FINAL REPORT

Reevaluation of the Ground-Water Resources

and Sustainable Yield of the Ewa Caprock Aquifer

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Background

The ground-water flow system in the Ewa Plain area is composed of a freshwater lens overlying a brackish zone transitioning to a saltwater body. Ground water moves generally toward the ocean through volcanic rocks but is impeded by a wedge of sediments (caprock) that overlie the volcanic rock near the coast. The Ewa Plain caprock is a thick wedge of interbedded marine and terrestrial sediments that were deposited on the flanks of the Koolau and Waianae volcanoes during sea level changes and isostatic subsidence of Oahu during the Pleistocene ice ages. At the coast this sequence is greater than 1,000 feet thick (Stearns and Chamberlain, 1967). Inland, the sediments thin and pinch out against weathered lava flows. Figure 1 is a typical cross-section of the Ewa caprock that was presented in Report R-79 (Mink, 1989).

The caprock contains multiple sedimentary layers representing both low and high permeability (Stearns and Vaksvik, 1935). Water from the inland basaltic aquifers is relatively fresh (less than one percent seawater), but as it moves toward the ocean it mixes with seawater forming a brackish transition zone within the upper caprock sediments. Ground water in the upper layers of the caprock flow system are unconfined, but water in the lower caprock layers and in the underlying basalt near the coast is confined or semi-confined by overlying geologic units.

Traditionally, major sources of water to the caprock aquifer in the Ewa area are recharge from irrigation, rainfall infiltrating the land surface, and lateral and upward subsurface flow from the volcanic or basal aquifer. Infiltration from irrigation water is derived from pumped wells within the caprock area, and water pumped from wells outside the area that was imported and distributed for cane cultivation.

The purpose of this report is to reevaluate the ground-water resources of the Ewa Caprock aquifer. This aquifer is also referred to the upper limestone aquifer. Reevaluation will involve reviewing historical data regarding chloride (Cl) concentration of water from wells, pumping records of wells and well batteries, water levels in caprock wells, precipitation records, land uses, irrigation practices, and sustainable yield estimates.

Description of the Caprock Aquifer

The primary aquifer in the caprock is the highly permeable upper coralline limestone layer (referred to as "Limestone Aquifer 1" in Report R-79). This unit is the uppermost layer in the caprock. The limestone layer continues offshore, but inland contacts alluvial sediments (Mink, 1989). Between the coralline limestone and the alluvial sediments is a marl (limey mud) layer of low permeability. Ground water within the aquifer is unconfined with water levels ranging from less than a foot to several feet above sea level. The general ground water gradient is toward the coast. However, at Honouliuli ground-water discharges as springs into West Loch.

Below this upper limestone layer, and found throughout the Ewa Plain, is an ubiquitous brown clay layer that acts as a low permeability bottom (aquitard) to the limestone aquifer. The clay layer is deeper at the coast than inland. Therefore, near the coast the brackish ground water floats on saline water as a Ghyben-Herzberg lens, but inland the brown clay truncates the salt water. Below the clay are other coral, sand, and mud deposits that contain very brackish to very saline water. All plantation caprock wells and most recent caprock wells exploit the upper limestone aquifer due to its high permeability. Alluvial ground water may be available in the Honouliuli area. However, developing alluvial water is not as easy as from the limestone due to the generally lower permeability of alluvium.

Prior to sugar cultivation, the caprock received a long-term constant flux of ground water as natural leakage from the Koolau and Waianae basal aquifers, and intermittent recharge from rainfall and occasional large storms which allowed dry streams, such as Kaloi Gulch, that flow to the Ewa Plain. The amount of ground-water inflow from the basalt into the caprock is a function of the height of the water table in the basalt and the permeability of the sediments receiving the water. The upper limestone aquifer is not in direct contact with the basaltic aquifers. Ground-water inflow from the basalt is along the geologic contact between the basalt and old terrestrial sediments.

Prior to 1879 visible basal aquifer inflow into the Honouliuli region was seen as springs and in drainage ways to West Loch (Stephen Bowles, personal communication, 1996). When the first artesian well was drilled near Honouliuli in 1879 ground water rose to an estimated height of 32 feet msl (Cox, 1981, p. 55). West of Honouliuli the original ground water level in the Waianae aquifer would have been about 10 feet less (Mink, 1980, p.37). The termination of recharge from sugar irrigation into the caprock aquifer is similar to pre sugar irrigation days, except that the amount of ground-water inflow is less due to the reduction of water levels in the basal aquifer.

Because of Ewa Plain's land use history, CWRM Report R-79 (Mink, 1989) divided the caprock into five broad areas: 1) Honouliuli; 2) Puuloa; 3) Kapolei; 4) BPNAS; and 5) Malakole. The Honouliuli and Kapolei areas essentially overlie alluvium, while Puuloa, BPNAS, and Malakole areas essentially overlie coral limestone. However, for convenience of management this report considers Honouliuli-Puuloa, Kapolei-BPNAS, and Malakole to be single regions. The upper limestone and alluvium aquifers are hydraulically connected throughout the management units, but there may be only a weak connection between this aquifer and the lower ones.

History of Ewa Caprock Aquifer Development

Irrigation With Basal Wells

The Ewa Plain has been irrigated with ground water since 1890. By 1930, Ewa Plantation had drilled 70 artesian basal wells (clustered as pumping batteries) through the Ewa Plain caprock sediments to irrigate cane lands south of Farrington Highway (Stearns and Vaksvik, 1935). From 1930-35, five shallow wells (EP Pumps 20-24) were dug into the Ewa caprock to produce more irrigation water. All of them penetrated a shallow coral aquifer and were capable of producing large quantities of irrigation water. Later, other caprock sources were brought on line (EP Pumps 26,27,28,29; EP Pump 30; and EP Pump 31). Figure 2 is a map that shows the location of Ewa Plantation basal and caprock pumps and other wells located throughout the Ewa Plain.

When the shallow caprock wells were constructed, they pumped brackish ground water which is the result of caprock water mixing with the basal water already irrigating the region.

Figures 3-5 illustrate the chloride and pumpage history of the Ewa Plantation's basal sources. Pumpage includes total draft from the basal Koolau Aquifer, and individual well battery pumpage. For convenience, water quality from the various pump batteries are shown separately. Figure 3 presents the most saline of the sources. EP Pumps 1 and 9 probably applied all of its water in the vicinity of Ewa Mill and near the first caprock sources. These batteries had deep wells that were drilled into the upper transition zone of the basal aquifer. To improve quality some were plugged back with cement, but EP Pumps 1 and 9 were abandoned and sealed by 1951. Figures 4 and 5 show the marginal quality and potable quality sources respectively.

The freshest source, EP Pump 15,16, was recommended by Stearns (Stearns and Vaksvik, 1935, p. 460) as a way to freshen up the limestone aquifer. He noted that chloride concentrations in the basal sources had approached high levels and that pumpage from the new caprock wells would increase chloride concentrations in the limestone aquifer by recirculating irrigation water. Transpiration by sugar cane concentrated the salts in the return water. Construction of EP Pump 15,16 began in 1937 and it was put on-line to irrigate cane fields around 1939 or 1940.

Effect on Caprock Chlorides

Figure 6 shows initial (first 10 years) conditions in the caprock when the shallow wells were first constructed. Average yearly pumpage from the caprock for 1930-1940 was about 11 mgd, while seasonal variations ranged from less than 5 mgd to more than 15 mgd. Average basal pumpage for the same period was about 60 mgd. Water quality varied slightly with pumpage and with the seasonal variation of applied basal water. Though Stearns mentioned (1935, p. 460) that much of the applied basal water had chlorides as high as 700± mg/l (and higher), Figure 6 shows that the caprock sources range between 700± mg/l to 1,050± mg/l.

Figure 7 presents the history of pumpage and chlorides for all caprock sources utilized by Ewa Plantation and Oahu Sugar Company (OSCo) for 1930-1995. Unfortunately there are missing monthly pumpage data between 1940 and 1963. The estimated average of 12 mgd is from CWRM Report R-79 (Mink, 1989). Until the 1970's the average imported amount of Koolau basal water was 60-70 mgd. After 1981, the average amount dropped to less than 50 mgd. The graph shows a significant rise in chlorides for all caprock sources during the 1940's. CWRM Report R-88 entitled, Drought in Hawaii, indicates that the period from 1940-1954 was dry, and that "drought" was reported to be moderate to extreme. To compensate for the dry weather a seasonal increase in pumpage may have contributed to the rise in chloride concentration around 1947 as seen in Figure 7. After EP Pumps 1 and 9 were abandoned and sealed in 1951, fresher basal water was used to irrigate Ewa cane lands. Specifically, EP Pump 8 was used for cane wash water at the mill before irrigating cane growing over the limestone near the mill (Stephen Bowles, personal communication, 1996). The result was a wholesale freshening of the caprock aquifer from about 1948-1952. Chloride concentration within individual wells remained relatively stable to the mid 1970's, with EP Pump 23 continuing to freshen.

Rise in Caprock Chlorides (Mid 1970s)

The rise in caprock chloride concentration beginning in the mid 1970's was due to several factors: 1) an increase in average caprock well pumpage from 20 mgd to 30 mgd; 2) continued use of marginal quality basal water on lands near Ewa Mill and Fort Weaver Road; 3) several "extreme drought" periods throughout the 1970's reported in R-88; and 4) switching from furrow-irrigated cane to drip-irrigated cane in the mid 1970's to early 1980's (Hugh Morita, personal communication, 1996). When OSCo took over from Ewa Plantation around 1970, they may have operated the irrigation system differently. Hugh Morita (personal communication, 1996) said that EP Pumps 3 and 7 supplied water to Field 57, which is just north of EP Pump 23. From here the water split, some was piped to the EP Pump 23 distribution system and the remainder was sent towards Ewa Mill. All of this water irrigated fields growing over the coral aquifer. EP Pumps 4 and 6 sent water west to a ditch system that runs at elevation 120± feet msl. EP Pump 5 supplied water to a ditch at elevation 160± feet msl. EP Pump 2 and Pumps 15 and 16 supplied water to cane in the Honouliuli area. All of this water irrigated fields growing on the alluvium. EP Pump 8 was for domestic use only.

Land-Use Changes in Late 1980s

Since the late 1980's, Ewa Plain land use changes occurred rapidly as many cane fields were replaced by golf courses and housing developments. Consequently, the amount and location of applied irrigation water changed considerably. By November 1994 all irrigation to Ewa Plain cane fields had ceased and all OSCo caprock sources stopped pumping (except EP Pump 22). This action reduced the average 1994 pumpage from the caprock aquifer in the Puuloa area from 17 mgd to 3 mgd, resulting in a smaller portion of irrigation water returning to the caprock aquifer.

Periods of Apparent Chloride Stability

Examination of Figure 7 shows that only two periods of relative chloride stability exist in the record. The first is from 1930 to about 1940, and the second is from 1952 to 1970. Though chloride concentration varies in individual wells by as much as 100 mg/l, the overall long-term trend is stable. These intervals represent periods of probable stable pumping (no record exists from 1940-1964), cultivated acreage, and irrigation methods. The chloride quality of the mixture of the applied basal water (Figures 3-5) was relatively stable during the early 1930's, and again between 1952 to 1970. Chlorides in the caprock wells rose in the early 1940's when water quality in EP Pumps 1 and 9 worsened.

All other periods in the record that show rising (1940-1949; 1975-present) or falling (1950-1952) chloride values are during times of non-equilibrium when a major change took place such as caprock pumpage, irrigation method, acreage, or quality of applied basal water.

It is interesting to note from Figure 7 that even after sugar ceased, and total pumpage reduced to less than 5 mgd, some wells, such as EP Pump 22 used by Hawaii Prince Golf Course continued to exhibit rising chlorides. As will be shown below, rising chlorides at EP Pump 22 may in part be due to localized upconing.

Any ground-water flow or solute transport model constructed for the Ewa Caprock should calibrate to the two the quasi-stable periods outlined above, or ideally when all conditions are known. Unfortunately, for the period of 1952-1970 caprock pumpage can only be estimated at 12 mgd, and ground-water inflow from the basal aquifer can only be estimated for any period.

Natural Sources to Ewa Caprock Ground Water

There are three natural sources that supply water to the Ewa caprock. Ground-water inflow from the basaltic aquifers may be the largest source, but the hardest to estimate. Hydrologic budgeting can estimate recharge from rainfall precipitation that falls directly upon the Ewa caprock. The third source of water is from infiltrating storm flow that originates inland of the caprock, but flows overland through a network of drainage channels to the coast.

Estimates of Basal Ground-Water Inflow

Report R-79 utilized a single cell chemical mass-balance mixing model to calculate ground-water flows and caprock water chloride concentrations. As stated by Mink (1989, p. 2), AThe mixing model is used for deriving groundwater fluxes and salinities for past plantation activities...@. The model calculated a steady-state inflow at Honouliuli-Puuloa area of return water and ground-water inflow for 1930 at 15 mgd. For the drip irrigation period between 1982-87 the model still assumes a 15 mgd total inflow of water with a quality of 550 mg/l chloride. The model calculated a steady-state mix of 1226 mg/l chloride for water pumped from the caprock. The mixing model assumes complete mixing within a control volume (caprock aquifer) and does not account for Ghyben-Herzberg conditions where brackish water volume is reduced where it overlies saltwater. Mink (1989) estimates that 4 mgd of the 15 mgd was due to basal ground-water inflow, and 11 mgd was return irrigation water. The 4 mgd is taken as long-term average inflow of basal water.

Nance and McNulty (March, 1991) constructed a computer ground-water flow model of the Ewa limestone aquifer. In their model report, recharge into the caprock from basal water inflow originates entirely from the Koolau aquifer and estimated to be 4 to 5 mgd (Nance and McNulty, 1991, p. 14). Their model also considered post-OSCo time, and concluded that basal ground-water inflow would be 6.5 mgd.

The Camp Dresser & McKee (CDM) modeling report (December, 1993) estimates ground-water inflow at 1.25 mgd/mile. This inflow rate assumes that leakage from the basalt into the caprock only takes place into the upper limestone (report neglects alluvium at Honouliuli). The CDM report uses a total basalt aquifer inflow rate of 3 mgd.

Bolke and Bauer (in prep.) constructed a cross-sectional model across the Ewa Plain. The model extends from the Koolau basal aquifer to five miles offshore. The base of the model is assumed to be 5,000 feet below sea level. Using the Ghyben-Herzberg principle (i.e. the depth to the saltwater interface is 40 times the freshwater head) the model calculated the flow for various values of head, ranging from 10.0 to 19.6 feet above mean sea level (msl). Ground-water inflow values varied from 3.6 to 6.3 mgd/mile. Leakage from the basalt into the caprock is calculated by the model to occur to the depth of the saltwater interface.

Eyre (1987, p. 12) estimated a net inflow of 30 mgd leaking into the caprock (Kapolei area) from the Waianae basal lens during the plantation era (after removing plantation pumpage), and 33 mgd for pre-development (pre 1879) time (8 mgd of rainfall and 25 mgd natural ground-water flow from Schofield). The hydrologic budget was based on work by Giambelluca (1986) and employed by Eyre to solve a mixing-cell model that determined the effects of drip irrigation to water quality in the basal aquifer.

More recently Eyre and Nichols (in press) simulated recharge and discharge rates for Southern Oahu ground-water flow system for pre-development and average conditions during the 1950's. The model calculated ground-water inflow from the Waianae aquifer to be 40.6 mgd and 17.5 mgd for pre-development and 1950's conditions respectively. Ground-water inflow from the Koolau aquifer is harder to discern since caprock leakage is calculated for the entire Pearl Harbor area.

Estimates to Recharge by Rainfall Precipitation

The average yearly rainfall for the Ewa Plain is ranges from 15-20 inches/year. The average pan evaporation for the area is approximately 85 inches/year. Direct recharge by a rainfall event can only occur when the intensity of the storm is sufficient to overcome evaporation and infiltrate past the root zone in the soil mantle.

The effective direct infiltration by rainfall was estimated in R-79 to be about 25 percent of actual rainfall. Assuming 20 inches/year (25% = 5 inches/year) at Honouliuli and Kapolei areas and 15 inches/year (25% = 3.75 inches/year) for the other areas, Mink (1989) calculated a total of 4 mgd infiltration for Honouliuli and Puuloa areas, a total of 1.5 mgd for Kapolei-BPNAS areas, and 1 mgd for Malakole.

Other studies (CDM modeling, Nance and McNulty) lump direct infiltration by rainfall as part of the irrigation component in the hydrologic budget for the ground-water models. Giambelluca (1991) estimates that for natural ground cover the direct infiltration is 3.9 inches/year for the Ewa Plain at about 5.2 mgd.

Estimates to Recharge by Storm Flow

Storm flow from the Waianae Mountains that reaches the Ewa caprock and the sea occurs infrequently. Stream channels from Kaloi and Makakilo Gulches cross the plain. Mink (1989, p. 23) suggested that if all of the runoff infiltrated, it would amount to 2 mgd. However, some of the flow reaches the ocean so that a more reasonable recharge number is 1 mgd. The CDM model (1993) uses a value of 2 mgd.

Estimated Sustainable Yield of the Ewa Plain

Report R-79 provided sustainable yield estimates for the Ewa Plain caprock aquifer. Unlike the methodology used to calculate sustainable yield (SY) for large basaltic aquifer systems (State Water Resource Protection Plan, Vol. II, 1992), the sustainable yield estimate for the caprock is based on an optimal amount of pumpage to achieve an acceptable water quality for irrigation (assumed to be =< 1,000 mg/l chloride). Irrigation water with chloride concentration greater than 1,000 mg/l can be detrimental to crop growth due to the absorption of the sodium ion by clay minerals in the soil. The type of soils found over the Ewa Plain are prone to sodium build-up especially if the chloride concentration exceeds 1,000 mg/l (Visher and Mink, 1964, p. 78).

Under steady-state conditions the inflow of water to the caprock formation equals the outflow of water from the caprock formation. Quasi steady-state conditions existed prior to sugar cultivation on the Ewa Plain and during periods of stable irrigation practices and plantation pumpage. These periods, as reviewed above, are reflected by apparent chloride stability. During the plantation period the sustainable yield for the caprock aquifer is defined as "net pumpage" or the difference between total pumpage and the return irrigation component. With the present land use and irrigation practices very much different than several years ago, the new sustainable yield estimate must be less than the total of the presumed ground-water inflow, recharge from storm flow and rainfall precipitation, and from golf course, park, and urban return irrigation. The present irrigation recharge component is localized and small when compared to sugar irrigation return. Ground-water inflow can also be estimated by computer ground-water flow models and geochemical mixing models. Precipitation recharge and recharge from other land uses can also be estimated (Giambelluca, 1991; Mink, 1989).

During the plantation era (1930-1994), water quality was a function of cane acreage, caprock pumpage, irrigation method (furrow or drip), and basal water quality. Assuming that ground-water inflow is constant (in reality it is a function of freshwater head), changes in the irrigation method and acreage changed net pumpage or sustainable yield. Since water in the upper limestone aquifer is a result of a 100 years of irrigation, past land use changes and irrigation methods have altered the sustainable yield several times. Return basal irrigation water and natural ground-water inflow from the Honouliuli alluvium into the limestone aquifer contributed to recharge. Table 1 below summarizes these changes as presented in R-79 and Figure 5 for the Puuloa area.

Table 1. Summary of Irrigation and Chloride Changes

Period	Average Caprock Pumpage (mgd)	Caprock Chloride (mg/l)	Irri. Method	Remarks
1930-1940	11	700-1050	Furrow	Apparent Cl stability 2500 acres of cane
1952-1970	13	500-850	Furrow	Apparent Cl stability EP Pump 15,16 on line Sealing EP Pumps 1&9

Period	Average Caprock Pumpage (mgd)	Caprock Chloride (mg/l)	Irri. Method	Remarks
1970-1980	22	600-800	Furrow Drip	Apparent Cl instability EP Pumps 20,21,22 increasing chlorides
1980-1989	21	900-1000	Drip	Apparent Cl instability
1989-1994	14	1000-1400	Drip	Apparent Cl instability Reduced acreage

Report R-79 estimates (p. 41) that fields irrigated by Koolau or Waianae basal sources return 53 percent of the applied water if furrow irrigation methods are employed or 41 percent if drip methods are used (using water balance coefficients applied in CWRM Report R-78, 1988). For caprock sources 49 percent is returned for furrow, whereas only 29 percent is returned for drip. Using 1981 and 1986 (mentioned in R-79 as predominately furrow and drip years respectively) to compare differences for return water quantities over the entire region, the report estimates that 32 mgd of basal water and 15.3 mgd of caprock water was return irrigation in 1981, while 16 mgd basal and 5.5 mgd caprock was return water in 1986. Net pumpage in 1981 was 15.7 mgd, while in 1986 it was 13.5 mgd (R-79, p. 43).

From the above analysis of the return component, R-79 (p. 48) estimated the sustainable yield for the three areas. The report defines sustainable yield as maintaining chlorides at "less than 1,000 mg/l for current [as of 1989] and anticipated land use conditions". "Future" means when sugar operations cease, our present condition, and when there is no significant amount of return irrigation water. Table 2, below, was presented in R-79 (p. 48).

Table 2. Report R-79 Estimated Sustainable Yields

Estimated Sustainable Yield Caprock Aquifer		
Area	Current (mgd)	Future (mgd)[1]
Honouliuli-Puuloa	10-15	<10
Kapolei-BPNAS	5	<5
Malakole	<1	<1

[1]The present time

Presently, and in the recent past, the Puuloa area caprock aquifer is in a state of non-equilibrium. All imported basal water has ceased. Though pumpage from private wells averages between 2-3 mgd, a small and localized fraction of that amount returns as recharge. Recirculation of the same water and salt build-up in the soil can only be alleviated by direct infusion of fresh water. This infusion comes from sporadic large winter storms and from inflow from the basal aquifer.

Changes to Sustainable Yield

Ground-water conditions in the caprock aquifer are currently changing. It will take a period of time for a new quasi-equilibrium to set in. One and a half years have elapsed since the cessation of both sugar and the infusion of basal irrigation water. Presently, ground water (residual cane irrigation water + storm recharge + basal ground-water inflow + minor irrigation return water) slowly moves through the coral aquifer. Hydraulic properties and hydraulic stresses in the aquifer will determine how long it takes to reach a quasi-equilibrium.

As stated above, estimated sustainable yield for the caprock was based on a net pumpage that supported a particular water quality. Net pumpage now does not include a large return irrigation component, but may include an increase in basal ground-water inflow due to reduction of 60± mgd of basal pumpage and attendant changes in the basal water level. Therefore, a new sustainable yield that would maintain irrigation quality water must be much less than previously assigned. For the Honouliuli- Puuloa area, estimates for ground-water inflow range from 3 mgd (CDM) to 6.5 mgd (Nance and McNulty), while rain recharge is about 4 mgd for the area. Though Eyre (1987) estimated 30 mgd basal water inflow from Waianae by hydrologic budgeting, future work needs to be done to refine this estimate. Presently the inflow is less due to the loss of return irrigation water on fields overlying the Waianae basal aquifer.

Golf course irrigation is different than drip irrigation for cane since it is less intensive and is concentrated over a small area. Giambelluca (1991, p. 43) estimates that recharge attributed to park irrigation is about 6 percent of recharge from that of drip-irrigated cane fields. That is, 1.5 inches/year as opposed to 24.8 inches/year. Golf courses may be somewhat greater. For natural areas Giambelluca's water balance puts recharge at 16 percent of drip irrigation or 3.9 inches/year.

The Commission granted a current allocated use of 28.115 mgd for the caprock aquifer (excludes salt-water uses). If everyone with a permitted use pumped their allocated amount, the aquifer would quickly salt up and become unusable for irrigation. Every user would have to either cease or drastically reduce pumping and wait for natural ground-water inflow or for some kind of artificial recharge to improve water quality. From Figure 7, nonuse of EP Pump 27,28 after 1994 drastically reduced the chloride concentration at that source. Figures 8-10 show a freshening of water in the area surrounding EP Pumps 27,28.

The profound changes in land and water use indicate a need to better understand the resultant changes occurring within the aquifer. The new sustainable yield for the Puuloa area will be less than 10 mgd, perhaps close to 5 mgd. Constant monitoring of pumpages and chloride data will provide a refined estimate. As will be discussed below, we know that low capacity wells in Puuloa Sector have maintained relatively stable or improving water quality, whereas large capacity plantation wells appear to cause localized up-coning and increasing chlorides.

Analysis of Caprock Aquifer Since 1994

Background

Anticipating the cessation of sugar and the accompanying widespread land and water use changes, the CWRM staff have regularly sampled OSCo and private wells since April 1994. Chloride samples and specific conductance measurements are collected from about 20 wells on a monthly to six week schedule, and over a single day. Most of the wells are located in the Puuloa Sector, three wells are in the Kapolei Sector, and two wells are in the Malakole Sector. Since the program began, several wells were dropped and others added depending upon access or reliability of the measurement. The primary purpose of sampling is to provide baseline data that can measure changes to the caprock aquifer with time.

Figures 8, 9 and 10 are computer-drawn isochlor (lines representing equal chloride concentration) maps based on chloride data collected from wells in June 1994, September 1995, and February 1996. The isochlor lines only relate chloride data between the wells from which they were collected. In June 1994 (Figure 8) sugar was still being cultivated in the vicinity of EP Pump 23. Figures 9 and 10 represent land and water use conditions after sugar irrigation was discontinued. Recharge by rainfall and ground-water inflow will lower chloride concentrations. What is apparent when comparing Figures 8 with 9 and 10 is the worsening water quality around EP Pump 22, and freshening taking place west and southeast of Kapolei Golf Course toward EP Pumps 27,28. The EP Pump 22 situation may be a result of pumping and irrigation practices at Hawaii Prince Golf Course, whereas changes in water quality west of Kapolei Golf

Course are probably natural.

Generally, the data collected since 1994 support an estimated sustainable yield that is less than 10 mgd for the Puuloa area (current pumpage averages 2-3 mgd). As will be shown later, individual wells equipped with small capacity pumps, show either a reduction or stabilization of chlorides, while EP Pump 22, fitted with a large capacity pump (700 gpm), shows a continuing rise in chlorides. Figures 8-10 provide a "snapshot@ of the changes now occurring. Under the present condition, a concept known as the "sustainable capacity" of a well or well field becomes important. That is, a large capacity pump can exceed the quantity of water that can be drawn without degradation, and therefore, surpass its sustainable capacity. This concept also applies to a well field where wells are closely spaced and the combined pumpage causes continued degradation of the resource.

In the Kapolei-BPNAS Sector, the majority of the pumpage from the caprock is for the Kapolei Golf Course. Chlorides in the golf course wells are stable, and may be a result of basal ground-water inflow from the Waianae aquifer. The sustainable yield estimated by Mink (R-79, 1989) was less than 5 mgd. Present usage is about 1.1 mgd. A large portion of this aquifer is located under BPNAS where no pumpage occurs. Ground-water inflow from the Waianae basal aquifer is no longer 30 mgd estimated by Eyre (1987) but some lesser quantity. This amount would be ground-water flux (estimated 33 mgd) minus total pumpage in Ewa-Kunia Aquifer System (present average about 9 mgd) or about 24 mgd. As stated above, irrigation water no longer is applied over the Waianae aquifer.

R-79 estimated the Malakole area sustainable yield to be less than one mgd after sugar irrigation. Most of the usage is industrial. The upper limestone aquifer supplies some water that is in excess of 1,000 mg/l. Pumpage from this sector is over 12 mgd. Some of the pumpage is from a lower coral aquifer in the caprock.

Honouliuli-Puuloa Area

Since the demise of OSCo the greatest aquifer changes will occur in the Puuloa area. Present pumpage from the caprock for the area averages 2.8 mgd. About 1.5 mgd of the pumpage is east of Fort Weaver Road at the Hawaii Prince Golf Course and Ewa International Golf Club. Gentry Development Company irrigation wells and the Honouliuli Sewage Treatment Plant wells make up the remainder with small capacity wells.

Figures 11, 11a, 12, 12a, 13, and 13a focus on chloride as related to pumpage and land use changes since 1992 at Hawaii Prince Golf Course. Six wells supply the course with water. HPGC wells 1, 2, and EP Pump 22 (wells 1901-03, 1900-17, and 1900-02 respectively) are located about 500 feet, 1,000 feet, and 2,000 east of Fort Weaver Road respectively. Water quality at HPGC wells 1 and 2 appears to be improving over time, whereas at EP Pump 22 the opposite is occurring. EP Pump 22 pumps about four times the amount of water produced from each of the other wells. Though not shown, water quality at the HPGC wells near EP Pump 22 are affected by the high pumpage, suggesting possible upconing. Evaporation from the large reservoir ponds prior to irrigation will increase the chlorides of the applied water. Pan evaporation in Ewa is about 85 inches/year (R-79, p. 43). Salt can build up in the soil, only to be flushed back into the aquifer after a storm. The wells closer to Fort Weaver Road may also be affected more by storm recharge because of improving quality.

Currently, there is a request to increase the usage at EP Pump 22. From the data presented in Figures 11 and 11a, an increase in pumpage is not warranted since chlorides are already in excess of what the grass can tolerate and exceeds the 1,000 mg/l associated with sustainable yield. Greater pumpage at this well could adversely affect their other sources by increasing the chloride mixture of the irrigation water applied to the west end of the course, as well as exacerbate the localized up-coning on the east side. Ewa International Golf Club, located south and down gradient of Hawaii Prince, could also be detrimentally affected.

Figures 14, 14a, 15, 15a, 16, and 16a illustrate chloride and pumping trends at three Gentry sources. Palm Villa 1 (2001-06), and Palm Court (2002-12) show a general decline in chloride concentration since 1994. Palm Villa 2 (2001-08) declined from 1,200 mg/l from a sample collected in 1993 to an average of about 800 mg/l since 1994.

Gentry Development is proposing two new wells and water use permits in Puuloa. Because of the small pump capacities proposed for these wells, the likelihood that they would detrimentally affect the aquifer or neighboring wells is unknown but the effect is likely small. What will occur will be a reduction of ground-water normally leaking from the caprock at the coast that is equal to the amount of pumpage.

Figures 17 and 17a show an unusual phenomena at the Honouliuli Sewage Treatment Plant (STP). Wells 1902-03 and 04 are about 20 feet apart, drilled to a bottom elevation of -15 feet msl. Differences in chloride concentrations range from 50-300 mg/l with concentrations ranging between 500 and 700 mg/l. The general trend shows that chlorides have increased in Well 1902-03 but have remained stable in Well 1902-04. The difference in water quality must be due to some geologic control, such as a crack or solution cavity within the coral aquifer.

Water Levels in the Puuloa Area

As stated above, water levels within the caprock do not enter into estimating sustainable yield as with basaltic aquifers. Water levels can fluctuate as much as 0.5 feet during the day due to the ocean tidal signal, and over time, appear to be influenced by long-term tidal signals. From 1957-1963 water levels were collected in EP Pumps 21-24. Figure 18 shows the variation of average monthly water levels during the six and half years of measurement. The average water level at EP Pump 24 was 1.95 feet msl.

Figure 19 plots 1995 water level data collected by Tom Nance at EP Pump 24 and average daily ocean tidal record with daily rainfall at Ewa Mill and Honolulu Observatory at Ewa Beach. There does not seem to be any correlation between storm events and rising water levels. In fact, several high water level periods are during the driest part of the year. The ocean tidal signal accounts for large water level changes observed in Figure 19. Other factors that can effect water level are pumpage, ground-water movement, and discharge of ground-water through the caprock aquifer. Storm events seem to have a greater impact on water quality. The average water level for the short period of record is 1.75 feet msl. These water level data are difficult to explain as a result of the post-OSCo conditions. Nance (personal communication, 1996) believes, though, that for those wells that he has measured, water levels reflect both positive and negative changes due to cessation of OSCo pumpage and irrigation.

Mink (1989, p. 32) used the Darcy equation to roughly calculate the natural leakage from the caprock to the ocean:

$$\mathbf{q} = \mathbf{Kb(dh/dx)}$$

Where:

q = ground-water flux in ft./day/ft.
K = hydraulic conductivity in ft./day
b = depth of ground-water flow in ft.
dh/dx = ground-water gradient in ft./ft.

Using a hydraulic conductivity of 2,500 ft./day, a gradient of 1.6 ft./mile (0.0003 ft./ft.), and an average water level of 2 feet (where **b** = 80 feet using Ghyben-Herzberg principle), Mink calculated an approximate discharge rate of 11 mgd leaving the

Puuloa area along the 25,000-foot long coastline. However, from the data presented in Figure 19, changes in natural leakage from the caprock cannot be calculated with confidence, but can only be derived for comparative purposes.

For the present condition the water level at EP Pump 24 is assumed to be 1.75 feet msl, then the gradient becomes 0.00025 ft./ft. from the well to the coast (7,000 feet), and **b** becomes 70 feet. Again using **K** equal to 2,500 ft./day, a rough estimate for leakage along the Puuloa coastline is 8 mgd.

Kapolei-BPNAS Area

Present water use in this area averages about 1.1 mgd. Most of the caprock pumpage occurs at the Kapolei (HFDC) Golf Course. Of the six wells drilled, five are pumping. Water quality has stayed relatively constant. Figures 20 and 20a present pumpage and chloride data for Well B (2003-02). Average chloride for 1992-1995 is 450 mg/l and is relatively constant. Leakage from the basal aquifer is thought to be the reason for the constancy of the chloride data because imported water from basal wells ceased in 1994 while chloride concentration remained nearly constant.

Other wells in the sector include the Kapolei Campbell wells 1905-08 and 1905-10. The primary source, 1905-08, pumps about 0.150 mgd with chlorides averaging 500 mg/l. The Desalt Plant wells are presently off line. Its caprock source, Well 1905-09, averaged about 700 mg/l. The Desalt Plant wells are close to the Malakole area boundary.

Water quality underlying Barbers Point Naval Air Station is unknown. Pumpage from the Kapolei Golf Course wells and the Kapolei Campbell wells will affect ground-water quality and its availability.

Malakole Area

Pumpage from the Malakole Sector is presently about 12.2 mgd. The estimated sustainable yield for 1,000 mg/l water is less than 1 mgd. Of the total quantity pumped, 2.6 mgd from is brackish water developed by Kalaeloa Partners (wells 1805-03-09). Specific conductivity of the water developed by them average about 10,000 umhos which is equivalent to a chloride concentration of 3,000-4,000 mg/l. The additional 9.6 mgd is essentially highly brackish and saline used for wash down, cooling and other industrial purposes.

CWRM personnel sample the Hawaii Raceway Park well (1905-01). This well is used infrequently for dust control. Chlorides ranged between 1,100 mg/l in June 1993 to 580 mg/l in October 1995. Most of the samples collected average around 870 mg/l.

As mentioned above, water quality for wells supplying cooling water for industrial purposes exist primarily south of Malakole Road, while better quality water exists north of Malakole Road. Total pumpage for new wells north of Malakole Road should be less than 1 mgd to maintain chloride concentration of 1,000 mg/l or less.

Refinement of Data and Future Projects

Water quality and pumpage data collected by CWRM personnel and by water users will be continually updated by graphs and isochlor maps. More sampling points need to be added to the CWRM network. Three or four test holes should be drilled within or near BPNAS. A network of small diameter water level wells and deeper monitor wells should be drilled throughout the Ewa Plain. Ground-water data below the upper limestone aquifer and brown mud layer are lacking. Several injection and pumping wells penetrate the mud layer into the lower limestone aquifer. These wells are located in the Malakole area. There are no data or sampling points in the Puuloa area where most development is occurring.

Bolke and Bauer (report in prep.) began a preliminary cross-sectional flow model to aid in understanding the ground-water flow system of the Ewa caprock. The modeled flow system included the basal aquifer and the caprock. The preliminary model was used primarily to test a range of hydraulic conductivity and ground-water inflow values from which reasonable results could be attained. These results included changes in water levels and salinities in the caprock after the cessation of sugar and the effects of marina construction. Additional work should be done to calibrate the model to the two stable periods as average conditions. Further modeling work combined with caprock monitor wells (outlined above) need to address the changes in ground-water inflow that are now occurring from both the Waianae and Koolau aquifers. Deeper wells are need to aid in model calibration. Several more cross-sectional models across the plain should be constructed. Future modeling could be 3-dimensional.

Conclusions and Recommendations

Several major conclusions can be drawn from the above discussion:

1. Salinity in the caprock aquifer, especially the Honouliuli-Puuloa area, has not reached stability since cessation of cane irrigation in 1994. The caprock aquifer in the region is undergoing the most profound changes since the beginning of sugar cultivation in the late 1800’s. The length of time to reach stability is unknown; however, because of the relatively small volume of the aquifer, a “quasi” stability should be reached over a short period of time.

2. Any estimate of sustainable yield for the caprock aquifer will be restricted by the limited area. More data regarding the natural post-OSCo changes that are

occurring within the limestone aquifer will be beneficial.

3. Sustainable yield for the caprock aquifer assumes that total pumpage within an area will maintain a chloride concentration of 1,000± mg/l. To achieve and maintain a good irrigation quality water will require a change in the sustainable yield estimate to about 5 mgd for the Malakole area. The historical record of the caprock aquifer argues for a reduction of permitted uses, unless there is a large increase in the inflow of ground water either naturally or from artificial means.

4. The Malakole area is pumping much higher than the sustainable yield of less than 1 mgd estimated in R-79. However, much of the pumpage is for industrial purposes in Campbell Industrial Park and chloride concentrations greater than 1,000 mg/l are acceptable. There should still be some limit established, because heavy pumpage could affect ground water underlying BPNAS. North of Malakole Street, sustainable yield should be 1 mgd.

5. Additional modeling efforts, including a 3-dimensional ground-water model to better simulate basal ground-water inflow and the areal effects of pumping, will be beneficial in better understanding the hydrology of the caprock. The period from 1955-1970 could possibly be used for establishing average hydrologic conditions in the caprock, because chloride concentrations during this period show the least variation of any comparable period from 1930 to 1995.

6. In conjunction with future modeling, or perhaps as a separate project, a more thorough water balance

investigation should be initiated as a result of the significant land use changes.

7. Separation of the Ewa caprock aquifer into three broad management areas has merit. These broad regions can be subdivided into smaller areas that require special management. Perhaps the concept of "sustainable capacity", the amount of water developed from a well or a battery of wells (such as Hawaii Prince Golf Course) that will allow stabilization of chlorides, should be more fully developed and used by the Commission for special management of smaller areas. Sustainable capacity of a source will limit pump size and well depth. A maximum depth for wells in Ewa could be limited to –15 feet msl.

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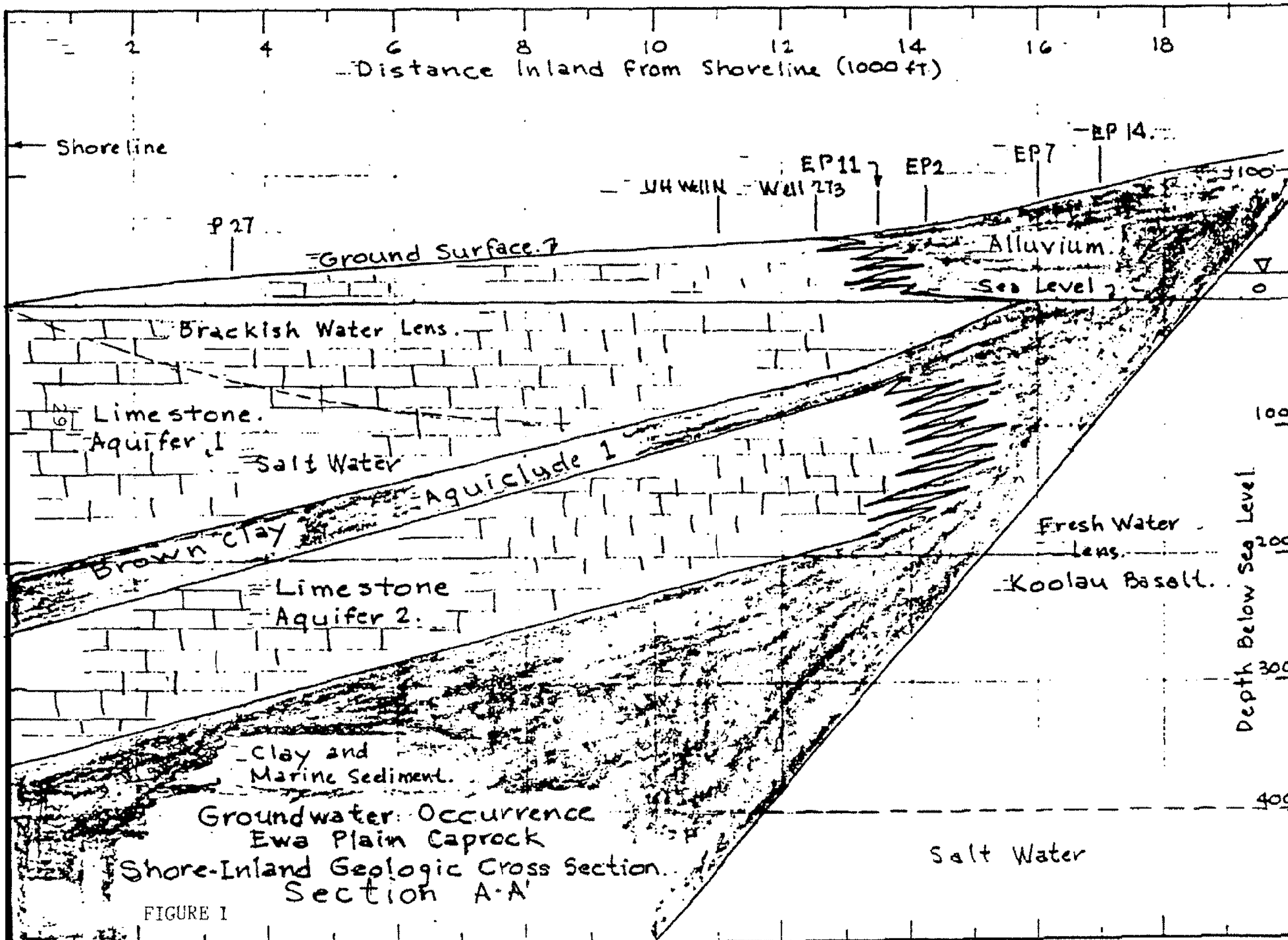
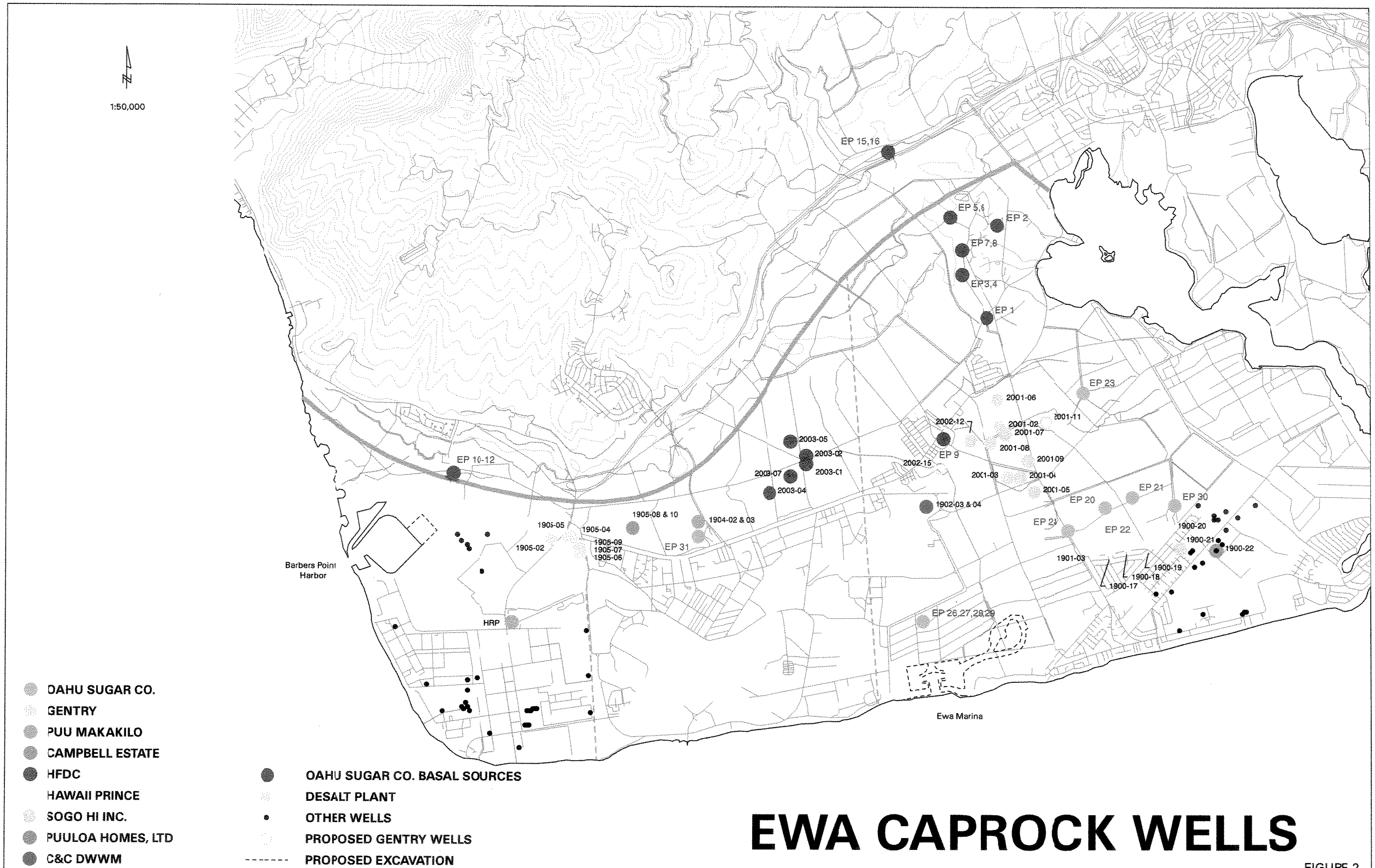


FIGURE I



EWA CAPROCK WELLS

FIGURE 2

03/21/1996

Map Projection: Universal Transverse Mercator

Most Saline EP Basal Sources
Chlorides and Pumpage

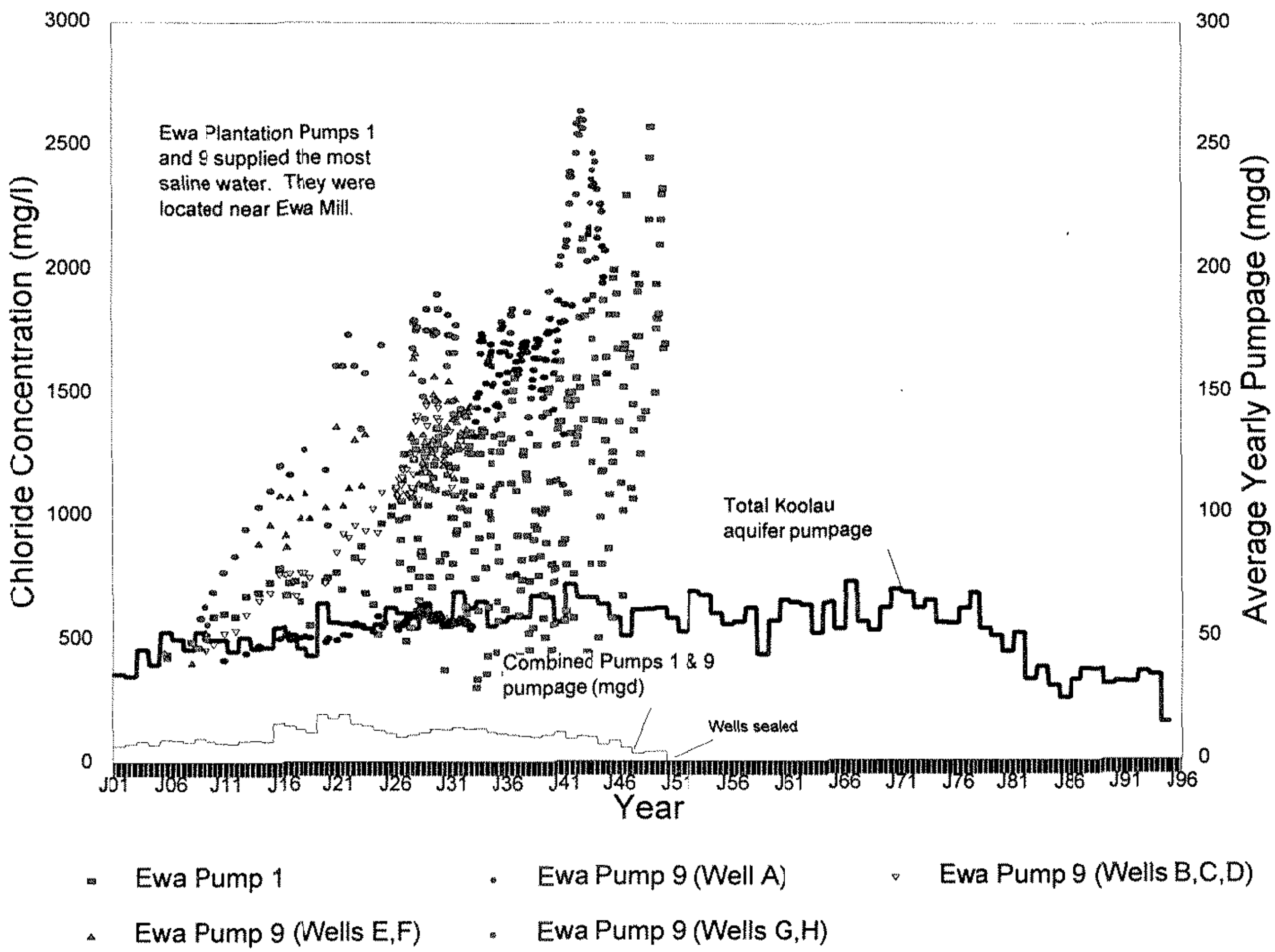


FIGURE 3

Marginal EP Basal Sources
Chlorides and Pumpage

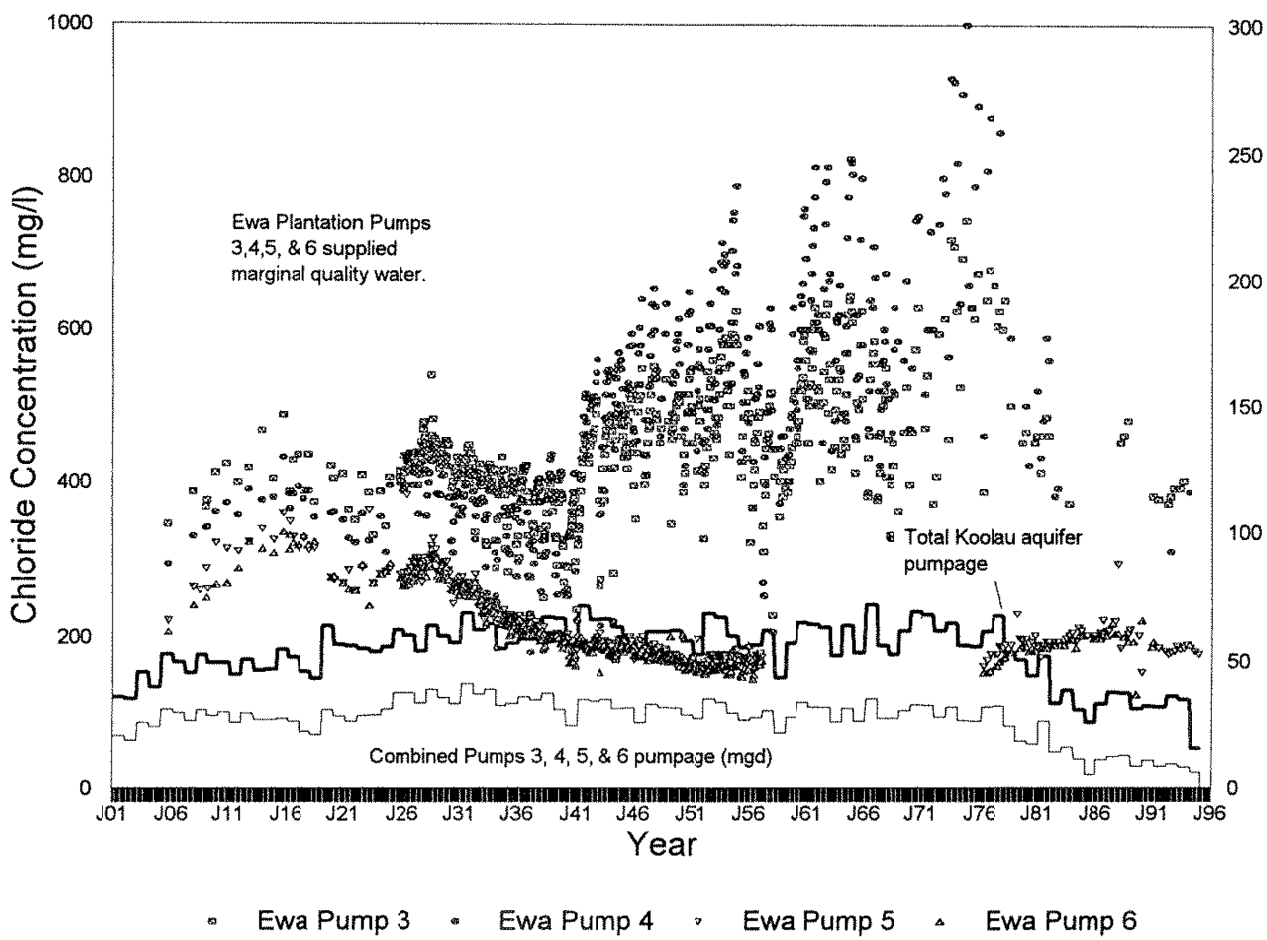


FIGURE 4

Marginal to Potable EP Basal Sources
Chlorides and Pumpage

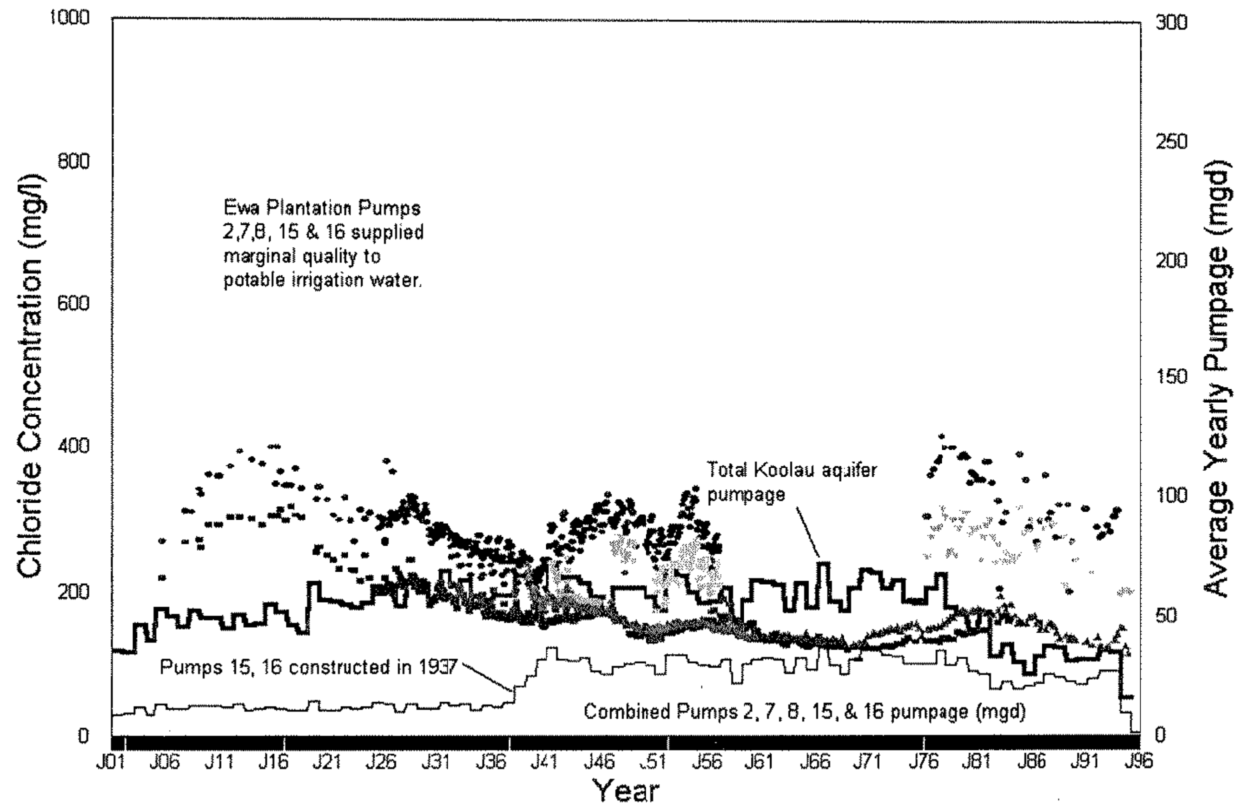
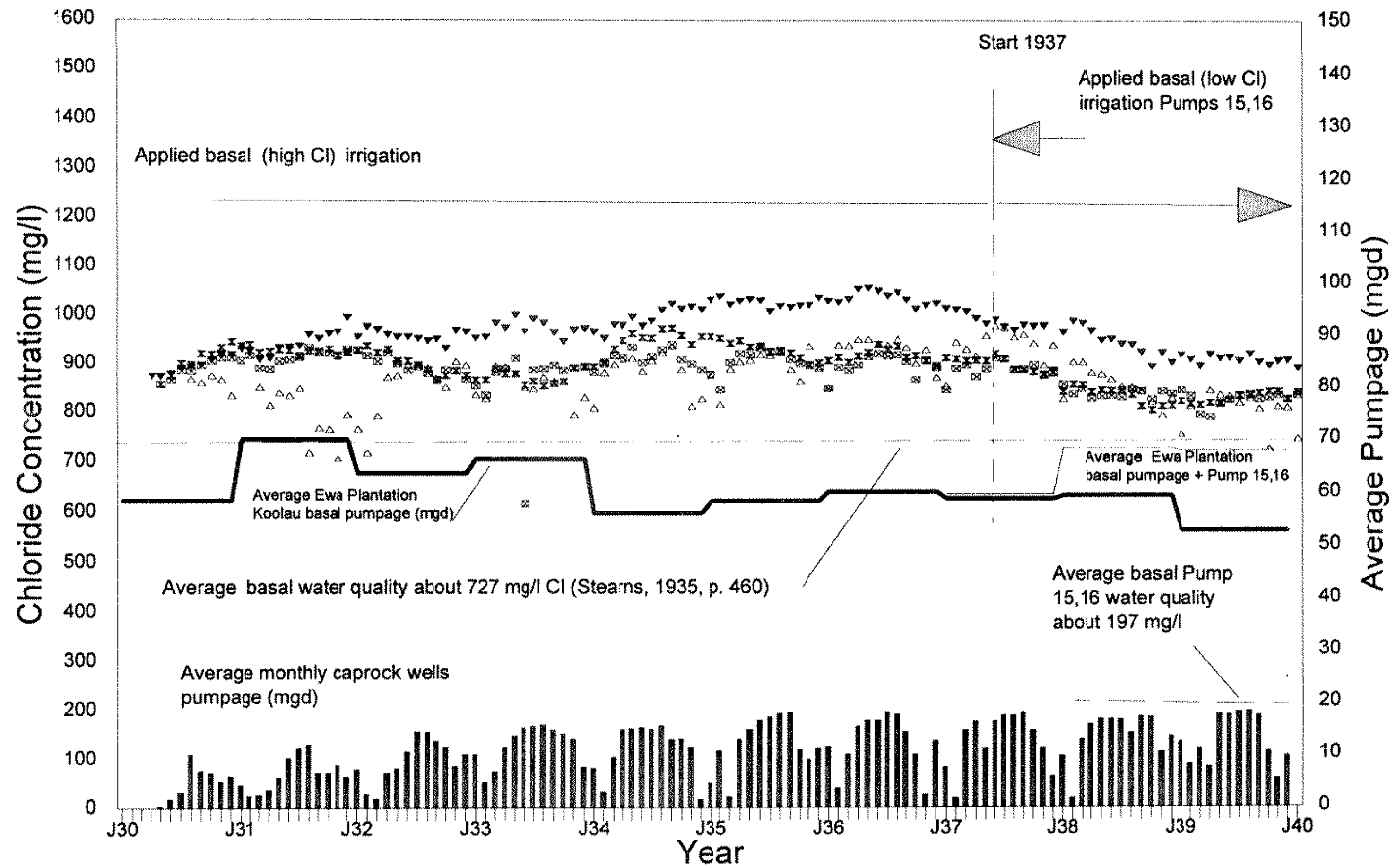


FIGURE 5 ▪ Ewa Pump 2 • Ewa Pump 7 Ewa Pump 8 ▴ Ewa Pumps 15,16

Chloride and Pumpage of Ewa Plantation Shallow Wells, Ewa Caprock, Oahu



Ref: CWRM, BWS files, & R-79, Stearns (1935, 1940)

FIGURE 6

EP-20 EP-21 EP-22 EP-23 EP-24

Chloride and Pumpage of Ewa Plantation Shallow Wells, Ewa Caprock, Oahu

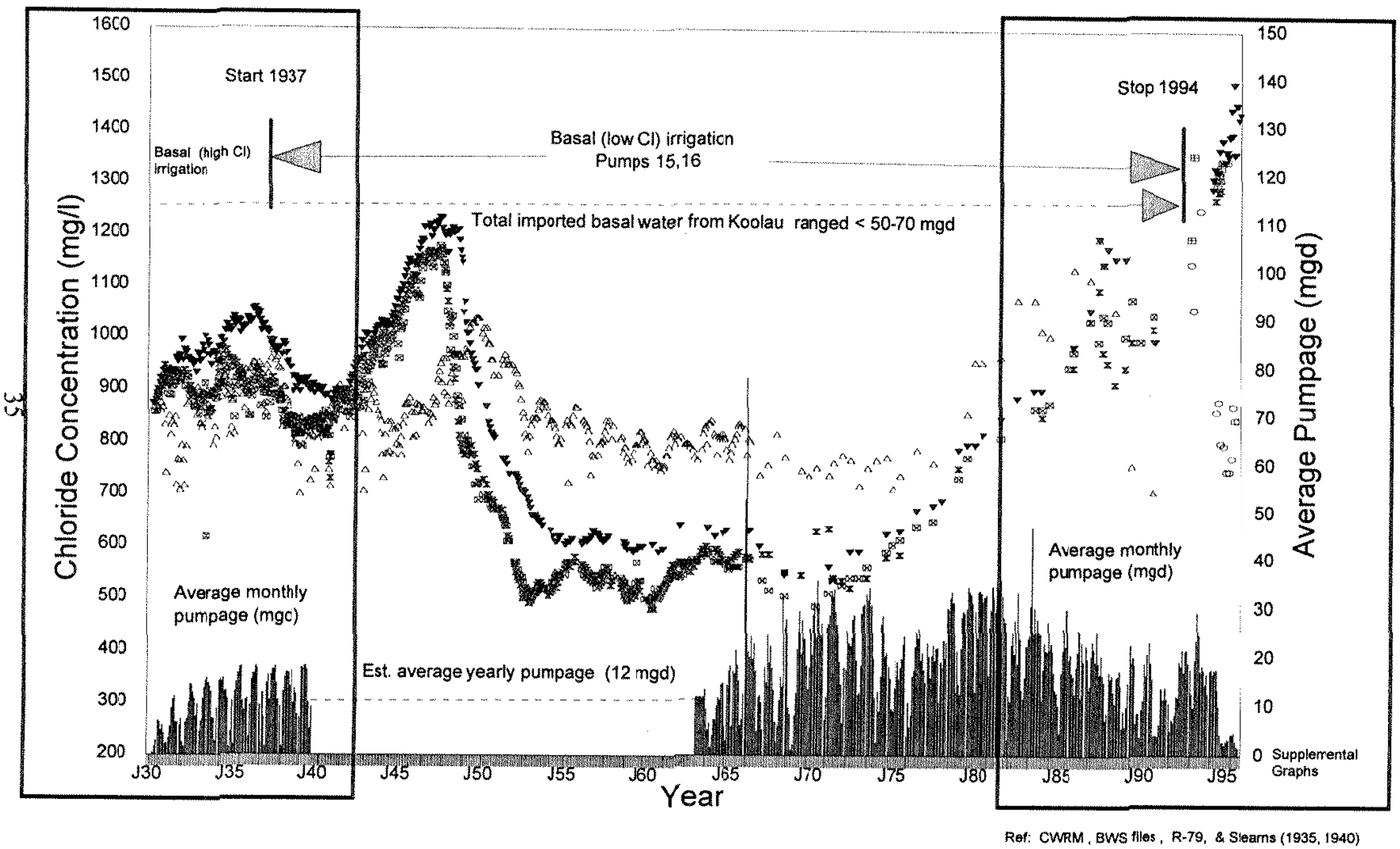


FIGURE 7 EP-20 EP-21 EP-22 EP-23 EP-24 EP27,28 EP30

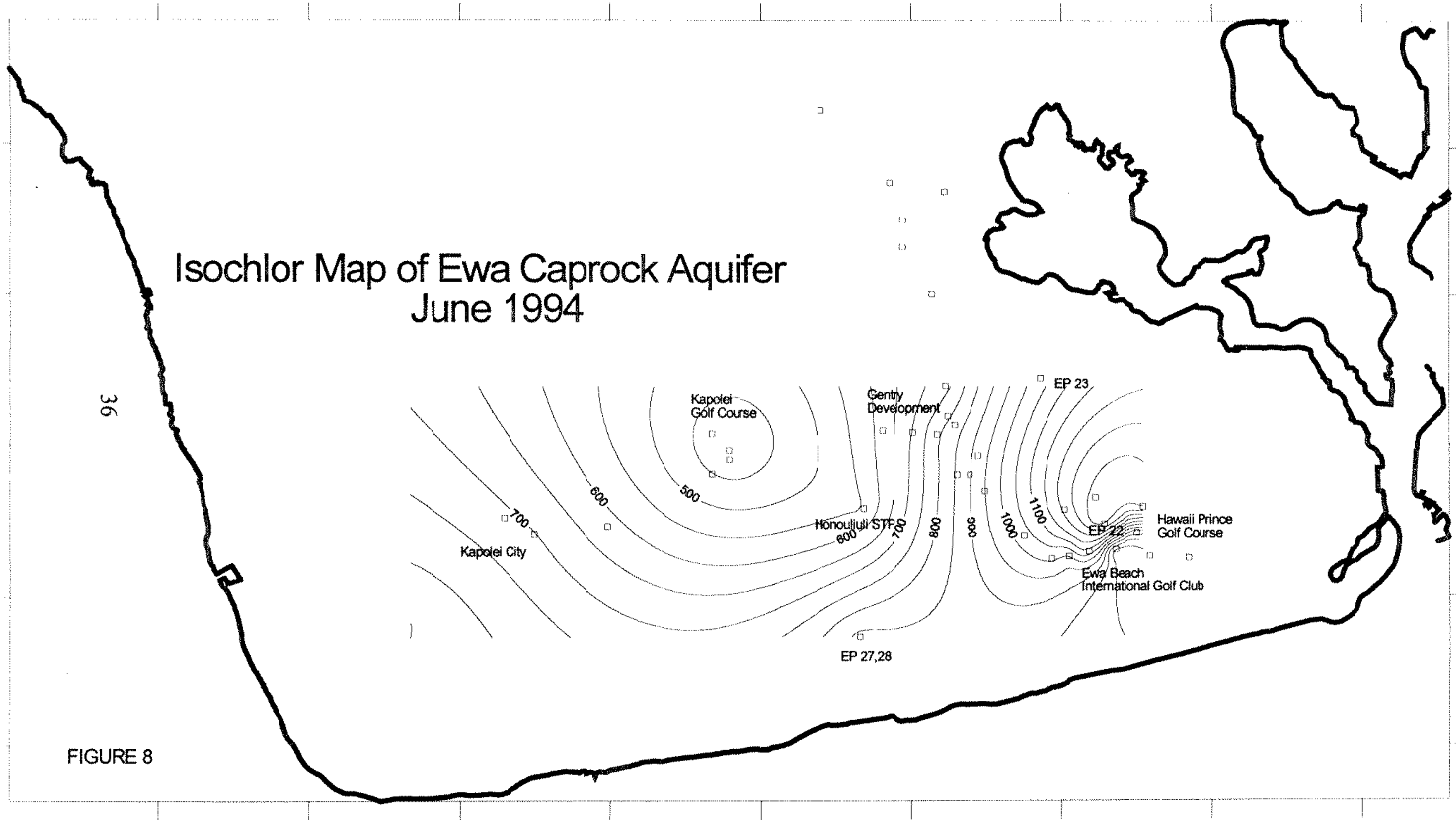
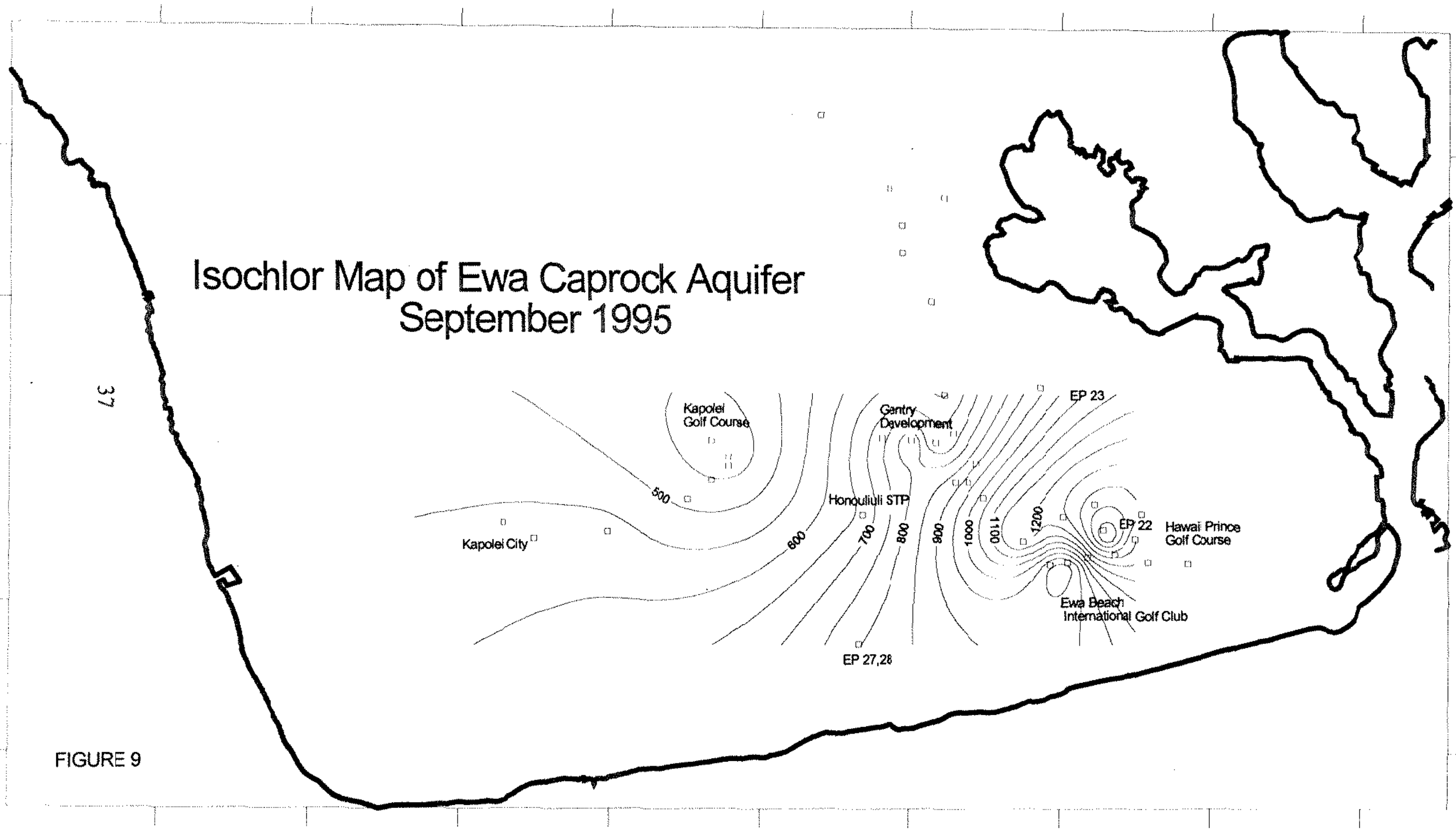

Isochlor Map of Ewa Caprock Aquifer
June 1994
Kapolei Golf Course
Gentry Development
EP 23
Hawaii Prince Golf Course
EP 22
Ewa Beach International Golf Club
Honouliuli STP
EP 27,28
Kapolei City
500
600
700
800
900
1000
1100

FIGURE 8



Isochlor Map of Ewa Caprock Aquifer
September 1995

FIGURE 9

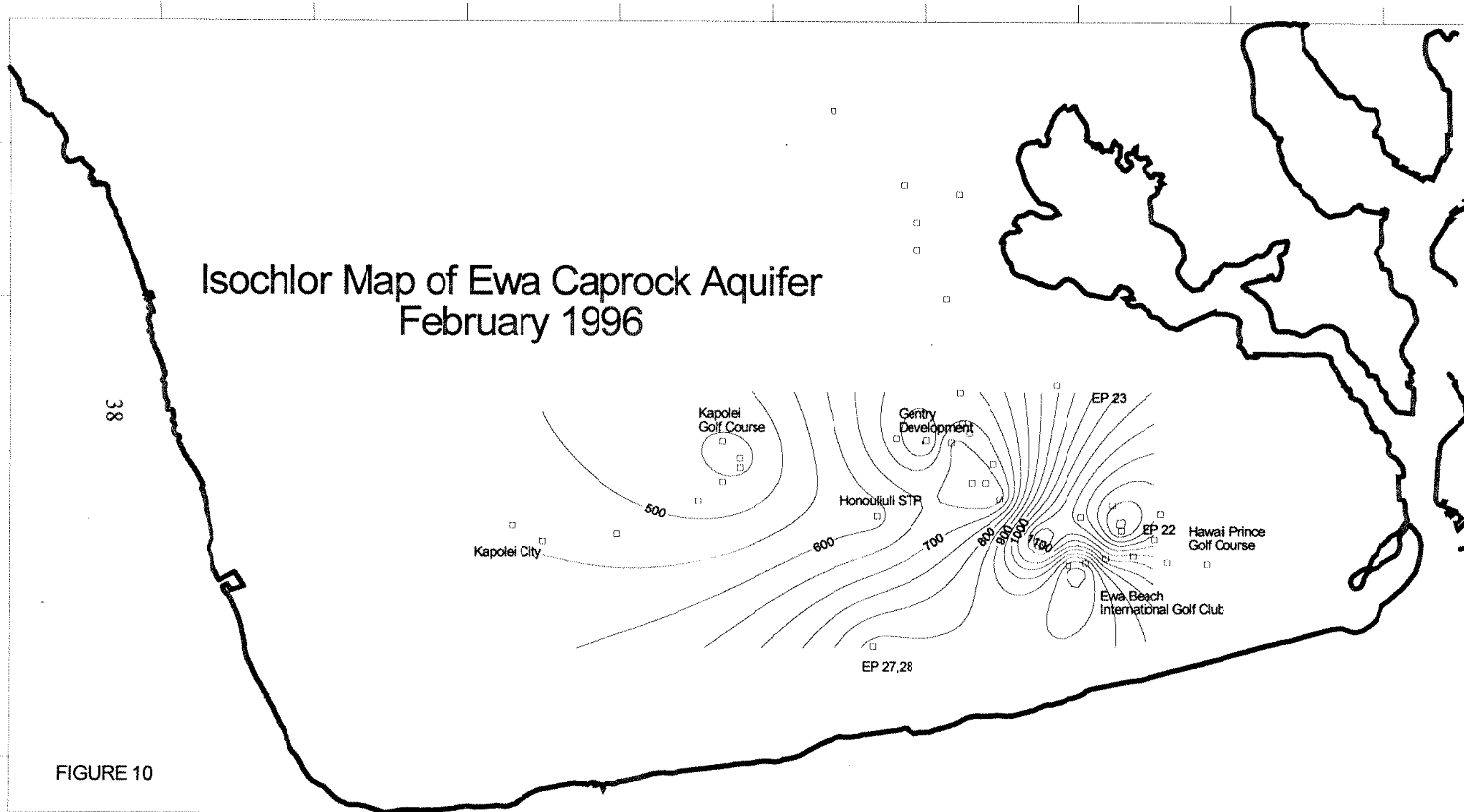
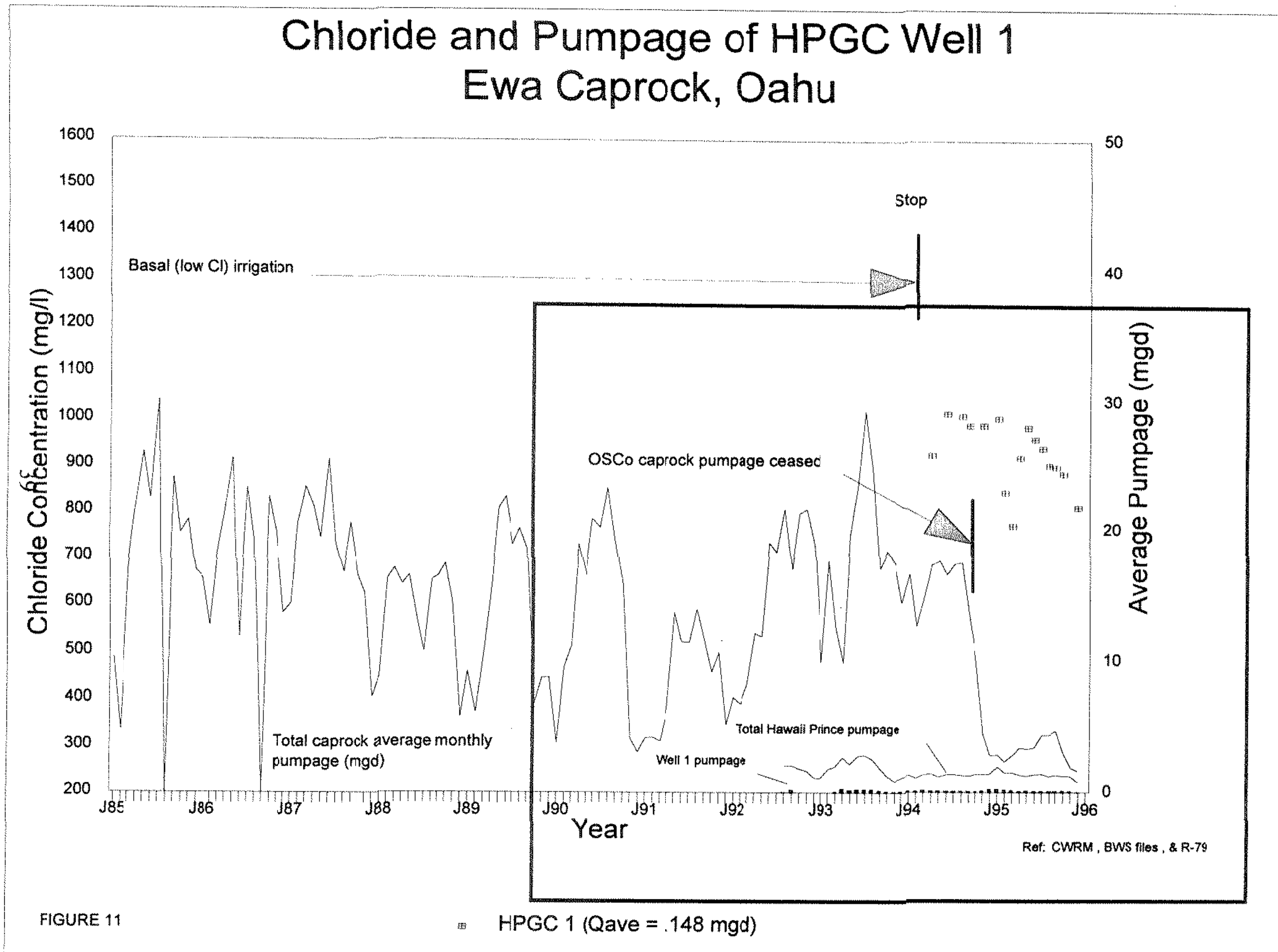

Isochlor Map of Ewa Caprock Aquifer
February 1996
Kapolei Golf Course
Gentry Development
EP 23
Honouliuli STP
Kapolei City
500
600
700
800
900
1000
1100
EP 22
Hawaii Prince Golf Course
Ewa Beach International Golf Club
EP 27,28

FIGURE 10



Chloride and Pumpage of HPGC Well 1
Ewa Caprock, Oahu
Chloride Concentration (mg/l)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
Average Pumpage (mgd)
50
40
30
20
10
0
Stop
Basal (low Cl) irrigation
OSCo caprock pumpage ceased
Total Hawaii Prince pumpage
Well 1 pumpage
Total caprock average monthly pumpage (mgd)
J85
J86
J87
J88
J89
J90
J91
J92
J93
J94
J95
J96
Year
Ref: CWRM , BWS files , & R-79
HPGC 1 (Qave = .148 mgd)

FIGURE 11

Chloride and Pumpage of HPGC Well 1
Ewa Caprock, Oahu

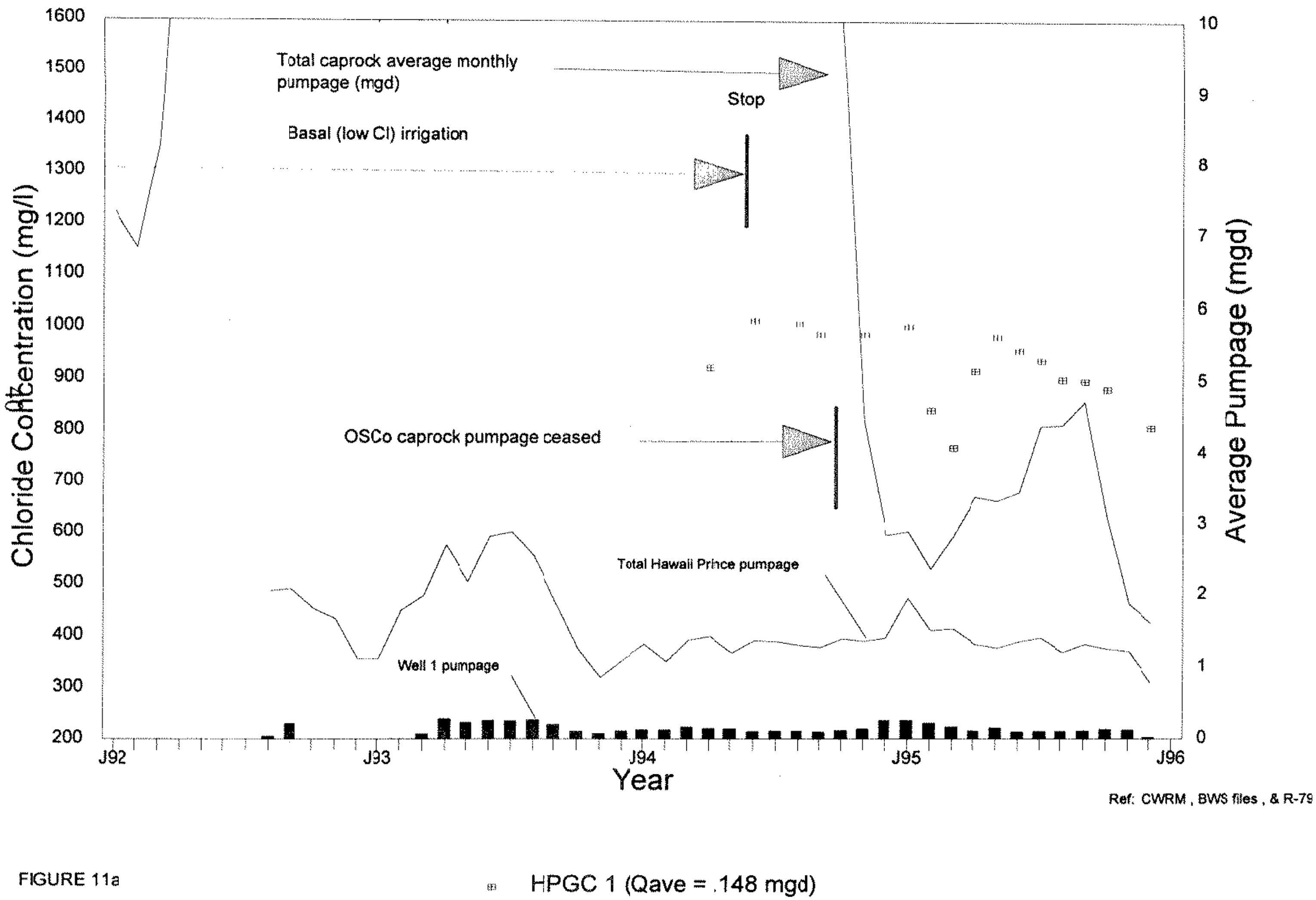


FIGURE 11a

Chloride and Pumpage of HPGC Well 2
Ewa Caprock, Oahu

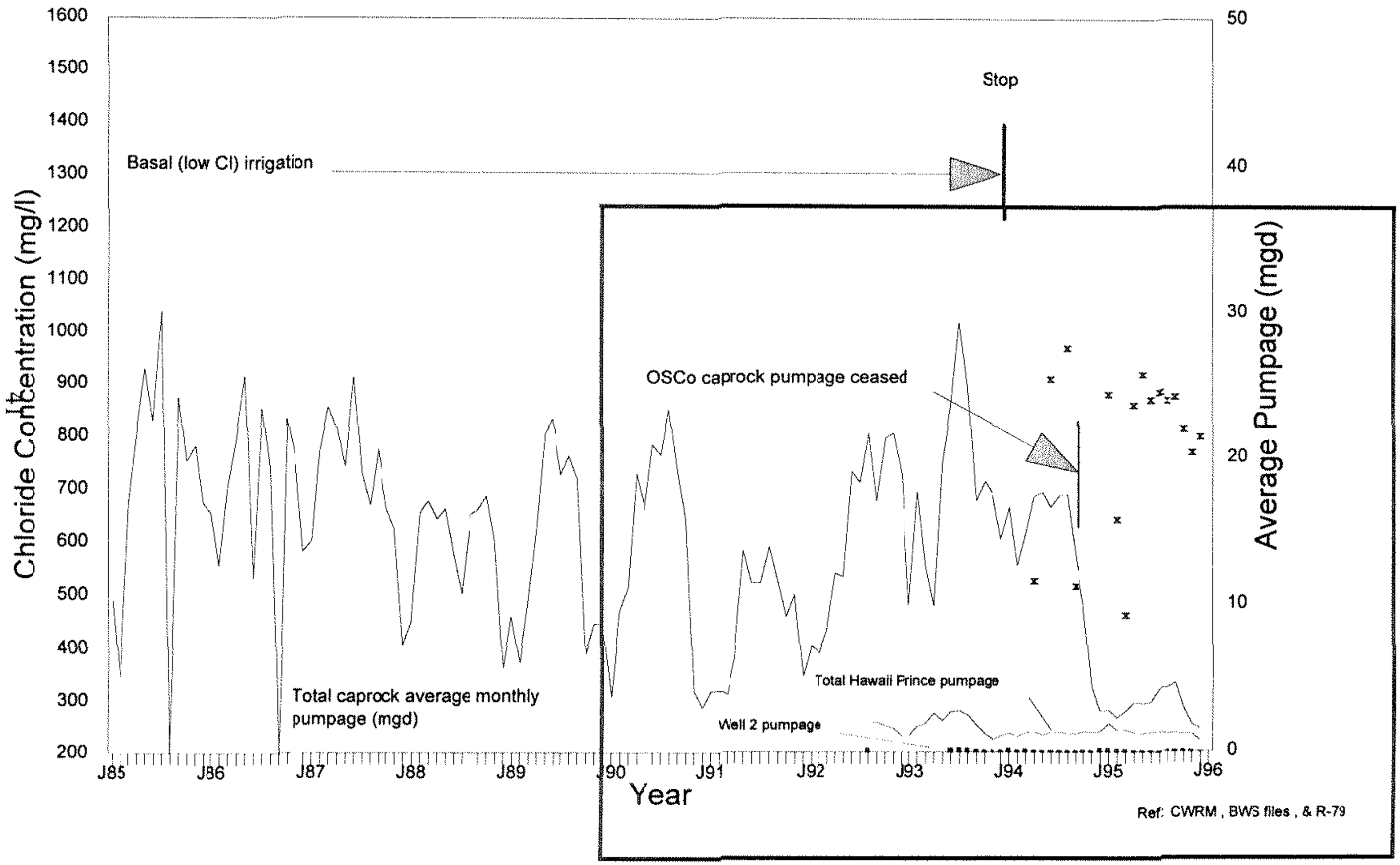


FIGURE 12

x HPGC 2 (Qave=0.160 mgd)

Chloride and Pumpage of HPGC Well 2
Ewa Caprock, Oahu

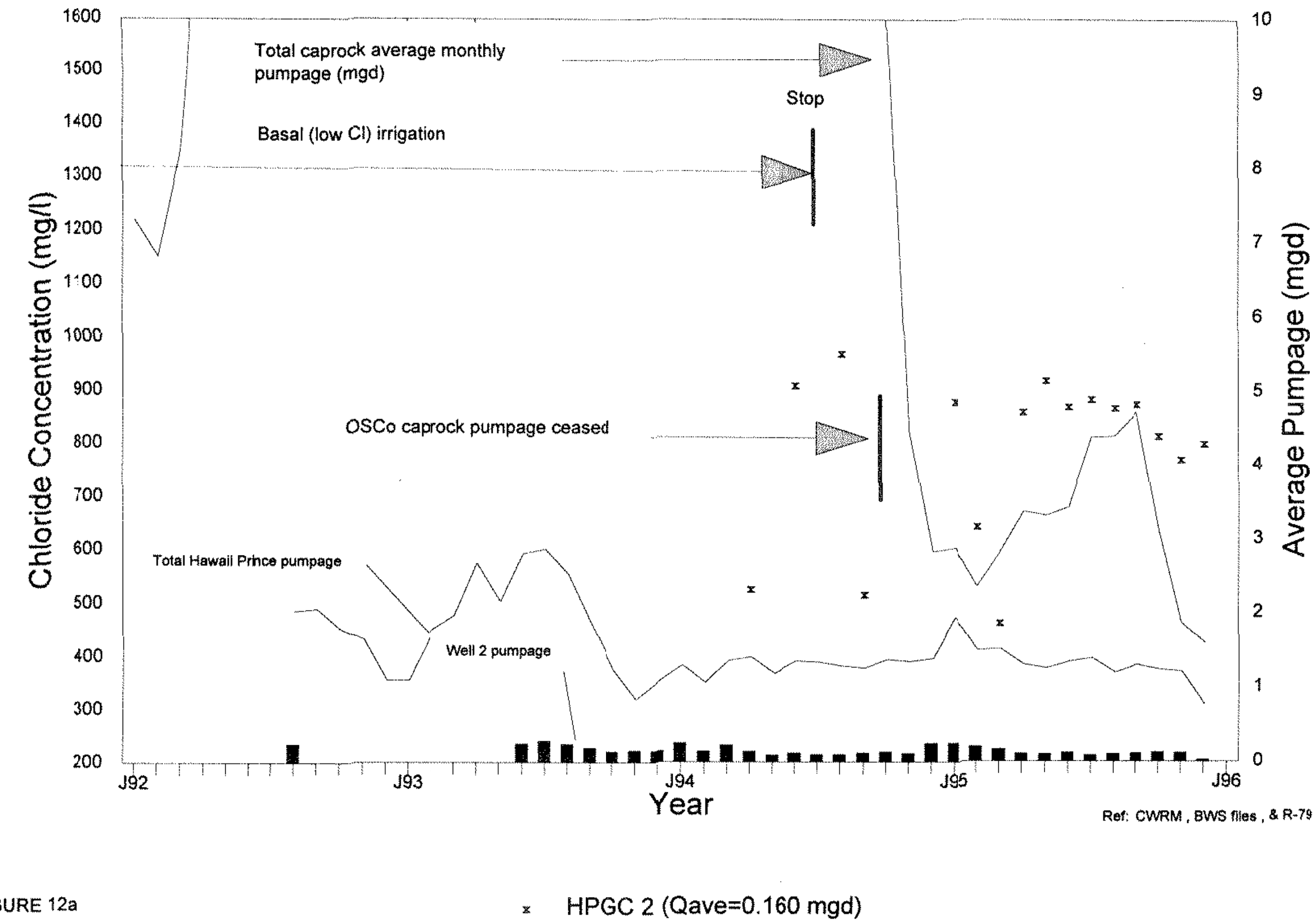


FIGURE 12a

Chloride and Pumpage of HPGC Well EP22
Ewa Caprock, Oahu

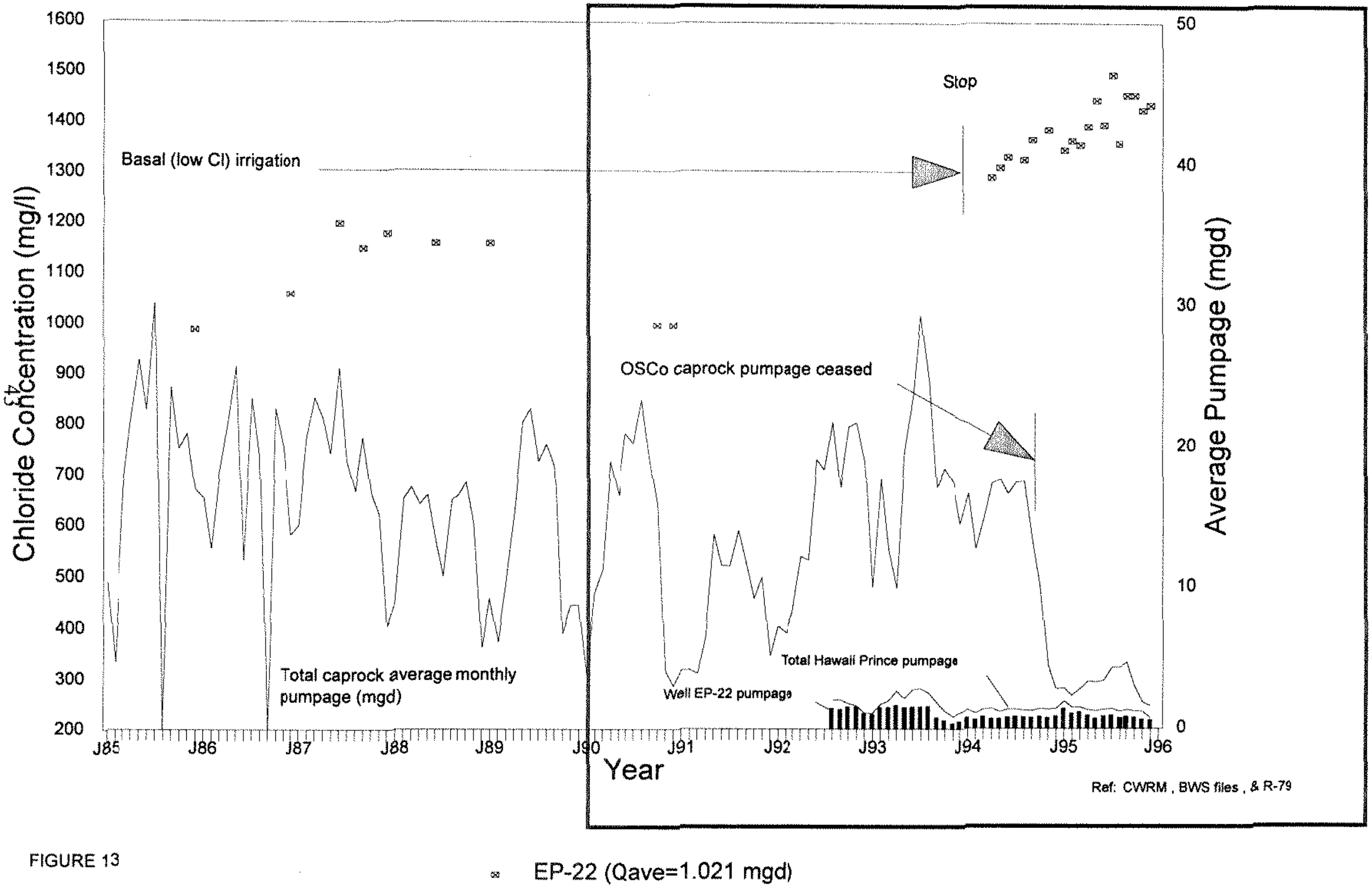
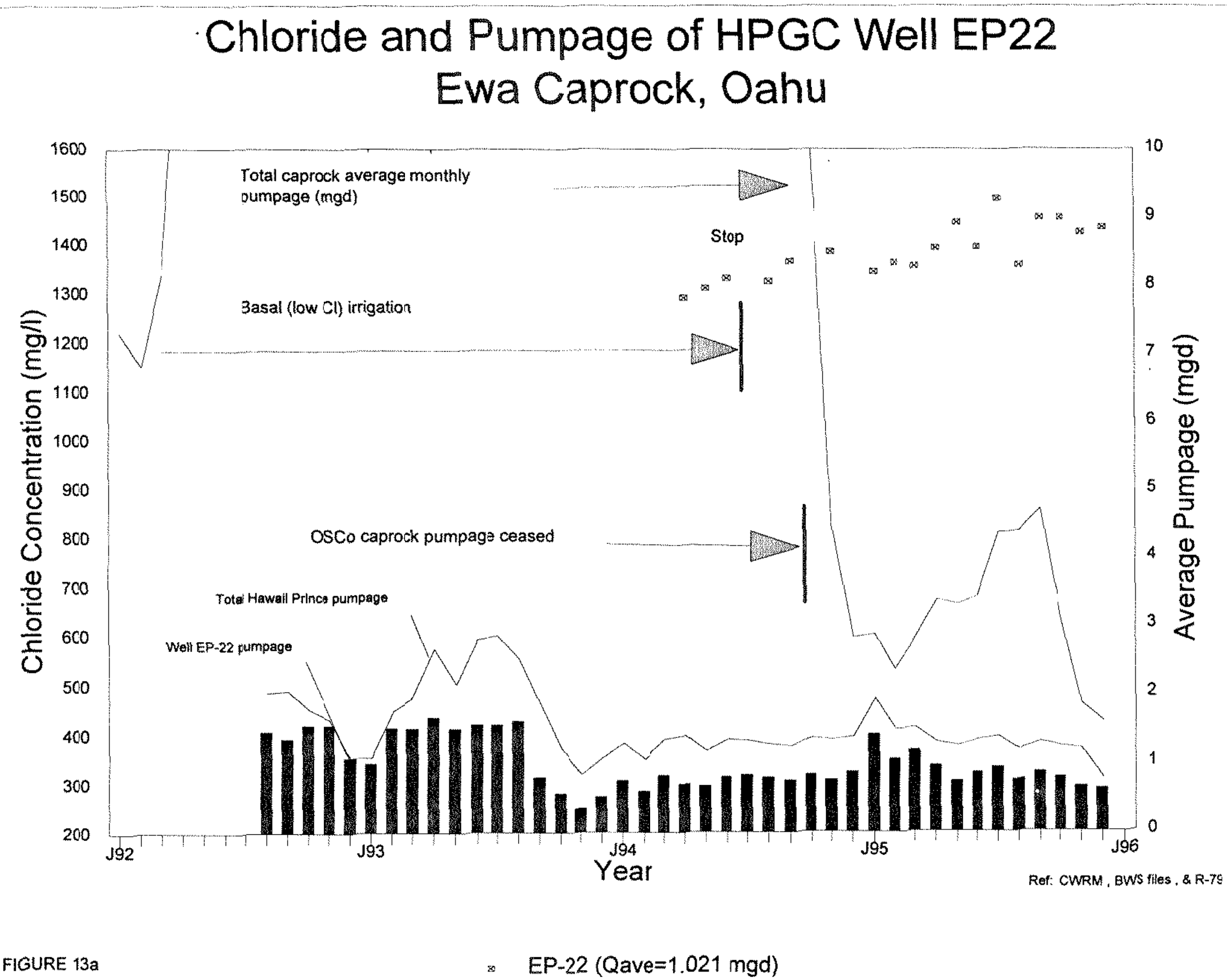


FIGURE 13



Chloride and Pumpage of HPGC Well EP22
Ewa Caprock, Oahu
Chloride Concentration (mg/l)
Average Pumpage (mgd)
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
10
9
8
7
6
5
4
3
2
1
0
Total caprock average monthly pumpage (mgd)
Stop
Basal (low Cl) irrigation
OSCo caprock pumpage ceased
Total Hawaii Prince pumpage
Well EP-22 pumpage
J92
J93
J94
J95
J96
Year
Ref: CWRM , BWS files , & R-79
EP-22 (Qave=1.021 mgd)

FIGURE 13a

Chloride and Pumpage of Ewa
Gentry Wells, Ewa Caprock, Oahu

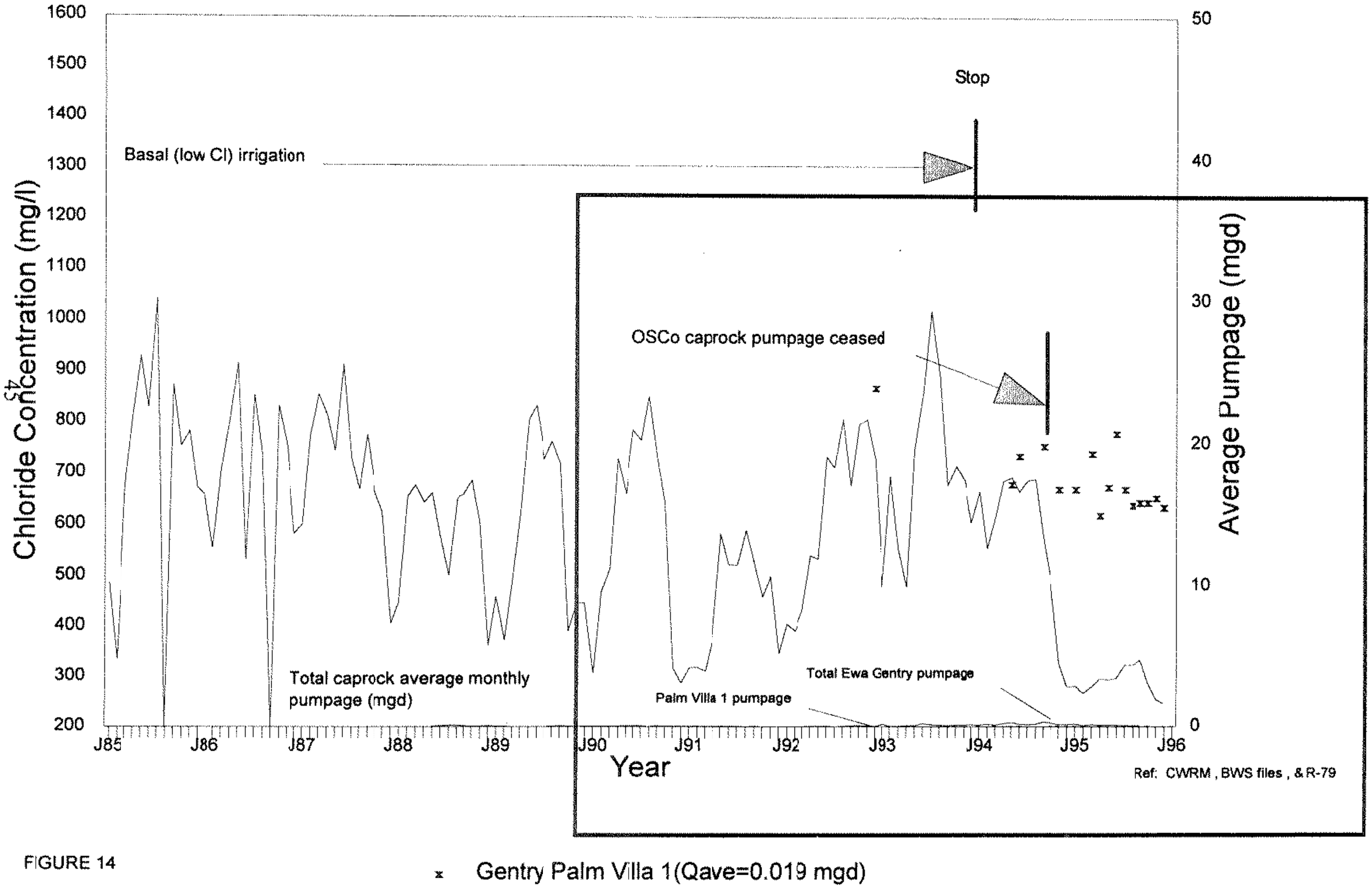
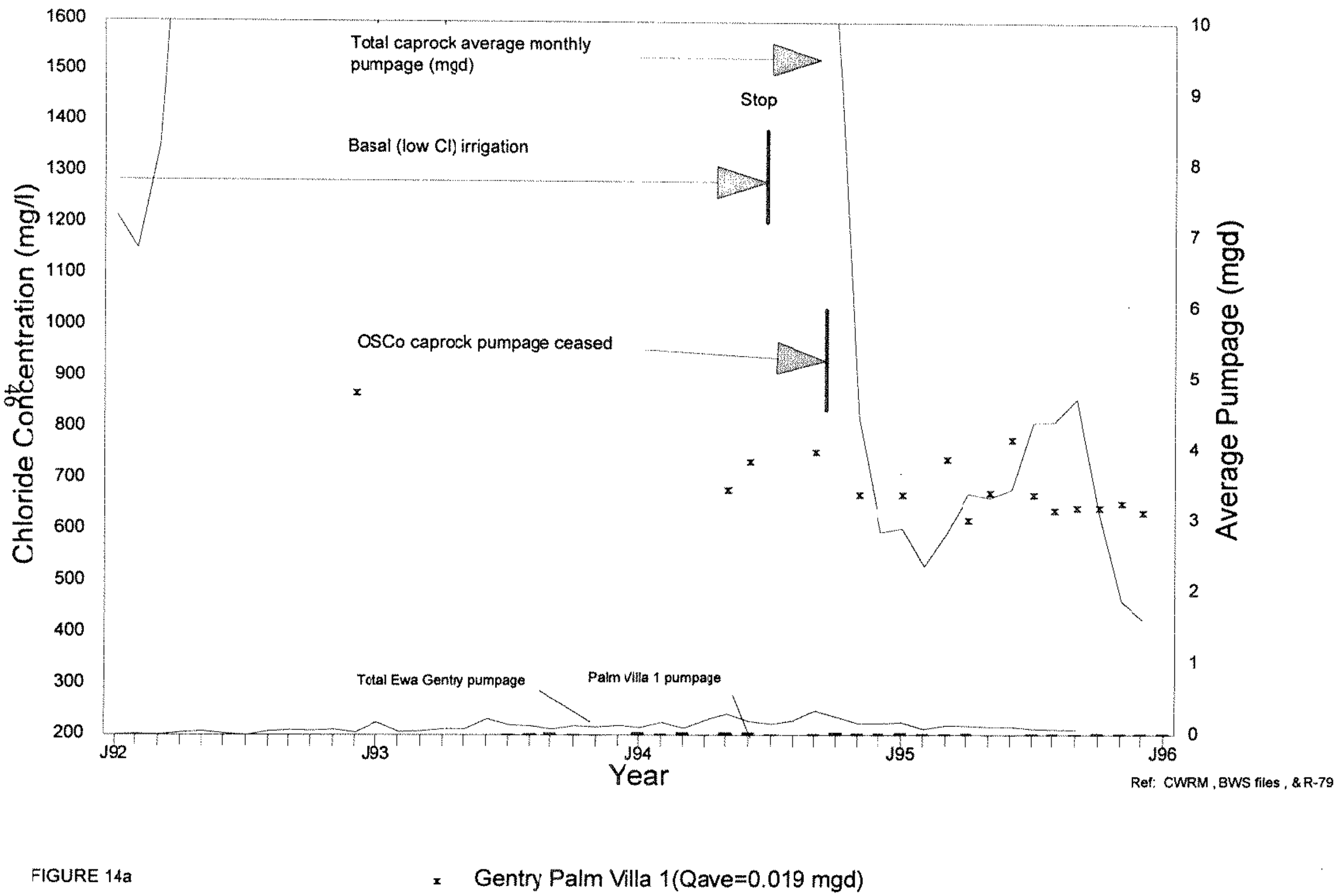


FIGURE 14

Chloride and Pumpage of Ewa Gentry Wells, Ewa Caprock, Oahu



Ref: CWRM , BWS files , & R-79

FIGURE 14a

Chloride and Pumpage of Ewa Gentry Wells, Ewa Caprock, Oahu

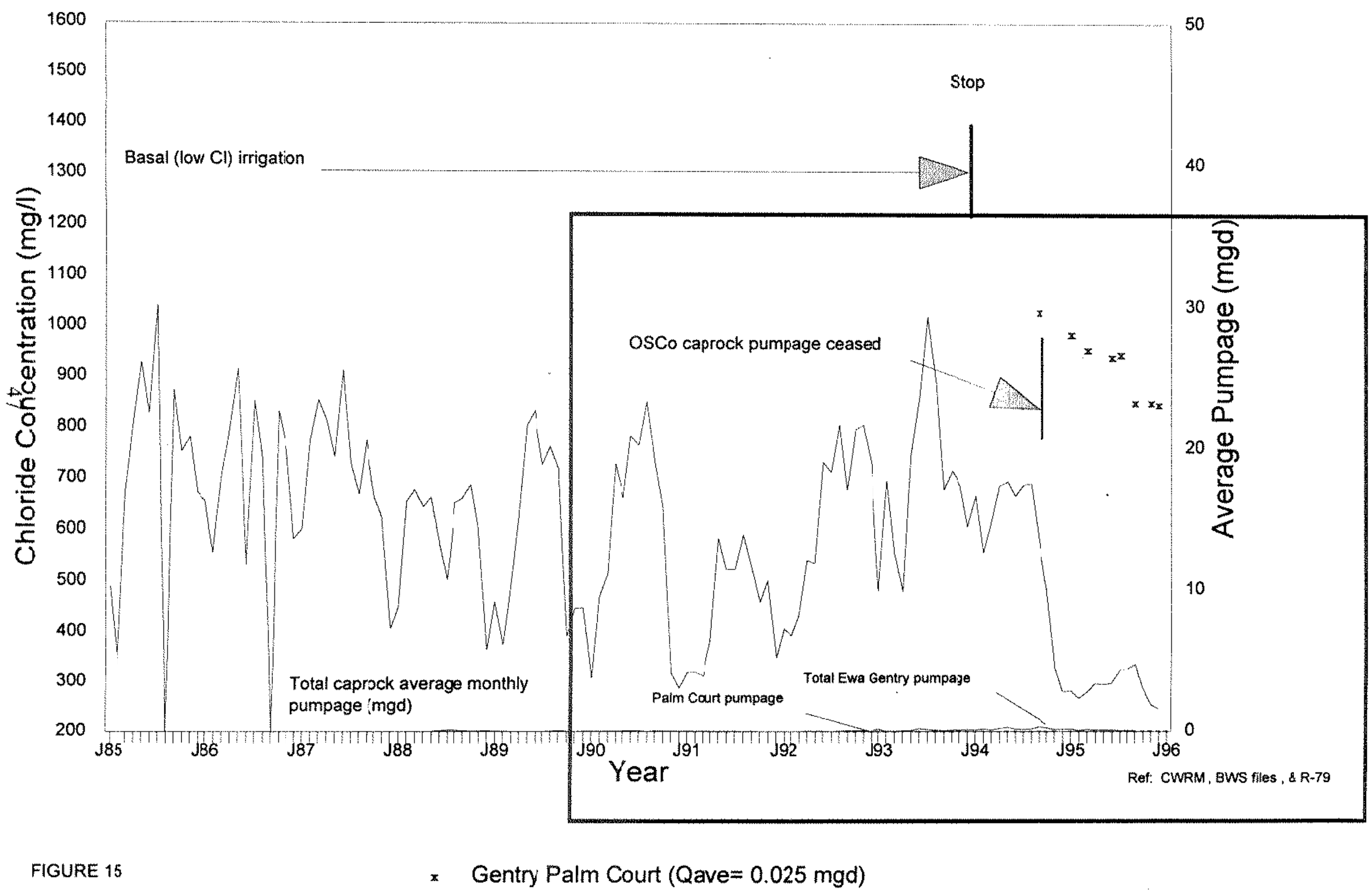


FIGURE 15

Chloride and Pumpage of Ewa Gentry Wells, Ewa Caprock, Oahu

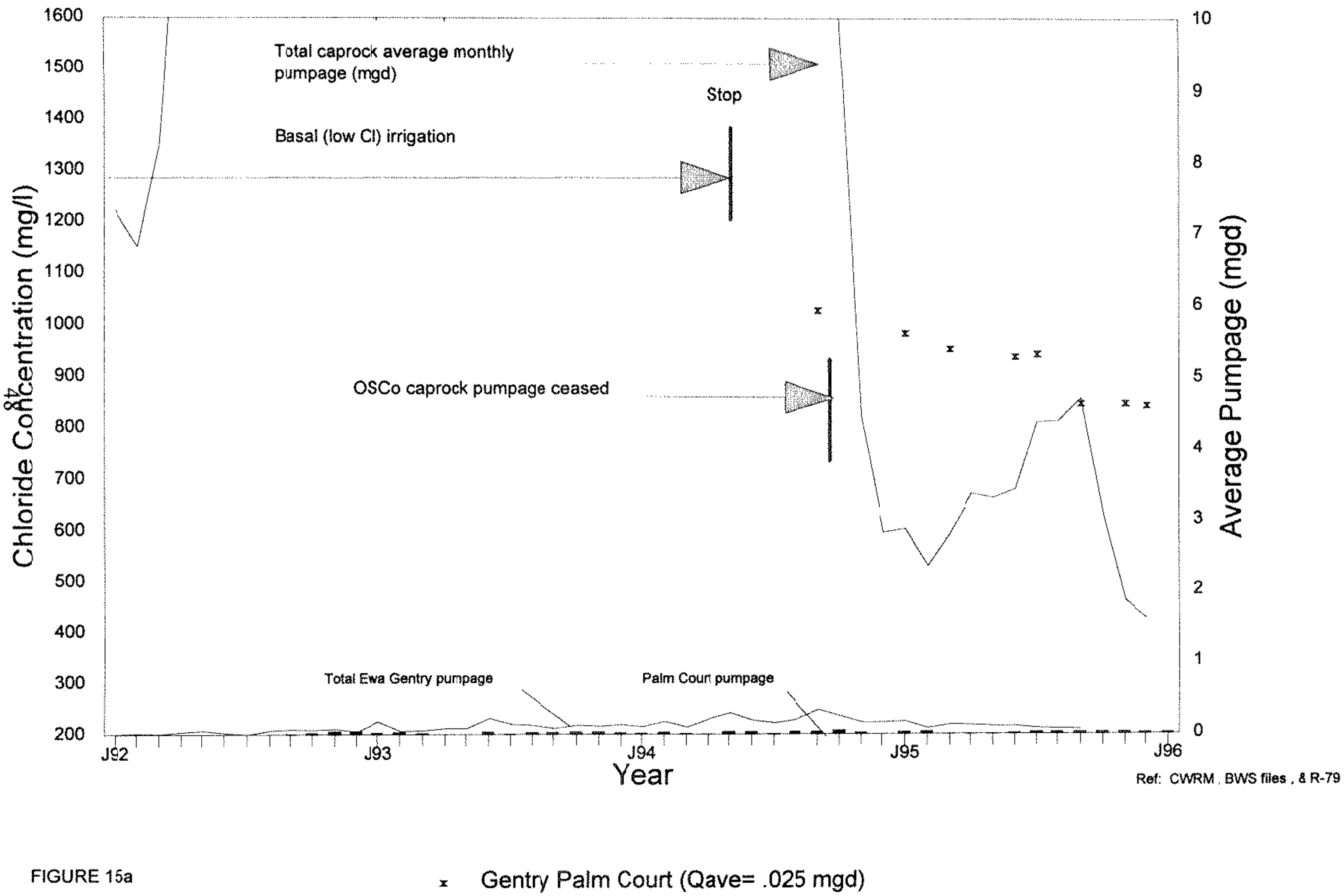


FIGURE 15a

Chloride and Pumpage of Ewa Gentry Wells, Ewa Caprock, Oahu

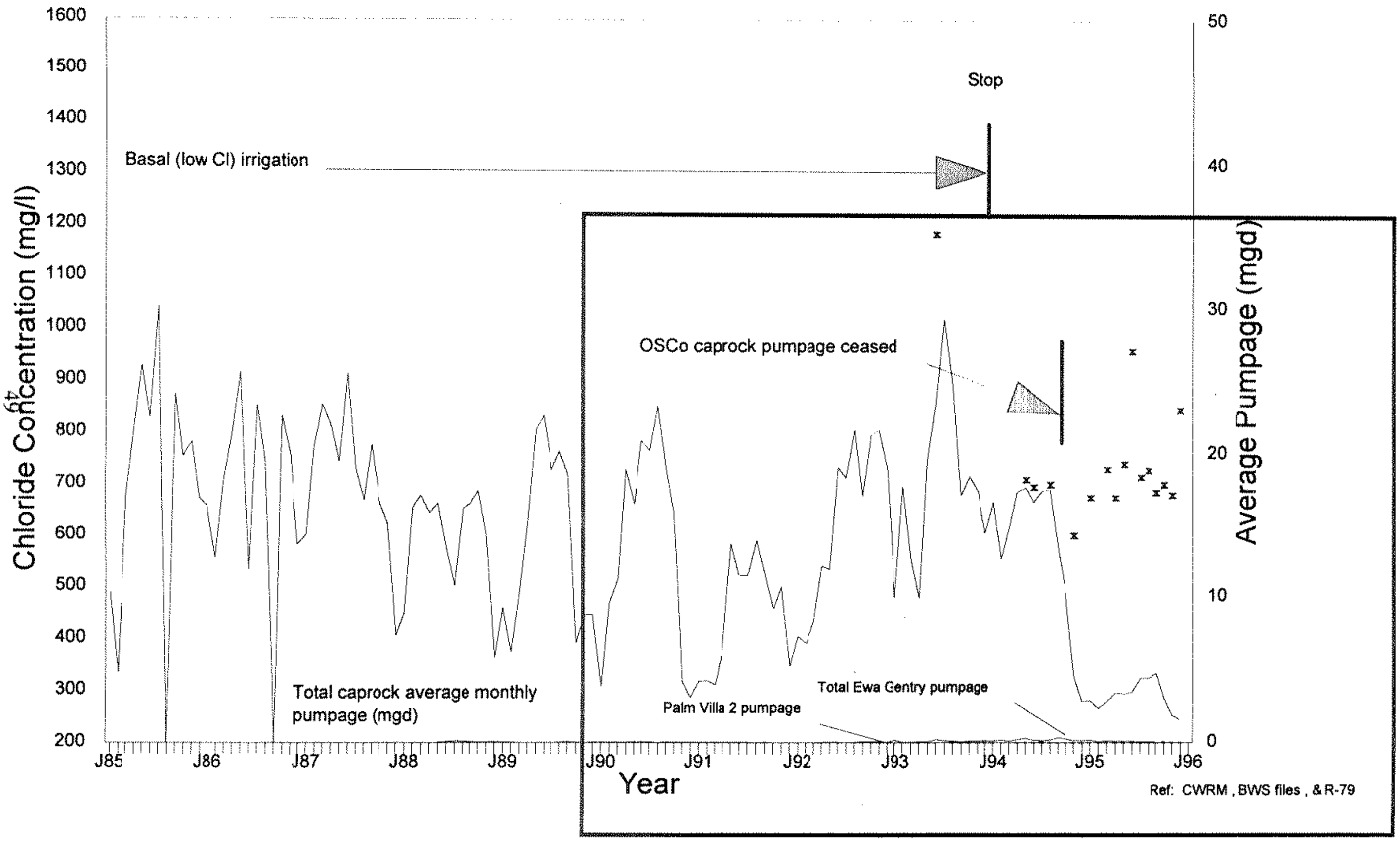


FIGURE 16

x Gentry Palm Villa 2 (Qave=0.031 mgd)

Chloride and Pumpage of Ewa Gentry Wells, Ewa Caprock, Oahu

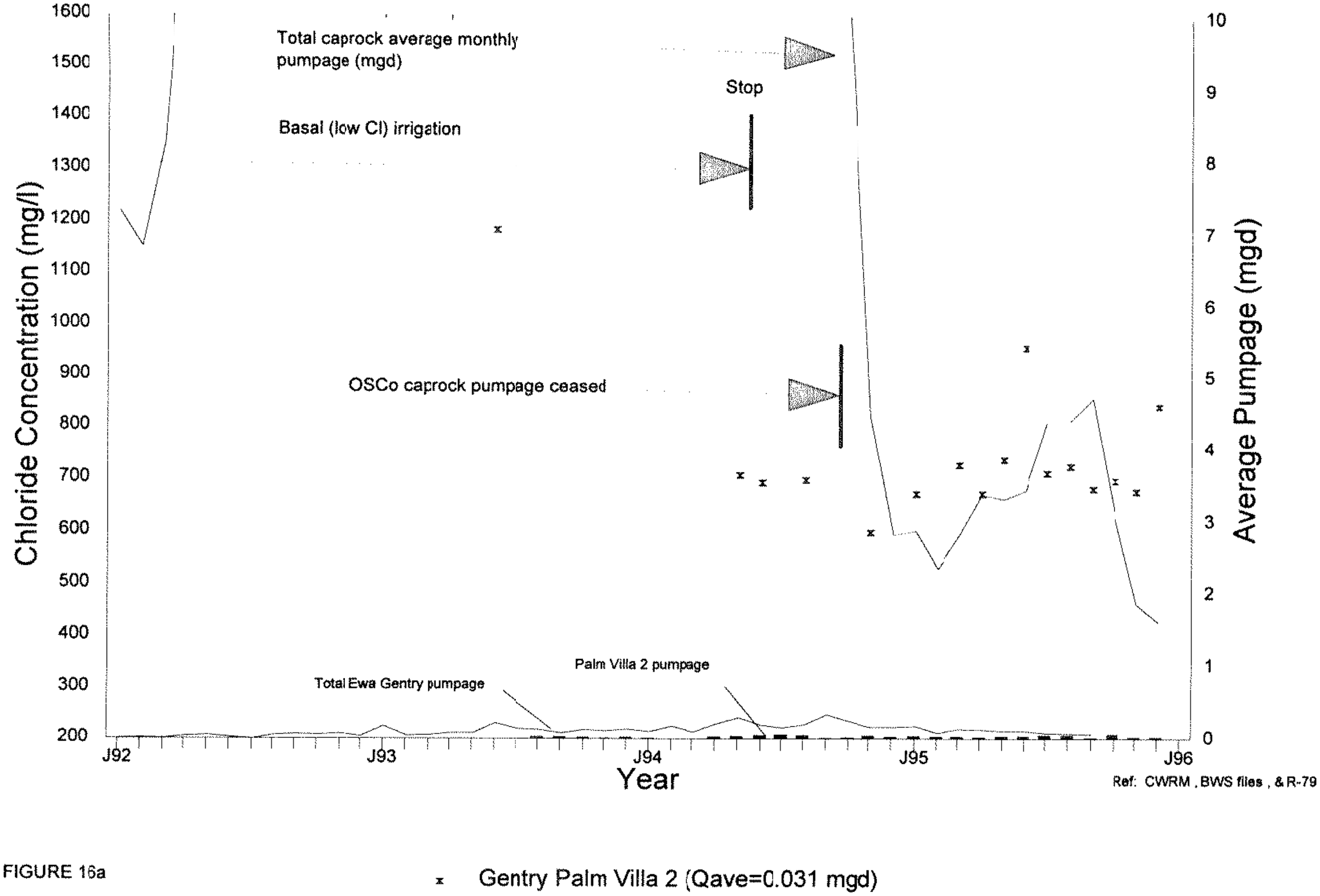


FIGURE 16a

Chloride and Pumpage of Honouliuli STP Wells, Ewa Caprock, Oahu

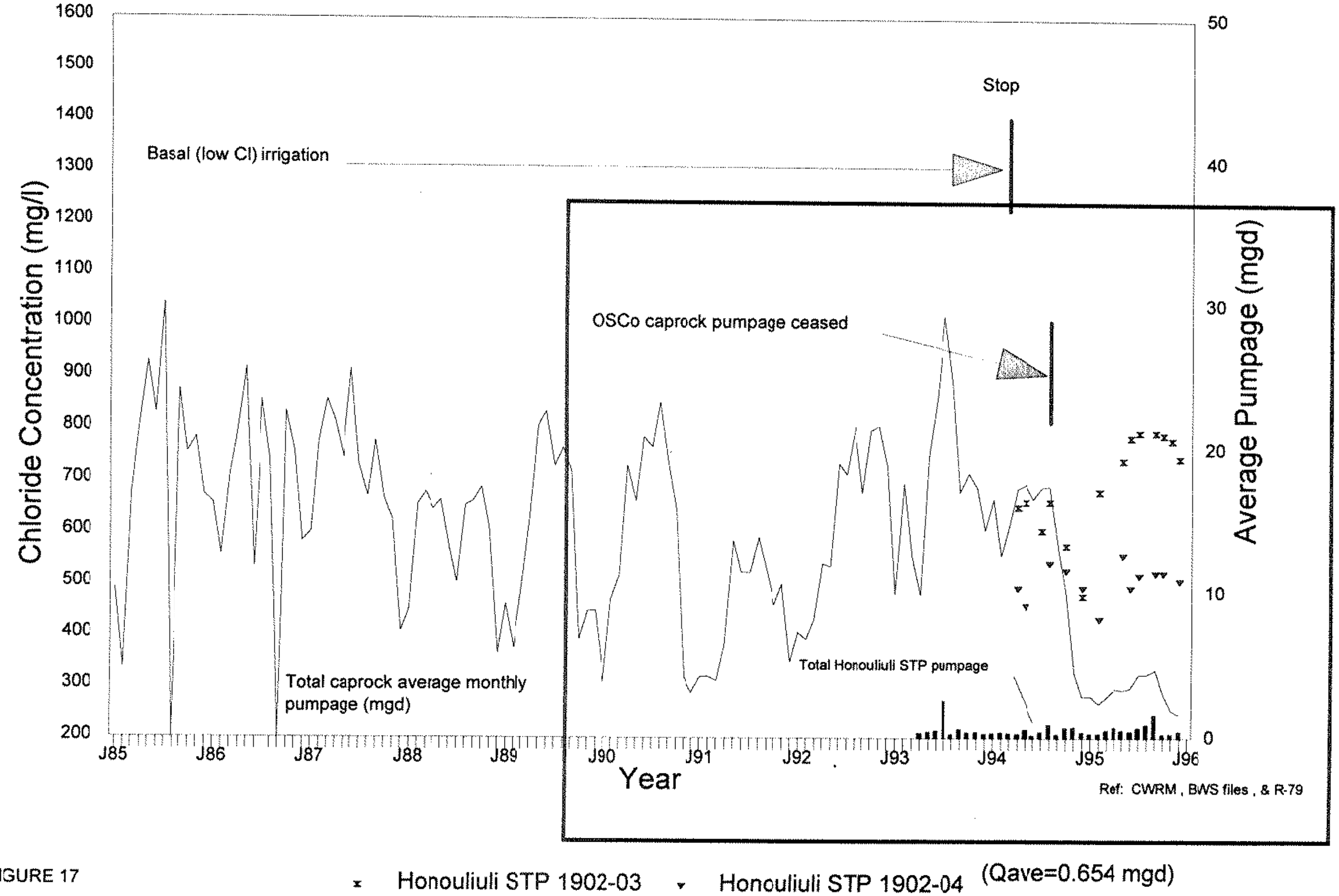


FIGURE 17

Chloride and Pumpage of Honouliuli STP Wells, Ewa Caprock, Oahu

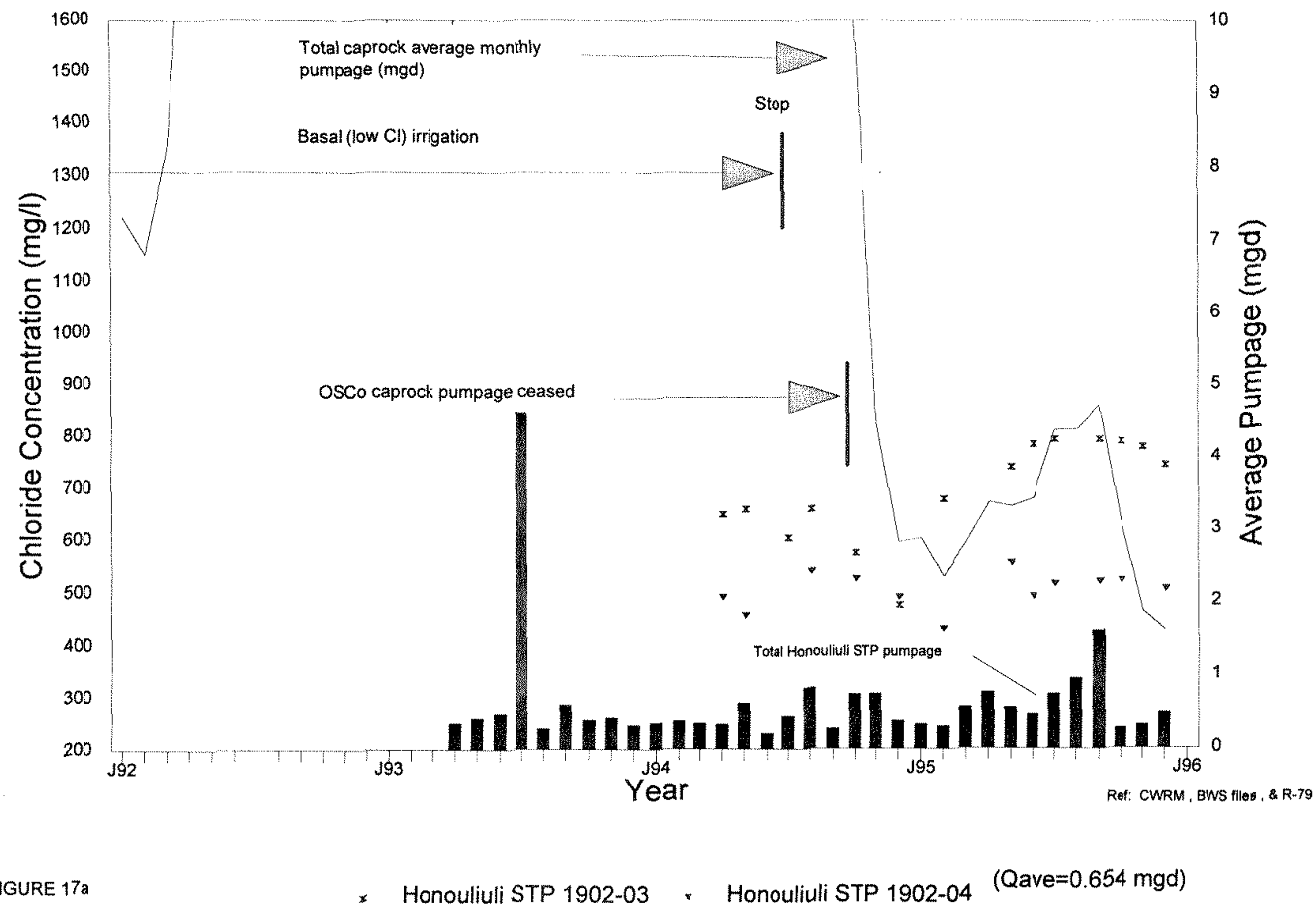
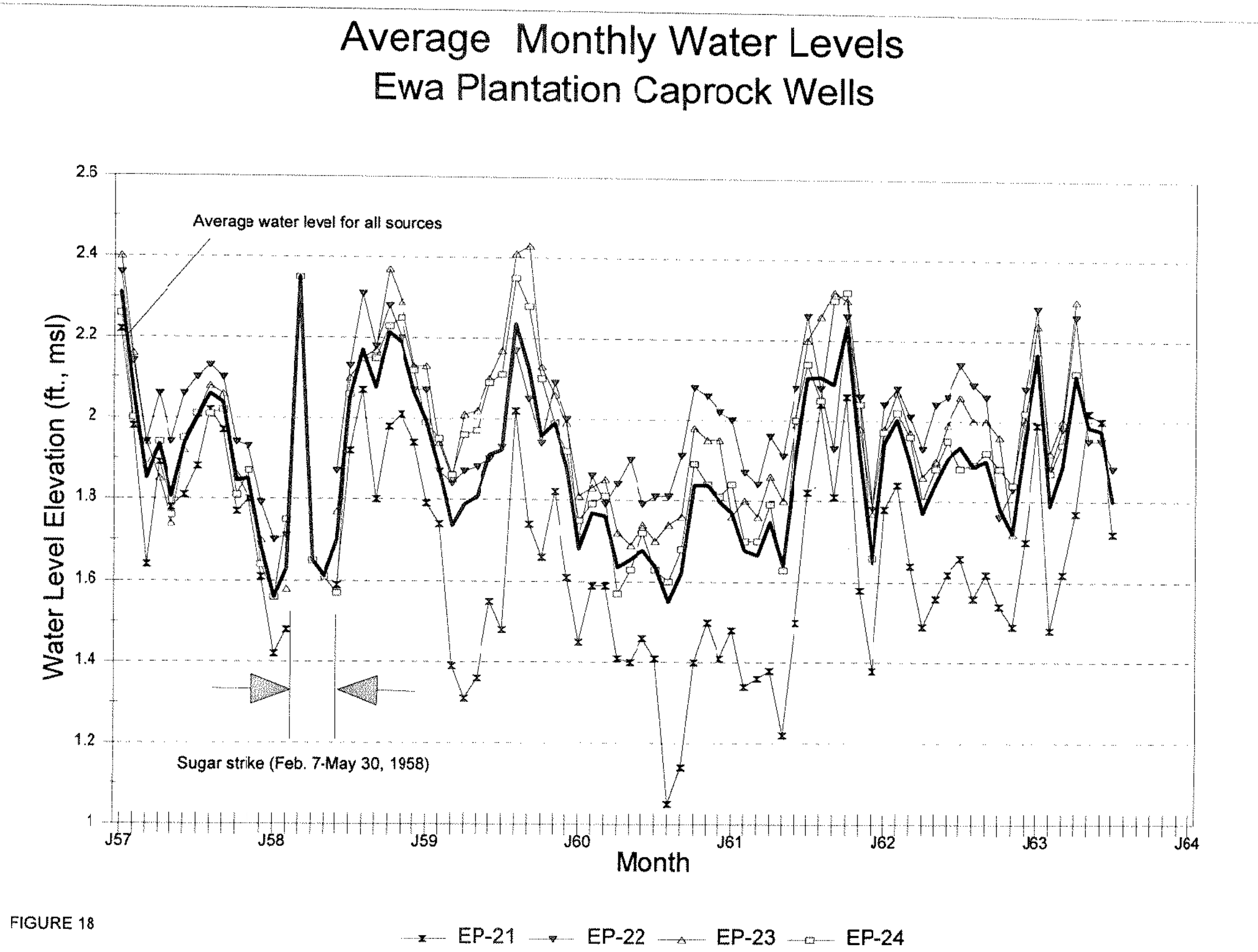


FIGURE 17a



Average Monthly Water Levels
Ewa Plantation Caprock Wells
Water Level Elevation (ft., msl)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
Average water level for all sources
Sugar strike (Feb. 7-May 30, 1958)
J57
J58
J59
J60
J61
J62
J63
J64
Month
EP-21
EP-22
EP-23
EP-24

FIGURE 18

Water Level @ EP-24 , Ocean Tide & Daily Rainfall, Ewa, Oahu

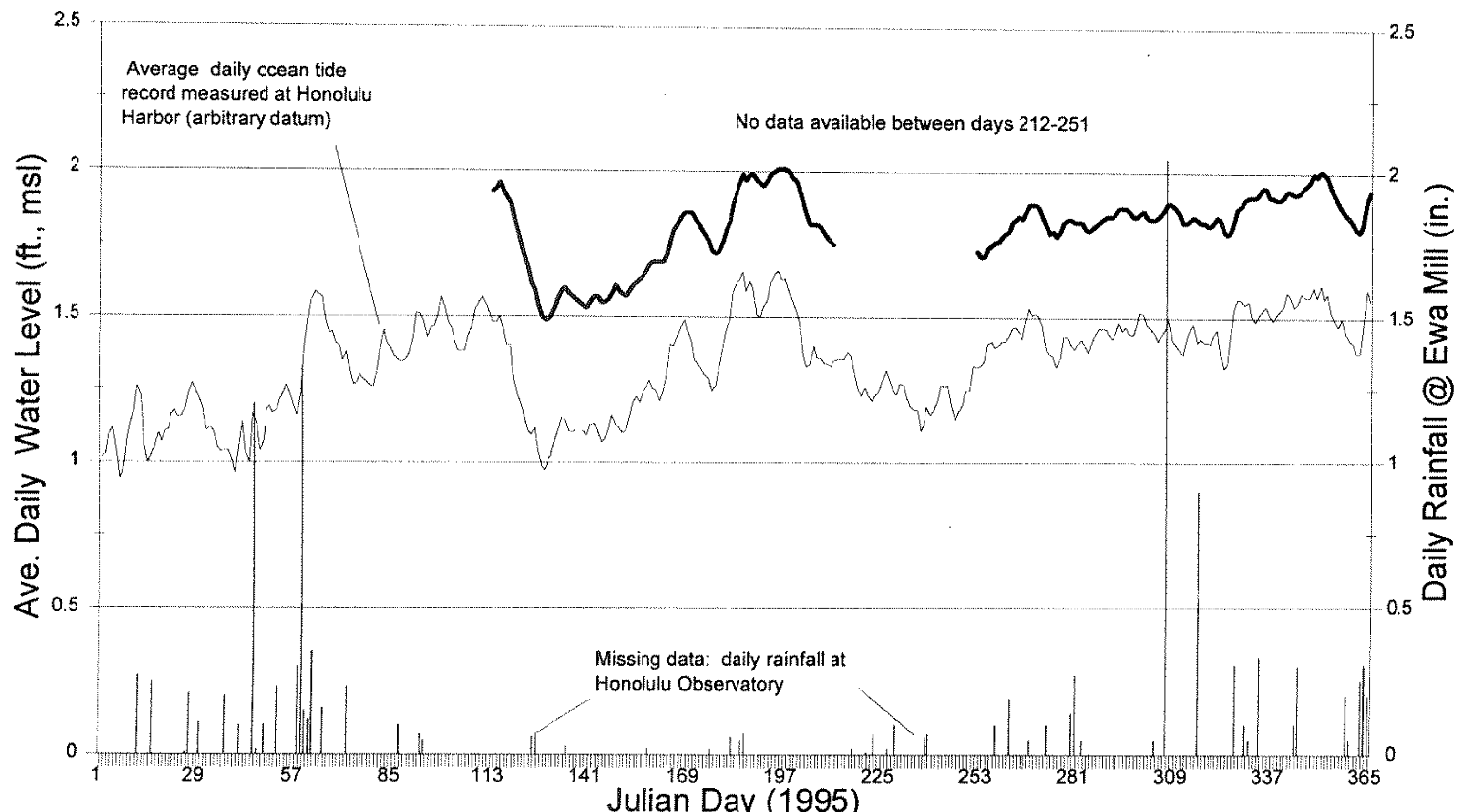


FIGURE 19

Ref: Tom Nance, water level data & tide data

Chloride and Pumpage of HFDC Golf Course Well B, Ewa Caprock, Oahu

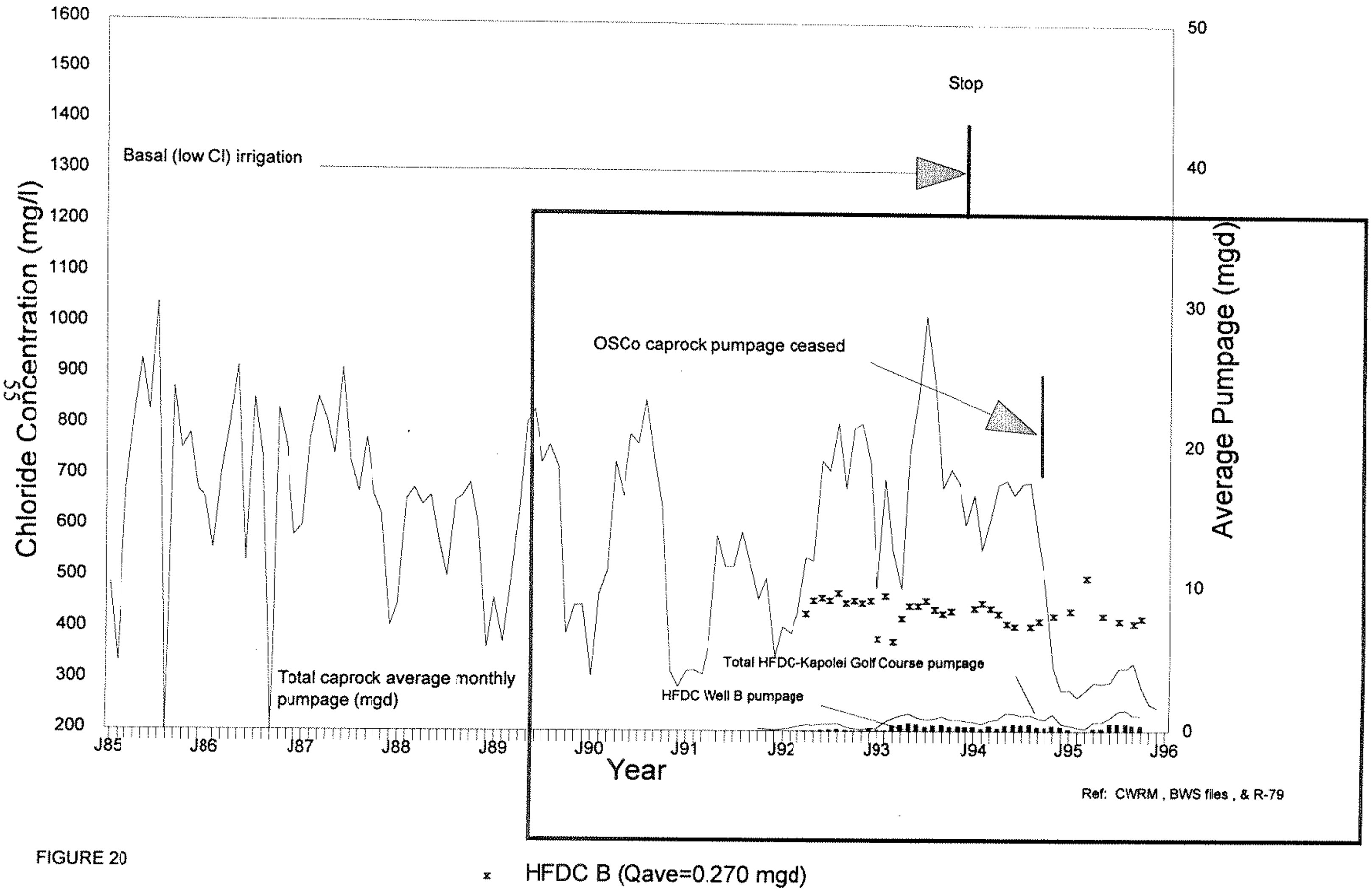


FIGURE 20

Chloride and Pumpage of HFDC Golf Course Well B, Ewa Caprock, Oahu

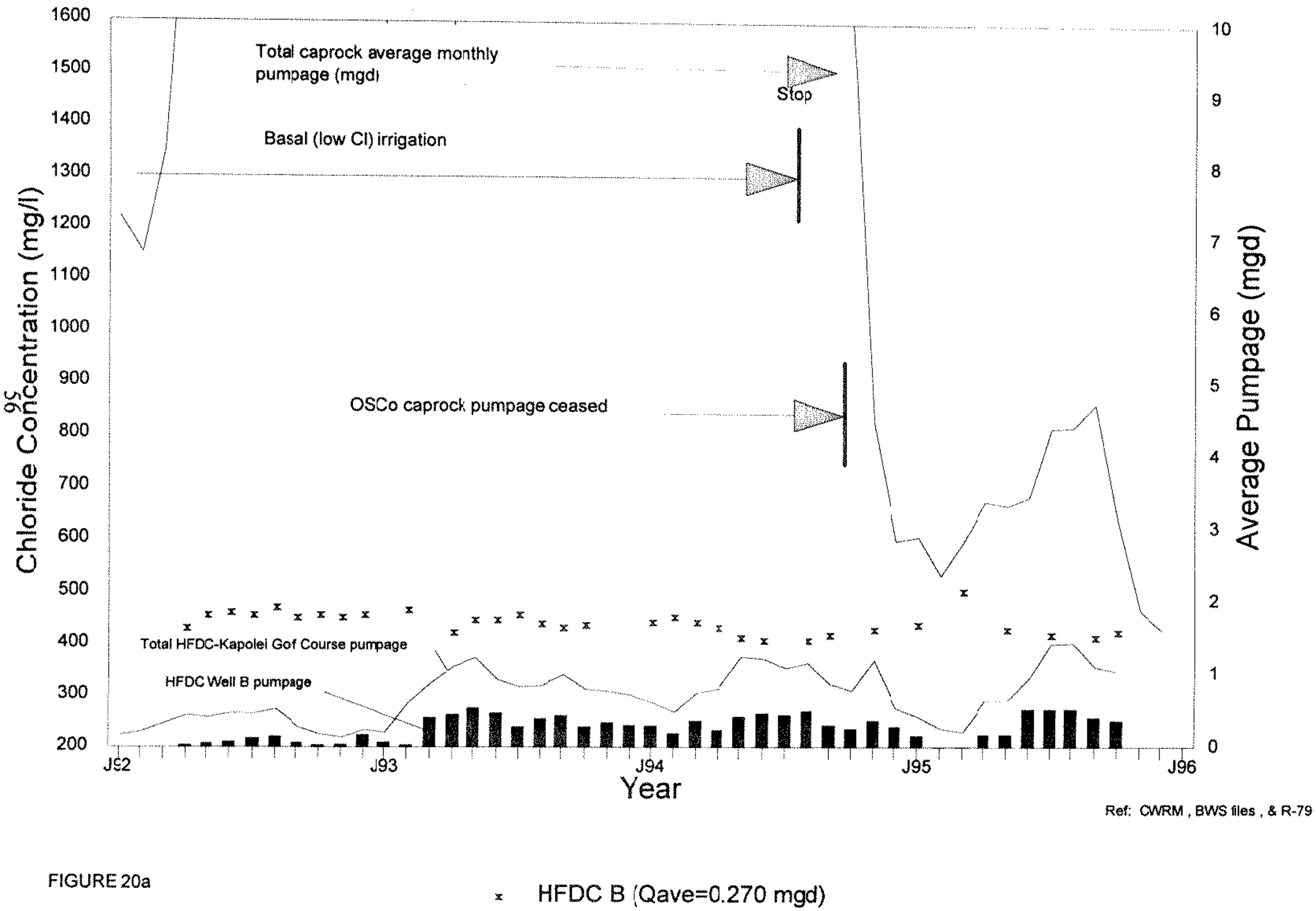


FIGURE 20a

APPENDIX A

Summary of Chloride Data[1]

Collected by CWRM Staff, 1994-96

	EP28	EP22	HPGC1	HPGC2	HPGC3	HPGC4	HPGC5	PV1	PV2	PC	HSTP	HSTP	KGC B	HRWP
	1902-01	1900-02	1901-03	1900-17	1900-18	1900-19	1900-20	2001-06	2001-08	2002-12	1902-03	1902-04	2003-02	1905-01
J94													440	
F													450	
M							1140						440	
A		1295	925	525	1110	1240					650	490	430	
M		1315					833	680	710		660	455	410	865
J		1335	1015	910	928	785		735	695				405	850
J	865						1090				605			
A		1330	1010	970	1105	1180	985		700		660	540	405	845
S	885	1370	990	515	1080	970		755		1030			415	
O	805						990				575	525		
N		1390	990		1005	925		670	600				425	910
D	800						860				475	490		
J95		1350	1005	880	930	810		670	675	985			435	830
F	750	1368	843	643			990				680	430		
M		1360	770	460	990	865		740	730	955			500	870
A	750	1397	920	860			1240	620	675					
M		1450	985	920	1135	1240	1300	675	740		740	555	425	870
J	775	1400	960	870	1190		1295	780	960	940	785	490		
J	875	1500	940	885	1230			670	715	945	795	515	415	865
A	850	1363	903	868			1245	640	728					
S		1460	900	875	1150		1160	645	685	850	795	520	410	580
O	850	1460	885	815	1045			645	700		790	520	420	
N		1430		770			1210	654	680	850	780			
D		1440	810	800	1100	1090		635	845	845	745	505		
J96														
F	875	1440	795	795	1105	1125	1225	730	640	825	755	505	430	
M	850	1510			1030	1135	1235	700	685	810	725	520	410	890
A														
M														
J														
J														
A														
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N														
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J97														

[1]Data in mg/l