of extensive injection well development there have been few, if any, complaints of coastal-water contamination; however, no comprehensive study has been conducted to evaluate this problem. Clearly, more work is needed in this area.

A second and more serious problem posed by subsurface waste injection in Hawaii is clogging and rapid reduction of injection capacity in the immediate vicinity of the wells (Figures 1 and 2). Work by Petty and Peterson (1979) indicates that with the exception of a

very few areas (the most notable being the Kona Coast region of Hawaii Island), well over half of all Hawaiian wastewater injection wells have experienced significant clogging problems. The problems are manifest at small private facilities as well as at larger municipal plants, and have ranged in severity from slow, gradual loss of injection capacity over many months or a few years, to rapid and sometimes almost complete loss of injection capacity due to catastrophic events, such as treatment plant failures. A frequent result of severe clogging is well overflow, where a portion of the effluent discharges onto the ground near the well head. Public health and aesthetic problems often ensue, and legal action has resulted in several instances.

Given the rather dismal past record of injection well operation, the question must be asked, "Can injection wells be used successfully in the Hawaiian environment, and if so, under what conditions?" To answer these questions we must understand how and why clogging occurs.

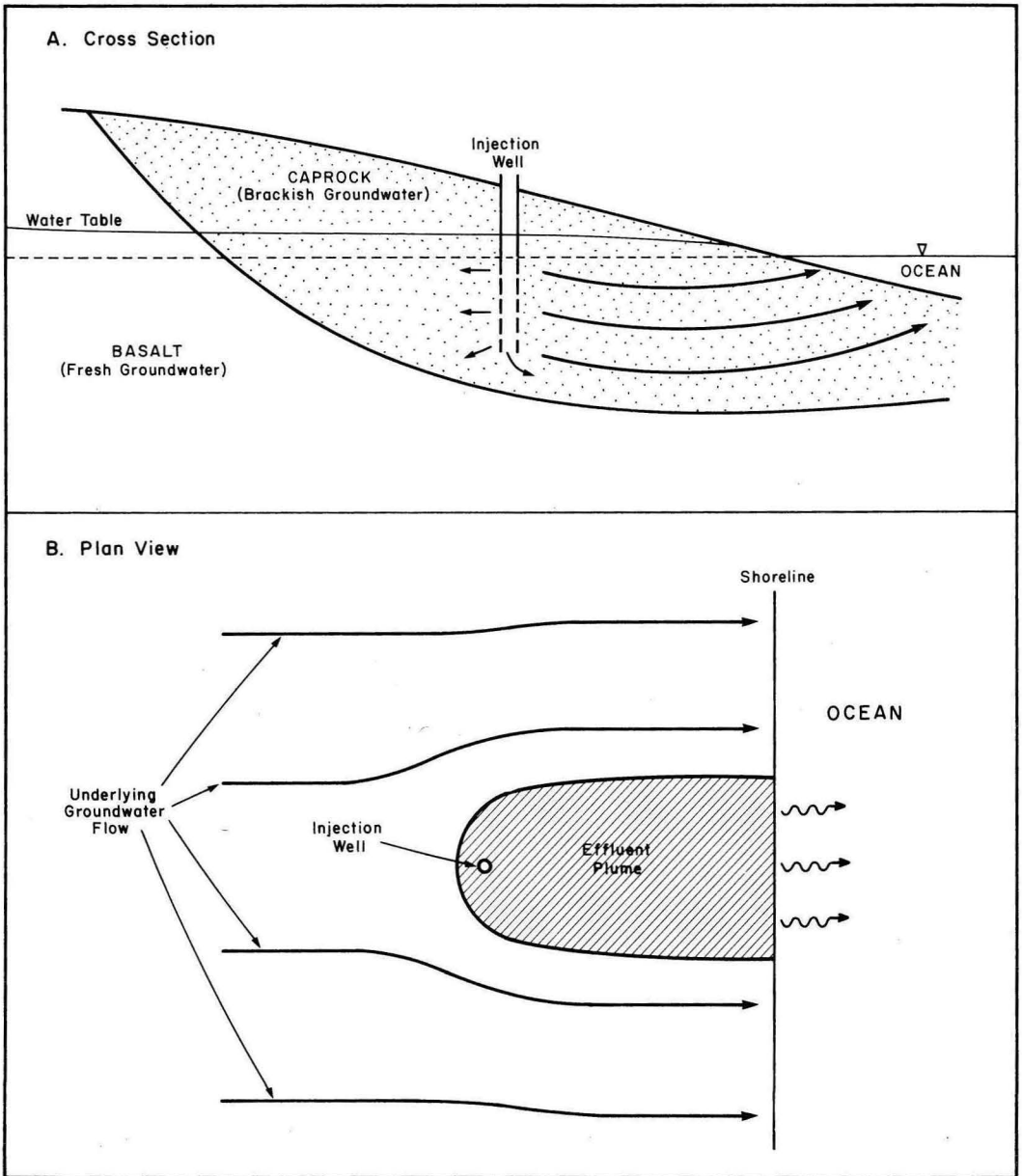


FIGURE 4. Wastewater injection into a typical coastal aquifer in Hawaii. *A*, cross-sectional view; *B*, plan view of wastewater movement and coastal discharge.

CAUSES OF CLOGGING

Virtually all the research done in Hawaii and elsewhere indicates that some degree of clogging of injection wells is inevitable, regardless of the suitability of the receiving formation, the quality of the injectant, or

the sophistication of the injection operation (e.g., see Ehrlich, Vecchioli, and Ehlke 1977, Harpaz 1971, Oberdorfer and Peterson 1982, Olsthoorn 1982, Petty and Peterson 1979, Ragone 1977, Rebhun and Schwartz 1968, Vecchioli and Ku 1972, Vecchioli, Ku, and Sulam 1980). However, past experience also

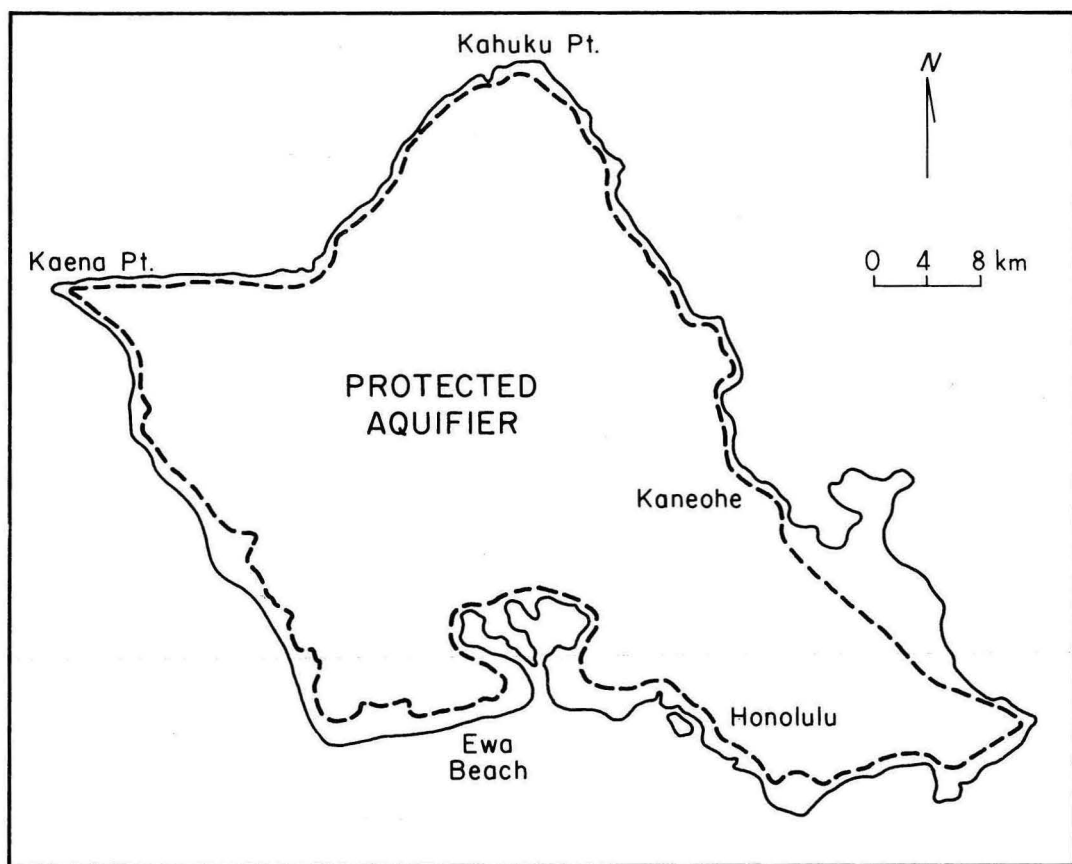


FIGURE 5. Proposed underground injection control line for Oahu. No injection wells are allowed inland of the dashed line. After Hawaii State Department of Health (1984).

clearly indicates that the selection of favorable injection sites, proper injection well operation and maintenance, and effluent quality control greatly enhance injection well success.

In their study of Hawaiian wastewater injection well problems, Petty and Peterson (1979) determined that several factors were largely responsible for injection well failures. The most important of these are (1) unfavorable hydrogeology, (2) underdesign of sustainable injection well capacity, (3) poor effluent quality, and (4) lack of proper injection well maintenance.

Most commonly, unfavorable hydrogeologic conditions result from low-permeability receiving formations. Generally, volcanic rocks comprise the most favorable injection formations, but in some cases poorly permeable lavas, especially ponded flows and weath-

ered zones, have experienced severe clogging problems. In the caprock, coral reef and reef rubble material are most suitable for injection, with the fine-grained sediments experiencing the greatest clogging problems. An additional factor of critical importance that is often overlooked in selecting injection well sites is that virtually all geologic formations undergo substantial reductions in permeability during injection. Thus, formations that initially have only modest permeability may be totally unsuitable for wastewater injection. Oberdorfer and Peterson (1982) recommend that a minimum injection capacity of 100 liters/min per well be required for all Hawaiian wastewater injection sites.

Shallow groundwater tables also contribute to injection well failures. In coastal regions the water tables usually are less than 5 m below

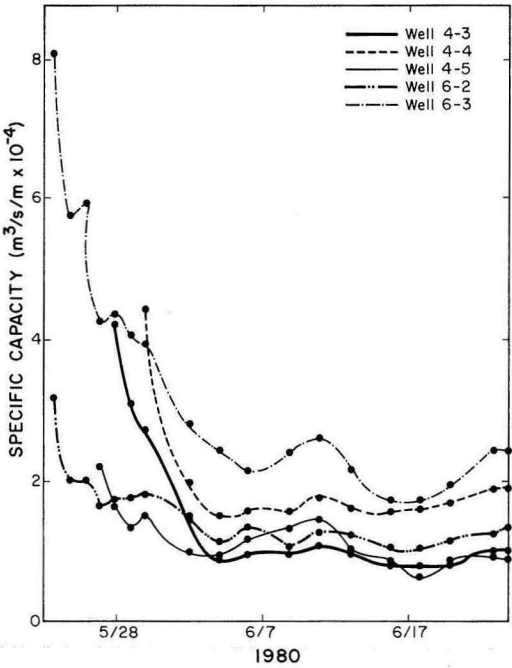


FIGURE 6. Injection capacity versus time for Waimanalo, Oahu, experimental injection wells. After Oberdorfer and Peterson (1982).

the ground surface and often are only 1–2 m deep. Because most injection systems in Hawaii operate by gravity flow, these shallow groundwater tables leave little room for the additional injection head buildup that almost inevitably results from well and aquifer clogging effects. Fluctuations of the groundwater table because of tidal effects, storm waves, and groundwater recharge further add to the problem. At some injection sites very close to the shore, water table fluctuations of 2 m or less, when combined with clogging effects, have resulted in well overflows.

Another common cause of failure of existing injection wells has been the consistent under-design of injection well capacity. Oberdorfer and Peterson (1982) conclusively demonstrate that clogging effects commonly reduce initial injection well capacities by 50% and, in some cases, by as much as 90% (Figure 6). A set of recommended reduction factors (Table 1) to be applied to the injection test results was determined for Hawaiian injection situations as a way of predicting the maintainable injection

TABLE 1		
INJECTION TEST REDUCTION FACTORS TO DETERMINE INJECTION CAPACITY		
TEST FLOW RATE OF SINGLE WELL		% OF TESTED CAPACITY
m ³ /sec × 10 ⁻⁴	gal/min	
> 60	> 100	33.3
30–60	50–99	25
15–29	25–49	20
< 15	< 25	*

SOURCE: Oberdorfer and Peterson (1982).
* Should not be used for injection.

tion capacity. For example, from Table 1, an injection test flow rate of $40 \times 10^{-4} \text{ m}^3/\text{sec}$ translates into an injection capacity of only 25% of that, or $10 \times 10^{-4} \text{ m}^3/\text{sec}$. If these clogging factors are not recognized and accounted for in the design, failure is inevitable.

Inconsistent and often poor-quality effluent, especially at many of the small private injection systems, has greatly accelerated the clogging process. All injected effluent supposedly undergoes secondary biological treatment, usually some combination of extended aeration and/or aerobic digestion; however, high concentrations of suspended solids, 5-day biochemical oxygen demand (BOD₅), nitrogen compounds, and oil and grease often persist. Table 2 shows the concentrations of selected constituents in wastewater at several Oahu injection well sites. As can be seen from this table, a significant portion of the sites did not meet the Environmental Protection Agency standards for secondary effluent of a maximum of 30 mg/liter of suspended solids and BOD₅. Most of the sites not meeting these standards have experienced severe clogging problems, including well overflow. Although clogging of most injection wells appears to be inevitable, in many cases the adverse effects of clogging can be significantly reduced and the overall lifetime of the well lengthened considerably if appropriate well maintenance and rehabilitation practices are followed. In Hawaii, regular injection well maintenance has been only rarely practiced, and well rehabilitation measures often have been undertaken only after a well is completely clogged, thus making the clean-out effort less effective

TABLE 2

INJECTANT WATER QUALITY FROM SELECTED OAHU WASTEWATER TREATMENT PLANTS, FEBRUARY 1980–DECEMBER 1981

	EWA VILLA	EWALANI	HALEIWA SURF	KAHUKU SUGAR MILL	KULANA VILLAGE	MAKAUA VILLAGE	MOKULEIA SANDS	PAALAA KAI WWTP	PAT'S AT PUNALUU	WAIMANALO WWTP
Number of samples	7	7	9	8	7	9	9	4	9	10
BOD ₅	41 (3–86)	52 (19–100)	33 (5–70)	6 (1–12)	15 (8–20)	27 (8–61)	25 (6–100)	10 (5–19)	9 (3–23)	13 (2–32)
Suspended solids	81 (23–214)	81 (16–239)	38 (6–86)	29 (2–60)	13 (4–24)	44 (1–260)	23 (4–57)	9 (3–15)	10 (1–22)	10 (4–29)
Dissolved solids	543 (490–613)	606 (512–678)	574 (411–776)	430 (365–550)	594 (563–632)	351 (282–454)	597 (382–795)	509 (318–738)	314 (267–408)	296 (148–388)
Oil and grease	4 (1–7)	3 (3–4)	9 (5–19)	9 (3–18)	3 (2–3)	4 (0–11)	7 (2–17)	2 (1–4)	5 (2–8)	3 (1–5)
pH	7.3 (6.9–7.6)	7.2 (6.9–7.7)	7.2 (6.7–7.7)	7.7 (6.7–8.3)	7.3 (7.1–7.7)	7.2 (6.6–7.9)	7.1 (6.7–7.5)	7.0 (6.4–7.4)	6.9 (6.4–7.6)	6.8 (6.0–7.6)
Alkalinity (as CaCO ₃)	152 (122–178)	121 (68–218)	133 (38–159)	38 (7–59)	182 (101–210)	88 (53–127)	30 (3–68)	141 (91–198)	38 (16–72)	72 (28–133)
Chlorides	180 (140–340)	130 (50–170)	190 (120–260)	90 (90–100)	150 (80–180)	90 (70–110)	190 (110–220)	140 (120–170)	70 (40–100)	70 (50–80)
NO ₂ + NO ₃ -N	0 (0–2)	5 (1–9)	0 (0–1)	8 (5–11)	2 (0–9)	3 (0–11)	17 (7–23)	2 —	7 (1–18)	8 (0–12)
Total Cl residual	0.2 (0–0.4)	0.1 (0–0.3)	0	0.7 (0.2–1.3)	0	0	0.2 (0–0.4)	1.1 (0.5–1.5)	0	1.5 (0–45.)

SOURCE: Oberdorfer and Peterson (1982).

NOTE: Averages; ranges within parentheses; all figures are in milligrams per liter except number of samples and pH.

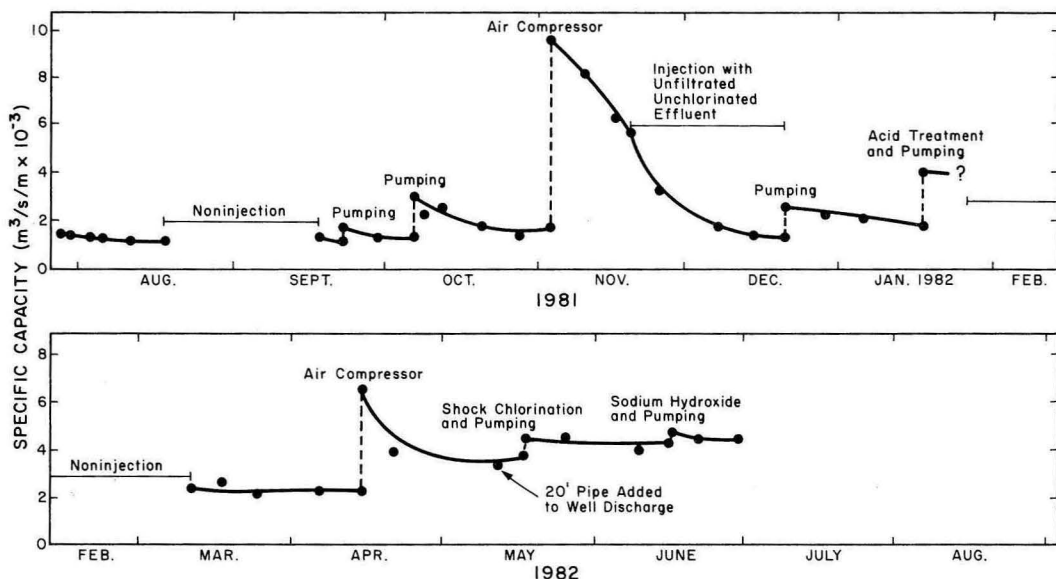


FIGURE 7. Injection history for the Paalaa Kai, Oahu, experimental injection well. After Oberdorfer and Peterson (1982).

than earlier attempts might have been. Findings from our own work (Oberdorfer and Peterson 1982) and those of others indicate that several physical and chemical techniques have been successful for Hawaiian injection wells. In particular, physical flow reversal methods, such as pumping or blowing out the water with compressed air, and chemical methods, such as acid and shock chlorination treatments, have proved successful in restoring most injection capacity. Figure 7 illustrates the restorative effects of various injection well rehabilitation methods.

To understand what the precise clogging mechanisms are, one must examine the detailed geochemical and biochemical processes that occur in the near-well environment during injection. Although injection wells are widely used in the United States and throughout the world, few detailed investigations of injection well clogging have been reported. Perhaps the most comprehensive study of this sort is a compilation by Olsthoorn (1982) of clogging problems associated with recharge wells. Other work pertinent to Hawaii's injection problems has been done by the U.S. Geological Survey on injection well clogging at Bay Park, New York (Ehrlich, Vecchioli,

and Ehlke 1977, Ragone 1977, Vecchioli and Ku 1972, Vecchioli, Ku, and Sulam 1980). The most significant conclusions from these studies are the following:

1. The major cause of clogging at most sites is filtration by the porous media of suspended solids contained within the injectant.
2. A second major cause of clogging results from microbial growth at the well face and within the aquifer pores.
3. Chemical precipitation processes are of lesser significance for clogging.
4. Clogging may occasionally result from entrapped air and gas bubbles introduced by the injectant.
5. Most of the clogging activity occurs at or very near the injection well aquifer boundary and, in many instances, a mat of filtration material forms directly on the well or aquifer surface.

To determine whether these same factors are important in clogging injection wells in Hawaii, the authors conducted a series of injection well field experiments. In these experiments, which ran for almost 2 yr, secondary-treated sewage effluent was injected into sedi-

mentary caprock receiving formations under conditions typical of those at most small private Hawaiian injection facilities. Data on injection head distribution and biochemical constituents in sediment cores and pore water within about 2 m of the injection wells, the zone most likely to experience severe clogging, were collected. These data suggest that during the first few days or weeks of injection, clogging by filtration of suspended solids and by microbial growth are most important. Over the long term, however, it appears that nitrogen gas is produced by denitrifying bacteria in sufficient quantities to be an important contributor to clogging of pore spaces by gas binding.

These results, which are described in detail by Oberdorfer and Peterson (1982, in press) and Oberdorfer (1983), are based on experiments at only two injection sites and must be further verified. If, however, nitrogen gas binding proves to be a significant clogging mechanism at other sites, we need to rethink some of our ideas on clogging control and injection well rehabilitation. To better control clogging in the first place, perhaps more emphasis should be placed on control of nitrogen compounds and denitrification processes; and to achieve more efficient well rehabilitation, more emphasis might be given to treatments that reduce gas binding.

OUTLOOK FOR THE FUTURE

Based on injection well experience in Hawaii during the past two decades, several observations seem appropriate. First, because of stringent control on the location of injection wells, contamination of potable groundwater bodies by injected effluent has not been, and in the future should not be, a significant problem. Likewise, with the possible exception of a few localized areas, contamination of shallow coastal waters should not pose a significant problem. Clogging will undoubtedly continue to be a major obstacle to the successful operation of existing and future injection wells.

It is possible, however, to achieve considerable improvement in injection well performance if steps are taken to eliminate existing

deficiencies. The most important of these involve better site selection, more realistic injection capacity prediction and design, better control of injectant quality, and the use of more diligent well maintenance and rehabilitation practices.

In conclusion, it is now quite clear that injection wells are not the low-cost maintenance-free wastewater disposal alternative they were once thought to be. Furthermore, it is quite likely that under all but the most favorable of conditions, the useful lifetime of injection wells is quite short, probably only a few years at the most, and perhaps their use should be considered only as an interim disposal solution. Nonetheless, at favorable sites, the use of wastewater injection wells can be moderately successful if adequate effort and money are expended to ensure their proper operation.

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