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<p>Phase II is a continuation of the Phase I study to explore means of extending the effective life of the granular activated carbon (GAC) used in three central Oahu plants established by the Honolulu Board of Water Supply for the removal of volatile organic compounds: TCP, DBCP, and EDB. The Phase II study only concentrated on the Mililani GAC treatment plant, which did not have a measurable concentration of EDB. Isotherms were developed for TCP, which were approximately two orders of magnitude higher than DBCP in Mililani well water, but the results were questionable due to relatively high TCP losses by volatilization. Fourteen laboratory dynamic filtration tests (minicolumn tests) were conducted, eight using a bituminous-based GAC (used in BWS' full-scale treatment plants) and six using a lignite-based GAC. The lignite-based GAC significantly outperformed the bituminous-based GAC, requiring 24% less carbon to remove a unit amount of TCP. Aeration treatment effectively removed TCP and DBCP, but neither aeration nor GAC treatment appeared to appreciably remove natural background organic compounds.</p>			

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**EXTENDING THE EFFECTIVE LIFE OF THE GAC USED TO TREAT WELL
WATER: PHASE II OF EVALUATIVE STUDY AT MILILANI**

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Project Report PR-95-07

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Project Completion Report
for
“Evaluative Study to Extend the Effective Life
of the GAC Used to Treat Mililani Well Water, Phase II”

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Principal Investigator: Gordon L. Dugan

WATER RESOURCES RESEARCH CENTER
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Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Water Resources Research Center at the University of Hawai'i at Mānoa.

EXECUTIVE SUMMARY

The herein presented final report represents the completion of the Phase II portion of the study to extend the effective life of GAC in Mililani well water.

The original laboratory and pilot-plant testing of methods for reducing the target organic compounds—EDB, DBCP, and TCP—were conducted in 1984 by GMP Associates Inc., a Honolulu consulting firm. Based on the results of the dynamic minicolumn filtration test, GMP Associates projected the GAC usage rates for the prototype facilities at Mililani, Kunia, and Waipahu. Unfortunately, under actual field operating conditions the effective service life of the GAC was only approximately 15% of its projected designed life. The objectives of the Phase I project (May 1990 through August 1991) and the Phase II project were to determine reasons for the less than expected GAC service life and to propose practical economically feasible methods for extending the effective GAC life.

The major findings of Phase I are as follows:

1. Levels of target organic compounds—DBCP, EDB, and TCP—in groundwater in the Pearl Harbor aquifer of central O'ahu do not appear to be decreasing at present.
2. The adsorption capacity of GAC for a particular target compound is directly related to the concentration of the compound in the influent water. This finding is based on the analysis of spent carbon samples from the contactors of the GAC treatment facilities.
3. Inorganic cations and anions do not appear to be significantly adsorbed by GAC; however, the total organic carbon concentration of the Pearl Harbor basaltic aquifer is typically a few tenths of a milligram per liter, which is considerably higher than the levels of DBCP, EDB, and TCP encountered at the contaminated well sites. Thus the background organic matter may be contributing to the shortened service life of the GAC contactors.
4. Various pretreatment processes should be considered for reducing the background organic matter which may be limiting the effective treatment life of the GAC.
5. Scaling-up calculations indicated that there are significant limitations when extrapolating results from minicolumns to prototype units.

The major accomplishments and/or findings of the Phase II study include the following:

1. The use of isotherms to depict activated carbon requirements for the low concentrations of TCP and DBCP encountered for the Mililani well water does not appear promising, inasmuch as volatile losses were 51% for spiked deionized water and 22% for spiked Mililani well water.

2. Fourteen minicolumn experiments were conducted using various treatment schemes, eight using bituminous-based pulverized GAC (same as used in BWS' full-scale treatment plants) and six using lignite-based pulverized GAC.
3. Spiked deionized water used 40% less bituminous-based pulverized GAC per unit of TCP removed than was required for the naturally contaminated Mililani well water, suggesting that background organic material is competing with the target organics (TCP and DBCP) by this amount. Although this amount of interference, presumably by background organic material, is noteworthy, it represents only a relatively minor quantity in comparison to the approximately sixfold increase from the project design GAC usage rate to that required for the actual full-scale treatment plant operation.
4. Aeration does not appear to appreciably remove natural background organic matter. Aerated Mililani water with approximately 40% of the original TCP removed absorbed about 40% less TCP than nonaerated Mililani well water samples when using pulverized bituminous-based GAC; however, the activated carbon life was nearly the same as that in the experiments using unaerated Mililani well water.
5. When treating Mililani well water, lignite-based pulverized GAC used 24% less carbon per unit of TCP removed than did bituminous-based pulverized GAC.
6. The activated carbon treatment was essentially ineffective in removing TC, TOC, and NPOC.
7. Potentially, spent GAC could be regenerated by desorption with tap water, but the process is time consuming and desorption frequently occurs on a random basis. Thus the procedure does not appear practical at present.

Based on the significantly higher treatment efficiency of lignite-based GAC in comparison to bituminous-based GAC, it appears that future research should be directed at analyzing different types of GAC using the minicolumn technique, rather than at attempting to remove natural background organics, which may not be appreciably utilizing or tying up GAC adsorption sites.

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INTRODUCTION

In 1977, a spill of approximately 1.9 m³ (500 gal) of 1,2-dibromoethane (EDB) within 18 m (60 ft) of the Del Monte Corporation's water-supply well at Kunia (2703-01) focused attention for the first time on the possibility of pesticide contamination of groundwater in Hawai'i. In 1980, the Del Monte Kunia well was the first well closed because of pesticide contamination after the discovery of 1,2-dibromo-3-chloropropane (DBCP) and EDB in water samples. From 1982 to 1983, after the detection of DBCP or EDB in well samples, nine additional potable water wells in central O'ahu were closed because of potential adverse health risks associated with long-term exposure to contaminated water. Affected sites included Mililani Wells I (2800-02, -04) and II (2859-01), Kunia Wells II (2402-01, -02), and the Waipahu Wells (2400-01 to -04). After the well closures, a third contaminant, 1,2,3-trichloropropane (TCP), was also detected in water samples from all nine wells.

DBCP is a soil fumigant that was first used on a significant commercial basis by Dole Company in central O'ahu in 1959. DBCP use by Dole Company was phased out in the 1977 planting season in response to findings of the potential health risks associated with the compound. Del Monte Corporation did not use DBCP on O'ahu except on an experimental basis (Hawaii Department of Agriculture 1983).

EDB was used in a tetraethyl lead mixture added to aviation fuels (Lau 1985). EDB was also used as a fumigant to control nematodes in pineapple fields. On O'ahu, EDB was the primary soil fumigant used by Del Monte Corporation since about 1948. Dole Company only began using EDB on O'ahu on a significant commercial scale in 1978, after it phased out the use of DBCP in 1977 (Hawaii Department of Agriculture 1983). In September 1983, the U.S. Environmental Protection Agency (EPA) announced its intent to cancel registrations of pesticide products containing EDB and ordered an emergency suspension of registrations of EDB for use as a soil fumigant. Under the terms of the cancellation order, the use of EDB on pineapple fields in Hawai'i would be allowed until 1 September 1984. However, use of EDB on O'ahu by pineapple growers stopped by the end of 1983.

Excluding the Del Monte Kunia well, EDB contamination of groundwater on O'ahu is limited to the Waipahu area. EDB may have entered the groundwater as a result of use and handling by pineapple growers. However, the presence of large fuel pipeline leaks in the vicinity of the contamination makes it difficult to identify the source of EDB in groundwater at this time.

TCP is used as a paint and varnish remover, a solvent, and a degreasing agent (U.S. EPA 1980). Also, it occurred as an impurity during the manufacturing process of the Shell Chemical Company product DD, which was introduced in 1942. Shell DD became the primary

soil fumigant used by Dole Company in 1948 and was later used as a pre-plant nematicide in conjunction with DBCP. DD has not been used on pineapple fields on O'ahu since 1977 (*Honolulu Advertiser*, 6 October 1983).

At the time of the well closures, no state or federal drinking water standards existed for DBCP, EDB, or TCP. Consequently, the Hawaii Department of Health (DOH) set an interim limit of 20 ng/l for DBCP and EDB, which was the accepted detection limit for both compounds during the period of contaminant discovery. DOH did not have an action limit for TCP because of the assumed lesser risk associated with its consumption. Currently, EPA is proposing enforceable maximum contaminant levels (MCLs) of 50 ng/l for EDB and 200 ng/l for DBCP (Federal Register, 22 May 1989, 54(97):22062-22160). DOH established, as of March 1992, stricter MCLs of 40 ng/l for EDB and DBCP and 800 ng/l for TCP.

The immediate response to the well closures by the City and County of Honolulu Board of Water Supply (BWS) was to increase production at well sites less affected by contamination. In the Mililani area, however, Mililani Wells I Pumps 1 (2800-01) and 3 (2800-03) remained open despite evidence of trace amounts of DBCP since no other wells were available to serve the area. In addition, uncontaminated water was delivered to the Mililani area in water trucks.

A number of studies were conducted to identify the best practical treatment technology to reduce contaminant concentrations to below detectable levels (Dugan et al. 1984; Oshiro 1986; GMP Associates, Inc. 1984). Dugan et al. (1984) conducted a series of laboratory bench-scale experiments in which EDB- and/or DBCP-spiked water was treated by passing various quantities through different types of granular activated carbon (GAC). Oshiro (1986) studied thin-film volatilization and heat volatilization as possible treatment alternatives. GMP Associates, Inc. (1984) examined GAC, packed tower air stripping, and cooling tower treatments. Despite its greater capital cost, GAC treatment was recommended because it provided (1) improved performance and comparable operational costs relative to that attained with air stripping, (2) performance stability under varying influent conditions, (3) operational ease and reliability, (4) enclosed treatment, and (5) no air emissions (GMP Associates, Inc. 1984).

Based on the recommendations of the GMP Associates, Inc. (1984) study, GAC treatment facilities were placed in service at Mililani in March 1986, at Kunia in May 1986, and at Waipahu in July 1987 (Figure 1).

Problem Identification

Original operational cost estimates for the GAC treatment plants at Mililani and Waipahu were based on assumed carbon requirements of 0.0028 and 0.0043 kg/m³ (0.023 and

0.036 lb/1,000 gal), respectively (GMP Associates, Inc. 1984). Original carbon requirements were estimated based on breakthrough of TCP from laboratory minicolumns. However, operational experience from the time the treatment units were placed in service to December 1990 indicated actual carbon usage rates of approximately 0.016 and 0.018 kg/m³ (0.135 and 0.150 lb/1,000 gal) for Mililani and Waipahu, respectively. The actual carbon usage rate is the ratio of carbon quantity to volume of water treated between successive carbon replacements. The GAC in the contactors are typically changed upon breakthrough of target organic compounds. Because actual carbon usage is significantly greater than originally predicted, operational costs are much greater than anticipated. Another contributing factor is the replacement of the GAC for all three treatment facilities at the same time for convenience and ease of negotiating contracts for their replacement, even though some of the units may still have adsorption capacity remaining.

Purpose and Scope

Based on its desire to reduce operational costs associated with its GAC facilities, BWS contracted the University of Hawai'i Water Resources Research Center (WRRC) in May 1990 to address the problem of extending the effective life of GAC used for the removal of target organic compounds from well water in central O'ahu. The scope of the study was to obtain the basic information necessary to understand the problem so that, potentially, based on economic considerations, corrective measures could be taken to extend the life of the GAC.

Reported herein are the results obtained for Phase II of the evaluative study to extend the effective life of the GAC used to treat Mililani well water. The Phase II project continues the work done in the Phase I project, with concentration on the Mililani GAC treatment plant.

The project objectives for both Phase I and Phase II of the evaluative study were basically as follows:

1. Examine the operations of the GAC facilities at the Mililani, Waipahu, and Kunia well sites
2. Employ and train a toxic chemist to effectively and reliably assay for the various target organic compounds of importance in the well waters and GAC
3. Conduct physical, chemical, and biological tests to characterize the influent water, effluent water, and GAC in various stages of operation
4. Test and characterize the spent carbon to determine its total adsorptive capacity to extend the life of the GAC

The Phase I portion of the study was initially a 12-month project, commencing on 1 May 1990; however, a four-month no-cost extension moved the completion date to 31 August 1991.

The results of the Phase I project are presented in a six-month progress report (Oki et al. 1991) and a project completion report (Oki et al. 1994).

The Phase II portion of the study was established as a 12-month project, officially starting on 15 October 1991; however, the research activities were maintained in the interim period between the end of Phase I and the start of Phase II. A six-month no-cost extension moved the completion date for Phase II to 16 April 1993.

The project objectives for Phase II basically reflected those of Phase I. In addition to continuing the basic objectives of Phase I, a greater emphasis was placed on (1) ascertaining the effects of nontarget compounds, total organic carbon, humic acids, and other naturally occurring organics which could limit the effective life of the GAC and (2) studying the effectiveness of pretreatment methods.

Project Management and Personnel for Phase II

The research project required multidisciplinary expertise and was accomplished through a number of coordinated activities. Project personnel, consisting of researchers in the fields of engineering, chemistry, and microbiology, are listed below. Overall responsibility for the project was vested with the principal investigator.

Dr. Gordon L. Dugan	Principal Investigator
Dr. Roger S. Fujioka	Co-Principal Investigator
Dr. L. Stephen Lau	Co-Principal Investigator
Mr. Henry K. Gee	Research Associate, WRRC
Dr. Gerald H. Takei	Toxic Chemist, WRRC
Ms. Terra L. McParland	Graduate Research Assistant, WRRC
Ms. Holly M. Chu	Former Graduate Assistant, WRRC

MAJOR ACTIVITIES AND RESULTS FOR PHASE I

Several new instruments were purchased to enhance the capabilities of the Toxic Chemistry Laboratory for the Phase I portion of the study. In addition, an experienced and academically trained toxic chemist was hired. A considerable amount of time was required for the toxic chemist to be trained and, in turn, to train other personnel in the operation of the newly acquired sophisticated instruments. As with most situations with highly technical instruments a certain amount of "shake-down" time was required. The major items of equipment include a gas chromatograph/mass spectrometer system, atomic absorption

spectrophotometer with graphite furnace, total organic carbon (TOC) analyzer, ion chromatograph, and high performance liquid chromatograph.

The principal findings of Phase I by Oki et al. (1991, 1994) are summarized below.

Levels of target organic compounds DBCP, EDB, and TCP in groundwater in the Pearl Harbor aquifer of central O'ahu do not appear to be decreasing significantly. In fact, based on the analysis of spent GAC samples from contactors at the Waipahu treatment facility, DBCP, which was previously undetected, now appears to be occurring at low levels (a few nanograms per liter) in groundwater near Waipahu. This discovery does not necessarily preclude the possibility that DBCP has been present near Waipahu for a number of years. However, it does seem to indicate that the plume of DBCP contamination in the aquifer may be moving slowly down gradient. Because recovery of the aquifer from such contamination may take many years, the need for continued treatment of the groundwater seems likely. Furthermore, recent EPA reports regarding the carcinogenicity of TCP may support the continued use of GAC and/or other high-level treatments of groundwater.

Based on our analysis of spent carbon samples collected from contactors at Mililani, Kunia, and Waipahu, it is apparent that the adsorptive capacity of the GAC for a particular target compound is directly related to the concentration of that compound in the influent water. For Mililani, for instance, where TCP in the influent occurs at levels of about 2000 ng/l, the spent carbon contained levels up to 400 mg/kg (400 ppm). For Waipahu, where TCP in the influent occurs at levels of about 200 ng/l, the spent carbon contained levels of about 40 mg/kg (40 ppm).

Various organic or inorganic compounds present in the groundwater could be responsible for occupying adsorption sites on the GAC, thus making fewer sites available for adsorption of target compounds. The results of this study indicate that naturally occurring background organic matter in groundwater exists at concentrations which are two to three orders of magnitude greater than concentrations of TCP, which is typically the target organic compound found at the greatest concentrations. Thus naturally occurring background organics could play a significant role in determining the effective life of the GAC.

The results of this study seem to indicate that inorganic cations and anions are not significantly adsorbed by the GAC. However, the behavior of compounds such as silica, relative to GAC, has not been established with certainty to date.

Bacterial growth may also play a role in the adsorption of target organic compounds. Although bacteria were isolated from spent GAC samples, subsequent scanning electron microscope (SEM) analysis did not reveal significant microbiological flora other than some suspected slime layer that might inhibit adsorption.

Specific results and conclusions from Phase I include:

1. The ultrasonic solvent extraction method developed for this study appears to be the most effective technique for desorbing target organic compounds from spent GAC samples.
2. TOC levels in groundwater samples from the Pearl Harbor basaltic aquifer are typically a few tenths of a milligram per liter, which is at least two orders of magnitude higher than the levels of DBCP, DCP, EDB, and TCP encountered at the contaminated well sites. Thus background organic matter may be contributing to the shortened service life of the GAC contactors.
3. TOC and infrared analyses indicate the presence of background organic compounds in groundwater. Further research is necessary to characterize the nature of the background organics, particularly humic acids.
4. The presence of background organic matter in groundwater suggests that different operational strategies could enhance the effective service life of the GAC. For instance, lag contactors kept off-line until needed may mean preloading the GAC in the lag contactor with background organic matter can be avoided.
5. The scaling equations presented proved that it was not feasible to obtain treatment results from the minicolumn test and scale them directly to the prototype or large-scale facility, as was done for the original design of the BWS GAC treatment facilities at Mililani, Kunia, and Waipahu. However, minicolumn studies could be used to assess the effectiveness of different GAC treatment facility operation modes.
6. Various pretreatment processes—including ozonation, ultrafiltration, and aeration—should be considered in examining the possible strategies for enhancing the effective life of the GAC.

METHODOLOGY FOR PHASE II

A major problem in determining the effective life of the GAC under various conditions and potential pretreatment options is the time required for breakthrough of target organics. At present DBCP and TCP are considered the target organics for Mililani well water. When the GAC contactors were initially designed, the effective life of the GAC under the operating conditions envisioned by BWS was upward of two years (GMP Associates, Inc. 1984), but actual operating conditions at the Mililani, Kunia, and Waipahu treatment facilities have shown that the GAC requires replacement approximately every six months. It is suspected that background organics are competing with the target organics for the adsorption sites.

It has been demonstrated that aeration alone effectively removes volatile target organics EDB, DBCP, and TCP (GMP Associates, Inc. 1984; Dugan et al. 1984). A prototype aeration tower that used Mililani well water and that was operated by BWS in 1983 proved the effectiveness of aeration. However, the use of GAC is attractive because it effectively removes a high percentage of most organics. Nevertheless, for GAC facilities, which were established to remove the organics of initial concern (EDB and DBCP, and later TCP), this high adsorption efficiency of all organics may be their operational downfall.

Preliminary economic analysis by BWS personnel, based on amortized capital costs and operational expenses, has indicated that it is more economical to continue to replace the GAC approximately every six months than to replace the GAC facilities with aeration units. Consequently, the Phase II portion of the study is based on the premise that the GAC facilities will continue to be operated and expanded as necessary and that efforts to extend the life of the GAC should concentrate on removing background organics (including target organics), adjusting operational procedures, and/or using different types of GAC.

Numerous treatment and operational schemes could be advanced for the purpose of enhancing the life expectancy of the GAC; however, the long time required (probably at least six months) for a pilot-scale GAC system to reach equilibrium (exhaustion of effective adsorptive capacity) limits the number of schemes or options that can be explored. Two basic methods were explored during Phase II to shorten the time to reach GAC breakthrough and/or equilibrium from months to days. These methods, initiated during Phase I, were not made operational or were not completed until Phase II. The principal methods are (1) the development of isotherms and (2) the use of the dynamic filtration test or so-called minicolumn test. The use of aeration to decrease the concentration of target volatile organics (DBCP and TCP) was also explored during Phase II, along with a study of the feasibility of GAC regeneration by desorption.

Laboratory Aeration Devices

Aeration in general is usually effective in removing a high percentage of most volatile organic substances. As previously indicated, DBCP and TCP are readily volatilized by aeration. In terms of economy, questions arise as to the type of aeration device to be used, quantity per unit flow, minimum detention times, and other variables.

Although numerous aeration configurations and operational modes could be explored, the aeration experiments conducted in this study were limited to three basic types: two batch systems and a continuous-flow system. Operational parameters varied for the three types. One of the batch aerators was a 2000-ml beaker stirred at varying detention times and speed. The second batch system utilized diffused air to induce volatilization. The continuous-flow system

consisted of a sustained water flow and diffused air for volatilization (Figure 2). The batch diffused-aeration system used the same apparatus (Figure 2) as the continuous-flow, diffused-air system, except that water was not pumped in or allowed to flow out.

The operational parameters for the batch diffused-air system were varying air flow, water depth, and detention times. The continuous-flow system used the same parameters plus various influent and effluent flow rates. The water being aerated was from the Mililani wells. The various operational conditions, together with the reduction percentage of TCP and DBCP, for batch mechanical aeration, batch diffused aeration, and continuous-flow aeration are shown in Appendix Tables A.1, A.2, and A.3, respectively.

The continuous-flow system (Figure 2) was used as the aeration device for the minicolumn experiments, which is discussed below. For the aerated minicolumns, the following parameters were used for the continuous-flow device: water height, 483 mm (19 in.); air flow, 2124 ml/min; water flow, 28 ml/min; and detention time, 35 minutes.

It should be noted that an attempt was made in all experiments to adjust aeration so that 100% removal of DBCP and TCP did not occur. This procedure was followed so that an identifiable concentration in the effluent could be measured. This was especially important in the minicolumn experiments when the pulverized GAC adsorption sites were saturated. A more complete description of the aeration experiments can be found in the master's thesis by McParland (1992).

Isotherms

Activated carbon has been long noted for its ability to remove organic compounds from solution by means of adsorption through its large surface area (e.g., approximately 1000 m² for 1.0 g of surface area). Eventually the surface becomes saturated and consequently lose its ability to absorb, a condition known as equilibrium. Isotherm experiments have proved to be a valuable tool in predicting adsorptive capacity. However, isotherm data are site-specific because of the varying types, combinations, and concentrations of compounds in the median being passed through the activated carbon and because of physical parameters such as temperature and pH and the variety, type, and size of the activated carbon itself.

Equilibrium Time

Contact time is another important parameter. To determine the equilibrium time for TCP, which had the highest concentration of the target contaminants in Mililani well water ($\pm 2.0 \mu\text{g/l}$), a series of five 1.0-liter Erlenmeyer flasks with ground glass stoppers were used. To each flask, 0.20 g of GAC (Calgon GAC Filtrasorb 400), 279.6 μg of TCP, and magnetic stir bars were added. Then deionized water was poured to the top so that when the ground

stoppers were inserted there was little chance of air space occurring, consequently reducing the likelihood of volatilization. After the ground stoppers were in place they were wrapped in parafilm, and the entire flask was covered with aluminum foil to keep light out. Each flask was placed on a magnetic stirrer and stirred at the same rate for specific contact times that ranged from zero to over 90 hours at a room temperature of approximately 25°C. It is noted that the concentration of spiked TCP is at least two orders of magnitude higher than the TCP concentration in Mililani well water. Using these higher concentrations was necessary due to problems encountered when using concentrations that approached that of Mililani well water.

At the end of each specific contact time, 600 ml of liquid was withdrawn from each flask and placed in a 1.0-liter round-bottom boiling flask, to which 10 ml of Fisher Optima-grade hexane and a boiling chip were added. Then the contents were heated to boiling point. Following this, the hexane and associated organic compounds were collected and their respective volumes recorded for use in subsequent calculations. A drying agent, anhydrous sodium sulfate, was added to the extract to remove any water. A 5- μ l aliquot of the extract was then injected into the Hewlett-Packard Model 5700A gas chromatograph. The details for operating the gas chromatograph are presented in Appendix B.

The results of the TCP equilibrium test are presented in Figure 3. There was a sharp increase in adsorption from the beginning of the test to 10 hours, followed by a slow increase to the end of the test. At a contact time of 24 hours the removal of TCP was 84%, which should allow sufficient time for equilibrium to be reached and which should be sufficiently beyond the point where the slope changes from rapid adsorption to gradual adsorption. A longer time would increase the potential for volatilization. Thus 24 hours was chosen as the basic equilibrium time for the isotherm study.

Isotherm Development

The isotherm experiments were conducted with the same basic equipment and methods as used for the equilibrium time experiments. However, pulverized GAC passing through a 200-mesh sieve and retained on a 325-mesh sieve was used in place of the standard GAC. The pulverized GAC was washed, dried in a 103°C oven, and stored in a glass vial in a desiccator for future use.

The isotherms tested both spiked deionized water and Mililani water. The reason for using deionized water was that it contained an insignificant concentration of background organics. The pulverized GAC ranged from 0.02 to 0.16 g in each flask, and the TCP added to each flask was a constant, usually around 230 μ g. Four flasks were prepared for each isotherm experiment, one of which served as a blank with no pulverized GAC added. The sealed and covered flasks were placed on a magnetic stirrer for 24 hours at room temperature (approximately 25°C) and then allowed to settle for about 6 hours. The contents of the flask

were then assayed for the remaining soluble TCP using the methods previously described for the determination of equilibrium time. Three isotherm experiments were conducted for each graph; thus a total of nine points were plotted on each graph to form a single isotherm. This was done to check the reliability of the experimental procedure, which subsequently proved to be fairly consistent.

Treatment of Isotherm Data

The Freundlich adsorption isotherm equation, one of the most commonly used isotherms, was used for plotting the data gathered in the experiments. The equation is empirical and used to describe the adsorption process in dilute aqueous solution. The Freundlich equation is as follows:

$$X/M = K C_f^{1/n}$$

where

X = $C_o - C_f$ the amount of compound adsorbed from a given volume of solution, μg

M = the weight of activated carbon, g

C_o = the amount of compound in the untreated solution or the amount of compound added, μg

C_f = the amount of compound remaining in the treated water, μg

The logarithmic form of the above equation is

$$\log X/M = \log k + 1/n \log C_f$$

The K and $1/n$ are empirical constants and are characteristic of the solution and type of carbon used in the experiment. The Freundlich equation can be represented by an equation of a line ($y = b + mx$) on logarithmic paper. From a graph of the data on logarithmic paper, K is the intercept of the vertical axis, X/M , at a value of $C_f = 1$. The intercept is an indicator of the adsorptive capacity of the pulverized GAC (Dobbs 1980). The loading factor or adsorptive capacity of the carbon X/M is a function of the equilibrium concentration of the solute. The slope of the line is $1/n$ when the data are plotted on logarithmic paper and is an indicator of adsorption intensity. An isotherm with a steep slope, $1/n$ close to 1, indicates that a higher adsorptive capacity would occur at higher equilibrium concentrations and a lower adsorptive capacity at lower equilibrium concentrations. For isotherms with relatively flat slopes the adsorptive capacity at low equilibrium concentrations is only slightly lower than for high equilibrium concentrations (Faust and Aly 1987). At an equilibrium concentration of C_f the concentration of the adsorbed compound in the adsorbent is expressed by X/M (Dobbs 1980).

The results of the deionized water and Mililani well water tests plotted on log-log scale are shown in Figure 4. The slopes of the two isotherms are similar (around 0.3). The equation of the isotherm for the deionized water is $\log X/M = \log 1031.34 + 0.260 \log C_f$, and the equation for the Mililani well water is $\log X/M = \log 1465.55 + 0.33 \log C_f$.

When compared, the isotherm for Mililani well water depicts a higher adsorptive capacity for TCP than the isotherm for deionized water, which was assumed to have a lower concentration of natural background organics. This is opposite from what was expected. It was expected that the natural background organics contained in the well water would compete for adsorption sites on the pulverized GAC, thus leaving less open sites for adsorption of the added TCP.

Losses between the initial blank and the final blank are assumed to be due to volatilization, although conceivably some unknown mechanism may be at least partially responsible. The average percentage of losses for the three separate test runs were 51% for the spiked deionized water isotherm and 22% for the Mililani water isotherm. Several possible scenarios could be advanced for this significant difference. One scenario is that the volatility of TCP in the Mililani water is lower due to the higher and undoubtedly wider range of natural background organics present. However, this is only speculation.

Overall, the methodology used in the isotherm experiments appears to have been reliable, based on the data groupings around the isotherms and the additional complementary isotherms yielding similar results (not herein presented). The losses due to assumed volatilization were quite high (51%) for the spiked deionized water isotherm and were of concern for the spiked Mililani water isotherm (22%). These losses may have significantly affected the results of the isotherm experiments. The volatilization losses, coupled with the approximately two orders of magnitude higher concentrations (than the Mililani water) of TCP required for the isotherm test, appear to significantly limit the use of isotherms in the present study. Previous isotherm tests conducted during this study period using concentrations of TCP approaching that of the Mililani water resulted in failure. A more complete description of the isotherm studies can be found in the master's thesis by Chu (1992).

Minicolumn Experiments

The minicolumn experimental procedure basically incorporates a small amount (~50 mg) of powdered activated carbon (PAC) placed in a small container and subjected to a high volume of flow per unit mass of GAC (~0.002 ml/min-mg of activated carbon) under high pressure (up to and occasionally over 1379 kPa [200 psi]). The procedure was originally called "dynamic filtration test," and the term "rapid small-scale column test" has been advanced by some investigators (Crittenden et al. 1989); nevertheless, for simplicity the procedure will be referred to as "minicolumn experiments" in this report. To keep the source of activated carbon the same, the bituminous-based GAC that was used in the Mililani, Kunia, and Waipahu GAC treatment facilities was pulverized to powdered size (200 × 325 mesh) for use in the minicolumn experiments during Phase I and the earlier part of Phase II (see carbon preparation in

Appendix B). During the latter portion of Phase II, a powdered-size lignite-based GAC (after pulverization) was used to ascertain if an alternate base had an effect on the adsorptive capacity and thus the useful life of the GAC.

The minicolumn experimental procedure definitely has its limitations in terms of transferring the results to full-scale operations. The limitations were indicated in scale-up calculations presented in the Phase I report (Oki et al. 1994). Pilot-scale columns using GAC, rather than pulverized GAC, and operating at a lower pressure are needed for scale-up projections to prototype field operations. Nevertheless, the minicolumn procedure is considered a valuable means of screening GAC tests within relatively short periods of time.

A cross section of the minicolumn is shown in Figure 5, and a schematic of the minicolumn testing system is presented in Figure 6. Various liquid samples to be tested are placed in the 10-liter influent reservoir and then pumped to the minicolumn and onto the 3.8-liter (1.0-gal) effluent collector (opaque reagent bottle). The pressure gage can be used to monitor the physical condition of the minicolumn. A minimum amount of pressure is required (e.g., up to 137.9 kPa [20 psi]), but a high pressure indicates minicolumn plugging. The tests were operated for 24 hours a day until designated breakthrough occurred for one of the two target compounds: 100 ng/l (or ppt) for TCP and 20 ng/l for DBCP. Since TCP was nearly two orders of magnitude higher in concentration than DBCP, it invariably exceeded the established breakthrough threshold first, which is in accordance with Henry's Gas Law since TCP has a higher Henry's constant and thus is expected to be volatilized easier than DBCP.

Influent samples for the minicolumn tests were prepared in two to eight batches. The concentration of TCP and DBCP during the minicolumn experiments was determined on a daily basis for both the influent and effluent samples. The effluent volumes and the system's pressure readings were also recorded daily. Each of the minicolumn tests was conducted under similar operational conditions. The bed heights and mass of pulverized GAC in the minicolumn were kept nearly constant for all tests. The empty bed contact time for the minicolumn calculated out to be about 5 seconds, and the flow-through rate averaged nearly 1.0 ml/min. A brief description of laboratory experimental methods involving carbon preparation, packing of the pulverized GAC column, preparation of the spiked deionized water influent, analysis of the pulverized GAC column influent and effluent, and gas chromatography can be found in Appendix B.

During the minicolumn experiments, numerous pump failures occurred. Pump seals would break down after relatively short continuous use, apparently because of the high pressure used. The primary problem was to find a pump that could be maintained at a continuous high pressure without leaking. Several pumps were tried and sent back to the manufacturer for replacement and/or repair when they failed to meet their advertised operational

specifications. Finally, a relatively expensive high-performance single-piston liquid pump which performed satisfactorily with minimal maintenance was obtained. Based on the apparent proven success of the new high-performance pump, an identical pump was purchased to serve as a backup and be available to conduct concurrent experiments.

Fourteen pulverized GAC minicolumn experiments were conducted during Phase II. Eight of the experiments used bituminous-based GAC (Calgon GAC Filtrasorb 400) that has been employed at the BWS Mililani, Kunia, and Waipahu GAC treatment plants, while the remaining six minicolumn experiments used a lignite-based GAC (American Norit Co.) that was provided by BWS. The minicolumn experiments utilizing the bituminous-based GAC involved (1) naturally contaminated Mililani well water, (2) deionized water (18 Mohm-cm) spiked with DBCP and TCP, (3) aerated Mililani well water, and (4) autoclaved Mililani well water. The minicolumn experiments with the lignite-based GAC involved the use of only naturally contaminated Mililani well water and deionized water spiked with DBCP and TCP.

Two of the spiked deionized water experiments using lignite-based GAC were preloaded (water pumped through the minicolumn) with water devoid of DBCP and TCP for 72 hours. One used distilled water and the other water collected from the BWS Pacific Palisades water well. The rationale for preloading was an attempt to ascertain the effects of natural background organics on the adsorption characteristics of the GAC. Two lignite-based GAC experiments using Pacific Palisades water spiked with DBCP and TCP ended in failure when the minicolumns became plugged prior to breakthrough of either organic compound. One became plugged at seven days and the other at five days. The results of these two failed experiments are not included in this report.

Minicolumn Performance

The basic data for 14 minicolumn experiments are tabulated in Appendix C. Also presented in Appendix C are data on the total volume of water to breakthrough, weights of TCP and DBCP to breakthrough, and total carbon usages per unit of flow. It must be emphasized that the breakthrough values of 100 ng/l for TCP and 20 ng/l for DBCP are arbitrarily assigned values. As noted in the introduction, the maximum concentration limit for drinking water is 40 ng/l for DBCP and 800 ng/l for TCP. As can be noted in Appendix C and as was expected, TCP always reached breakthrough before DBCP.

A graphical representation of the behavior of TCP and DBCP for each of the 14 minicolumn experiments, based on the basic data from the tables in Appendix C, is presented in Appendix D. As can be observed from the applicable Appendix C tables and Appendix D figures, most of the TCP values were in the 1000 to 2000 ng/l range, whereas DBCP values generally ranged from 30 to 60 ng/l. However, there were a notable number of individual values outside these ranges.

A summary of the 14 minicolumn experiments involving TCP is tabulated in Table 1. Values for DBCP are not included inasmuch as TCP always reached breakthrough first. The 14 minicolumn experimental runs are not presented in chronological order in two cases because it is desirable for convenience of comparison to place similar kinds of tests next to each other. Also included in Table 1 are the values from the minicolumn experiment conducted in 1984 by GMP Associates. The values from Run No. 2 is suspect, based on the results from the other runs. The low volume of liquid and corresponding relatively short time to breakthrough may be due to short circuiting and/or inexperience in conducting minicolumn experiments at that time. As can be noted in Table 1 the first eight runs used pulverized bituminous-based GAC, which was obtained from the GAC supply used in the established BWS treatment plants at Mililani, Kunia, and Waipahu. The last six runs used pulverized lignite-based GAC.

In one notable minicolumn experiment, Run No. 4, Mililani well water was autoclaved prior to being pumped to the minicolumn. Because it is known that heating water containing volatile organics enhances volatilization, this experiment was conducted to observe the effects that lower levels of TCP and DBCP would have on the effective life of the GAC. The autoclaving operation consisted of heating Mililani well water to 110°C for 50 minutes. It is readily recognized that this approach to reducing TCP and DBCP is not practical or economically feasible, but it is a way to reduce the concentration of these naturally occurring contaminants. Surprisingly, breakthrough for Run No. 4 occurred after only 13 days and 12.1 liters of water had passed through the minicolumn; this was the lowest volume recorded for all experiments except Run No. 2. However, the amount of TCP adsorbed (2565 ng) was only a small fraction of that of the other 13 minicolumn experiments, including Run No. 2. Perhaps the elevation of temperature altered the adsorption characteristics of the background organic matter, or possibly it was some type of fluke in the test. Nevertheless, since it was an impractical approach anyway, the autoclaving experiment was not repeated.

Similarly, the two aerated Mililani well water samples (Run Nos. 7 and 8) had their TCP and DBCP values reduced by nearly 40% by aeration, while the volume of water passed through (19.6) was higher by up to 40%. Compared to the unaerated Mililani well water samples, the amount of TCP adsorbed was down by a near equal amount. Thus the indication exists that apparently aeration does not have an appreciable effect on natural background organics, which some investigators have assumed to be competing with TCP and DBCP for adsorption sites. Other overall comparisons of the values in Table 1, such as the higher GAC removal efficiencies for the spiked deionized water experiments and the noticeably higher TCP removal efficiencies for lignite-based GAC in comparison to bituminous-based GAC, can be more conveniently observed in a subsequent table and figure.

Similarly grouped GAC minicolumn experiments (or individual experiments in some cases) and their resultant average GAC usage per unit volume and the amount of GAC required to remove a like amount of TCP are tabulated in Table 2. The value for the Run No. 2 experiment in Table 1 was omitted from the average for pulverized bituminous-based Mililani well water in Table 2 because of the aforementioned suspicion that the results were faulty. The extremely high amount of GAC (19 610 ng) required to remove an equal amount of TCP is readily apparent in the last column for the autoclaved Mililani well water experiment. Likewise, when this type of comparison is made, the value for the aerated Mililani well water experiment is noticeably higher, about 36%, than the value for unaerated Mililani well water experiments. This is consistent with the previous observation that the influent TCP values were lower in the aerated samples by approximately 40%.

This type of comparison again indicates that aeration does remove the target volatile organic compounds but does not remove, to any appreciable degree, the suspected natural background organic materials. Another known factor about GAC performance is that the higher the concentration of the organic material that is being removed, the greater the efficiency of removal. This factor could contribute to the especially high usage of GAC for the autoclaved Mililani well water sample since the maximum influent TCP value was less than 290 ng/l. This may also apply to a lesser degree for the aerated Mililani well water sample.

The amount or ratio of GAC to remove an equal amount of TCP in the Mililani well water minicolumn experiments using bituminous-based GAC was 2599:1, whereas for the spiked deionized water minicolumn experiments it was only 1560:1, or 40% less (Table 2). As previously discussed, the rationale for using deionized water was to ideally conduct the experiment without the presence of natural background organic material that may be competing with the target organic compounds for adsorption sites on the GAC. However, as reported in the Phase I project report (Oki et al. 1994) and in a subsequent section of this report, deionized water had measurable amounts of natural organic material in the tenths of a milligram per liter concentration range in comparison to the target organic compounds that were measured in the nanogram per liter range, which is a million times more sensitive.

It was noted previously in this report that the isotherm determinations for spiked deionized water revealed a TOC loss of 51% (presumed to be mainly by volatilization), which is much higher than that for Mililani well water at 22%. From this it could be postulated that volatilization and/or some other as yet unknown mechanism is the primary reason why spiked deionized water is losing a higher percentage of the target organic compounds, rather than the reason being that natural background organic materials compete with target organic compounds for adsorption sites on the GAC. The influent and effluent TCP and DBCP values used for the

isotherms were determined after 24 hours of stirring and six hours of settling, whereas the values for the minicolumn experimental runs were determined on a daily basis.

The aspect that is most obvious in Table 2 is the notably higher efficiency of lignite-based GAC over bituminous-based GAC, which was used in the BWS treatment plants during the Phase I and II study period. The data in Table 2 indicate that in Mililani well water lignite-based GAC used 24% less GAC than bituminous-based GAC (2599:1 compared to 1968:1) and in spiked deionized water it used 10% less (1560:1 compared to 1404:1).

Interesting results were noted for the minicolumn studies using pulverized lignite-based GAC in which, prior to being tested with spiked distilled water, the GAC in one experiment was presoaked with a flow of deionized water for 72 hours (Run No. 13) and the GAC in a companion experiment received a flow of Pacific Palisades water (BWS well) for 72 hours (Run No. 14). The presumed rationale was that during the presoaking period the deionized water would have a significantly lower amount of natural background organics than the Pacific Palisades water. The Pacific Palisades water was devoid of measurable quantities of TCP and DBCP but was assumed to contain the general concentration and types of natural background organic material typical of central O'ahu water wells, notably the Mililani water wells. It was expected that in the Pacific Palisades presoaked water experiment more GAC would be utilized per unit of TCP removed than in the presoaked deionized water experiment. Surprisingly, the results for the presoaked deionized water and Pacific Palisades water experiments were nearly identical (Tables 1 and 2).

As previously reported, two additional experiments using spiked Pacific Palisades water ended in failure in five and seven days due to minicolumn plugging, which occurred prior to TCP/DBCP breakthrough. Perhaps a 72-hour presoaking period is an insignificant amount of time to alter the capacity of GAC adsorption sites, but the essentially identical results do suggest that perhaps natural background organics actually do not play as significant a role in decreasing GAC adsorption as was assumed at the initiation of this project. As can be noted in Table 2, the two spiked deionized water experiments involving presoaking required 12% less lignite-based GAC than the one without presoaking. The reasons for the increased life of the presoaked GAC and the plugging of the minicolumns in the spiked Pacific Palisades water experiments are unknown at present.

A graphical representation of the higher efficiency of lignite-based GAC over bituminous-based GAC is clearly shown in Figure 7. The higher efficiency of spiked deionized water over Mililani well water is also indicated in Figure 7; however, as previously discussed, a higher percentage of TCP loss by spiked deionized water over Mililani water, as was noted in the isotherm determinations, may be a factor contributing to the indicated higher efficiency. Inasmuch as the basis for the data in Figure 7 is volume of liquid passed through the

minicolumn prior to breakthrough, a lower amount of TCP in the influent would indicate a higher removal efficiency. This was the case for the lower TCP levels in the aerated Mililani well water experimental run. The relationship for the higher efficiency minicolumn runs using the presoaked method is also quite apparent in Figure 7.

The results of the minicolumn experiments using pulverized GAC at high flow rates and pressure cannot be directly compared to the actual full-scale operation results of the GAC facilities, which is in agreement with the scaling-up calculations (laboratory to prototype units) presented in the final Phase I report (Oki et al. 1994). Even though approximately eight years separated the GMP Associates (1984) minicolumn tests from those reported here, and even though GMP used commercial powdered activated carbon where the project tests used pulverized GAC, the estimated carbon usage results are relatively in the same range. However, GMP Associates (1984) assumed that the minicolumn method can be used to make “relatively accurate estimates of carbon usage for a full scale plant.” Consequently, GMP’s prototype at the Mililani GAC treatment facility was based on its minicolumn carbon usage results of 0.00276 kg/m³ (0.023 lb/1,000 gal) (GMP Associates, Inc. 1984). Unfortunately, this assumption was proved incorrect by the actual operation results of the full-scale BWS GAC treatment facilities at Mililani, Kunia, and Waipahu, as well as by the scale-up equations. However, the present study has the advantage of hindsight rather than foresight in this situation. Nevertheless, the minicolumn experiments are useful for obtaining comparative values for various operating parameters or for different sources of activated carbon, in a relatively short period of time.

Organic Carbon Relationships

When the total organic carbon concentrations of the lead and lag paired contactors were determined in the Phase I portion of this study (Oki et al. 1994), there was an indication that the GAC treatment did reduce TOC concentrations slightly. During Phase I a concerted effort was made to reduce TOC levels by using deionized double-distilled water, virgin GAC, and a settling period of six days. The results indicated that the concentration of TOC in the deionized water before and after treatment was nearly the same. Thus it was concluded that the GAC treatment was ineffective in reducing TOC (Oki et al. 1994), at least within the measured accuracy of the TOC test.

The analyses for total carbon (TC) and nonpurgeable organic carbon (NPOC) for the various minicolumn tests using bituminous-based GAC with specific dates or periods of time, during the Phase II portion of the study, are tabulated in Appendix Table E.1. The high values of TC and NPOC for spiked deionized water (nearly 75 and 69 mg/l, respectively) were the result of the methanol with which TCP and DBCP were prepared. Apparently, methanol is not adsorbed by activated carbon or purged off at pH 2 and remains in the water samples as

NPOC. The TC values found in Mililani well water appear to be equal to or lower than those at the other sites on the island of O'ahu, and NPOC concentrations are not significantly higher. The data in Appendix Table E.1 do not show a correlation between increased detention times and increased TC or NPOC removals, nor do they show a relationship between increased water heights and TC or NPOC removals for the aerated Mililani water minicolumn experiments. Also, there was only a slight decrease in the NPOC values between the influent and effluent of the aerated minicolumn experiment (Run No. 7, Table 1). Thus, if natural background organic materials are indeed interfering with the adsorption sites of the GAC, this fact is not confirmed by the NPOC results.

DESORPTION OF TCP AND DBCP FROM SPENT GAC

Studies were continued to determine the feasibility of regenerating spent GAC, economically, by desorbing the contaminants, TCP and DBCP, with tap water washings. Initially, minicolumns with spent GAC were flushed by passing tap water through them in the same direction and manner as was done with the minicolumn experiments. The tap water effluents were collected and analyzed for TCP and DBCP concentrations to monitor the progress of the desorptions and the efficiencies of the washdowns. Some anomalies were experienced with these minicolumn tests, and the desorptions appeared to be inconsistent, random, and time consuming. Therefore, a laboratory-scale system was designed to further study and to determine some of the basic characteristics involved with the desorptions of TCP and DBCP from spent GAC with tap water washdowns.

A laboratory GAC desorption system was assembled (Figure 8). A glass chromatographic column (22 mm I.D., 50 cm length) with a teflon stopcock and spent GAC in it was used to simulate the full-scale GAC contactors. The tap water flow was by gravity and was controlled by maintaining a water head in the system, as shown in Figure 8. At first, 100 g of spent GAC was used in the system, but this quantity readily compacted in the column and caused difficulties with the control of tap water flow through the system. A 10-g sample of spent GAC was then used in a subsequent trial; this reduced quantity was more appropriate for the dimensions of the system and facilitated the flow of tap water through the system. As with the minicolumn desorption runs, the effluents were collected and monitored for TCP and DBCP concentrations.

The GAC used was a combined sample collected from a spent Mililani contactor. It contained 167 and 9.46 $\mu\text{g/g}$ dry weight GAC of TCP and DBCP, respectively. The analysis

of the spent GAC was performed by ultrasonic extraction, followed by gas chromatography processing, as described in the Phase I report (Oki et al. 1994).

The results of the desorption study are tabulated in Table 3. Although the desorption procedure potentially appears to be a possible cost-effective process, the desorptions occur randomly and difficulties arise in determining relationships for the predictions of desorption regenerations. Furthermore, the desorptions are lengthy and time-consuming; consequently, the reuse of desorbed GAC for TCP and DBCP removal does not appear to be practical at present.

CONCLUSIONS

The primary purpose of the Phase II project was to study the means of increasing the operational life of the GAC used in the BWS treatment plants in Mililani, Kunia, and Waipahu. These plants were placed in operation for the purpose of removing the target volatile organics: EDB, DBCP, and TCP. Under actual operational conditions the life of the GAC was only approximately 15% of the ultimate designed life, which was based on the results of the laboratory bench-scale dynamic filtration tests using actual water from the Mililani and Waipahu wells. The GAC in the full-scale facilities required replacement approximately every six months, rather than more than every two years as originally predicted. The GAC was considered "spent" when one of the target volatile organics exceeded breakthrough, which was set at 20 ng/l for EDB and DBCP and 100 ng/l for TCP. The present study only involved Mililani well water contaminated by DBCP and TCP, but not by EDB.

Inasmuch as pilot-scale GAC treatment systems require an exceptionally long time (probably at least six months) to reach GAC breakthrough, two basic methods were explored during Phase II in order to shorten the time required to a matter of days. These methods, initiated during Phase I, were not made operational until Phase II. The principal methods are (1) the development of isotherms, and (2) the use of the dynamic filtration test or so-called minicolumn test. The use of aeration to decrease the concentrations of the target volatile organics was also explored during Phase II, along with a study of the feasibility of GAC regeneration by desorption.

In the development of isotherms, only TCP was considered because it was frequently found to have concentrations over 2000 ng/l, whereas DBCP was, with few exceptions, always below 100 ng/l. In addition, Henry's Gas Constant is higher for TCP than for DBCP; thus a higher amount of volatilization would be expected for TCP. A basic problem encountered with the isotherms was that it was not practical to utilize TCP concentrations as

low as that encountered in Mililani well water. Consequently, the concentrations used for the isotherm developments required spiking to approximately two orders of magnitude higher than the concentrations in the Mililani well water.

Two types of isotherms were studied: (1) deionized water spiked with TCP, which was intended to represent water without any appreciable natural background organics, and (2) Mililani well water spiked with TCP. Overall, the methodology used in the isotherm experiments appeared to have been reliable. However, the losses due to assumed volatilization were quite high: 51% for the spiked deionized water isotherm and 22% for the spiked Mililani well water isotherm. These high losses, particularly for spiked deionized water, and the apparent need for the TCP concentrations to be two orders of magnitude higher than conditions encountered for Mililani well water appear to significantly limit the use of isotherms in the present study.

The dynamic filtration test, simply referred to in this report as the minicolumn test, for the present study consisted of subjecting approximately 50 mg of powdered or pulverized activated carbon in a container to a relatively high pressure and volume of flow per unit mass. Fourteen minicolumn experiments were conducted, eight using pulverized bituminous-based GAC (the type used in full-scale BWS GAC treatment plants), and the remaining six using pulverized lignite-based GAC. The minicolumn experiments using bituminous-based GAC involved (1) naturally contaminated Mililani well water, (2) deionized water spiked with DBCP and TCP, (3) aerated Mililani well water, and (4) autoclaved Mililani well water. The lignite-based GAC experiments only involved the use of naturally contaminated Mililani well water and deionized water spiked with DBCP and TCP. In all 14 minicolumn experiments TCP reached breakthrough (>100 ng/l) before DBCP (>20 ng/l). The general results for the GAC bituminous-based minicolumn experiments are as follows:

1. The GAC requirement per unit of TCP removed was 40% less for spiked deionized water than for naturally contaminated Mililani well water.
2. Aeration does not appear to appreciably remove natural background organic matter. The two Mililani well water minicolumn experiment samples that were fed aerated water with about 40% less TCP than was pumped to the unaerated Mililani well water samples experienced approximately 40% less TCP adsorption.
3. Autoclaving at 110°C for 50 minutes reduced the concentration of TCP to <300 mg/l, however, the TCP breakthrough for autoclaved Mililani well water occurred at approximately the same time as that for the naturally contaminated Mililani water. In terms of GAC required per equal quantity of TCP removed, the autoclaved water required more than seven times that required for the naturally contaminated water.

The general results for the GAC lignite-based minicolumn experiments are as follows:

1. In the lignite-based GAC minicolumn experiments 24% less GAC was used per unit of TCP removed than in the bituminous-based GAC experiments for Mililani water; and for spiked deionized water, a 10% saving was noted in the lignite-based GAC experiments.
2. A companion set of minicolumn experiments that involved presoaking the GAC for 72 hours prior to receiving spiked deionized water revealed that the experiment presoaked with a flow of deionized water had nearly identical results as the one presoaked with a flow of Pacific Palisades water (devoid of measurable quantities of TCP, DBCP, or EDB), thus suggesting that natural background organics may not be adversely competing with the target volatile organics for GAC adsorption sites. Surprisingly, the minicolumn experiments involving 72 hours of presoaking used 12% less GAC per unit of TCP removed than the nonsoaked spiked deionized minicolumn experiments.
3. Experiments of effluent TCP concentrations versus volume of liquid passed through up to and beyond breakthrough clearly showed that lignite-based GAC significantly outperforms bituminous-based GAC, which is being used at the BWS full-scale GAC treatment plants.

In both Phase I and Phase II the GAC treatments used were essentially ineffective in removing TC, TOC, and NPOC.

The results of a study to regenerate spent GAC by desorption with tap water revealed that it could potentially be cost effective, but the desorption process frequently occurs randomly and difficulties arise in determining relationships for predicting desorption regeneration. In addition, because it is a relatively lengthy process, the procedure does not appear practical at present.

Considering the results of the isotherm determinations, in which spiked deionized water had a TCP loss of 51% compared to 22% for spiked Mililani water, the question arises as to whether these types of losses also occurred to some degree with the spiked minicolumn experiments. However, because the influent and effluent of the minicolumn experiments were monitored daily for concentrations of TCP and DBCP, it appears that this potential source of error (presumably from mainly volatilization) is reduced.

The results of the Phase II project seem to indicate that natural background organics are not adversely competing with the target volatile organic compounds; in other words, they do not appear to be significantly occupying GAC adsorption sites, as was considered at the beginning of Phase I.

What is clear is that the premise used in scaling up from the results of the minicolumn experiments to the full-scale facility in terms of effective GAC life was incorrect. This was

indicated by the results of the scale-up equations in the Phase I report (Oki et al. 1994) and the results of the actual operation of the BWS GAC treatment plants at Mililani, Kunia, and Waipahu.

The results of the study seem to indicate that efforts to economically remove the elusive natural background organic matter in an effort to increase GAC life do not appear fruitful at present. What does appear promising is the use of lignite-based GAC in place of bituminous-based GAC. It follows that it would be desirable for future studies to concentrate on testing different types of GAC using the minicolumn method to find the one or a combination of GACs thereof that provides a more cost-effective GAC treatment.

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TEXT FIGURES

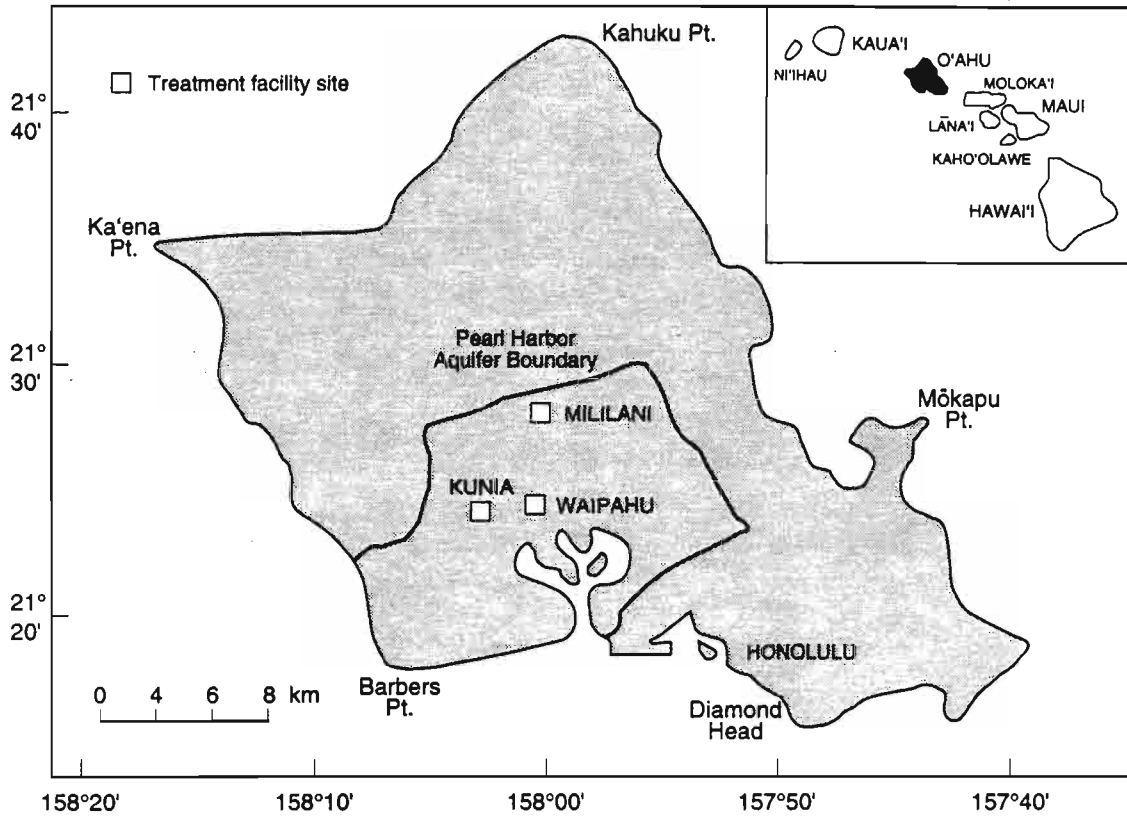


FIGURE 1. GAC treatment facility sites, central O'ahu, Hawai'i

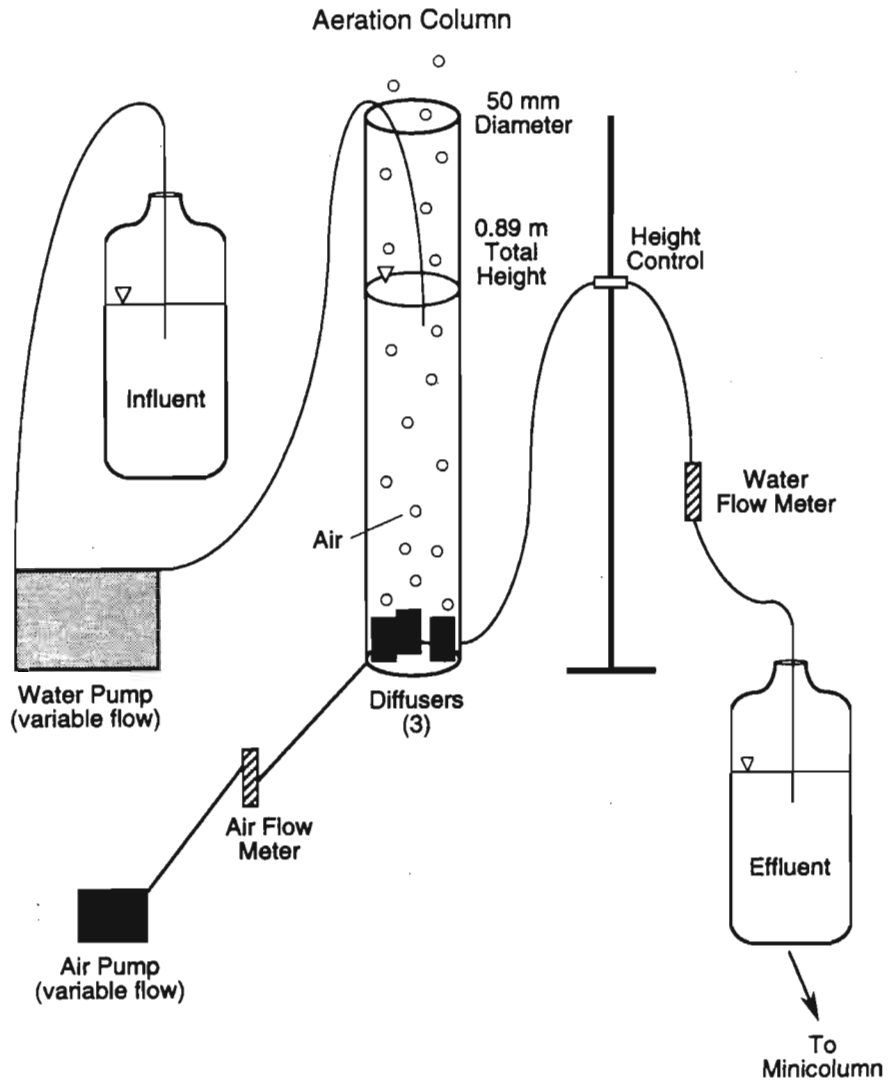
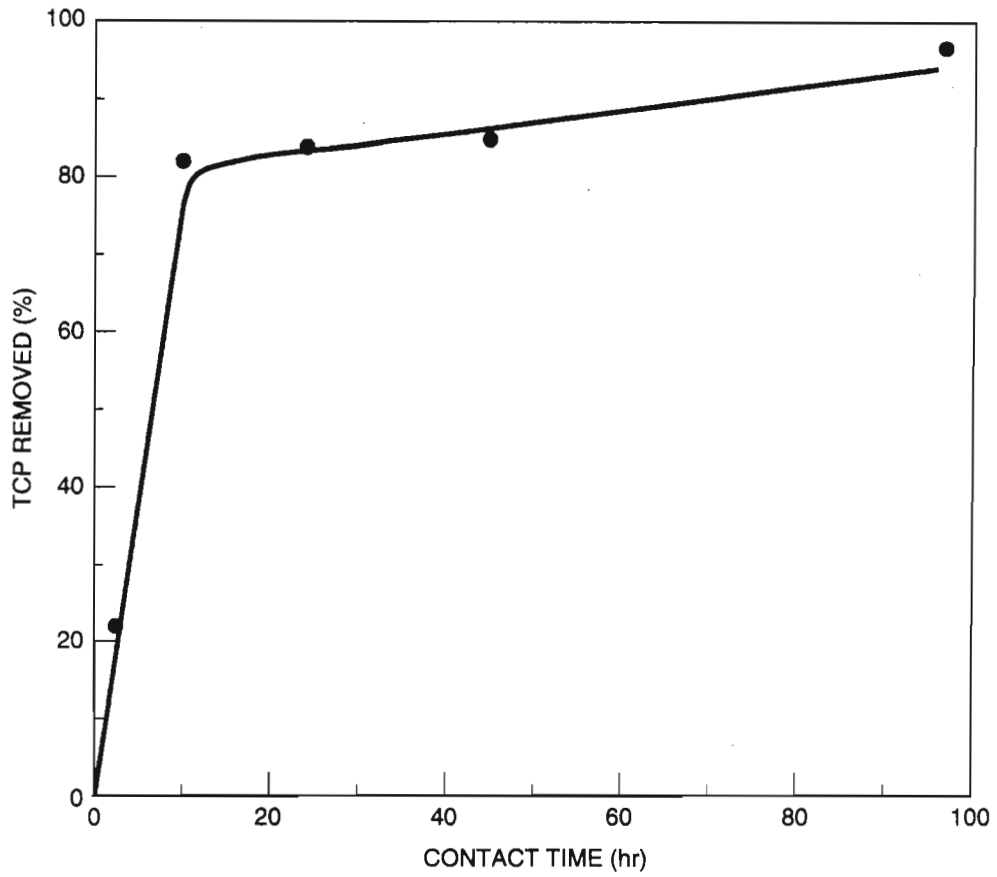
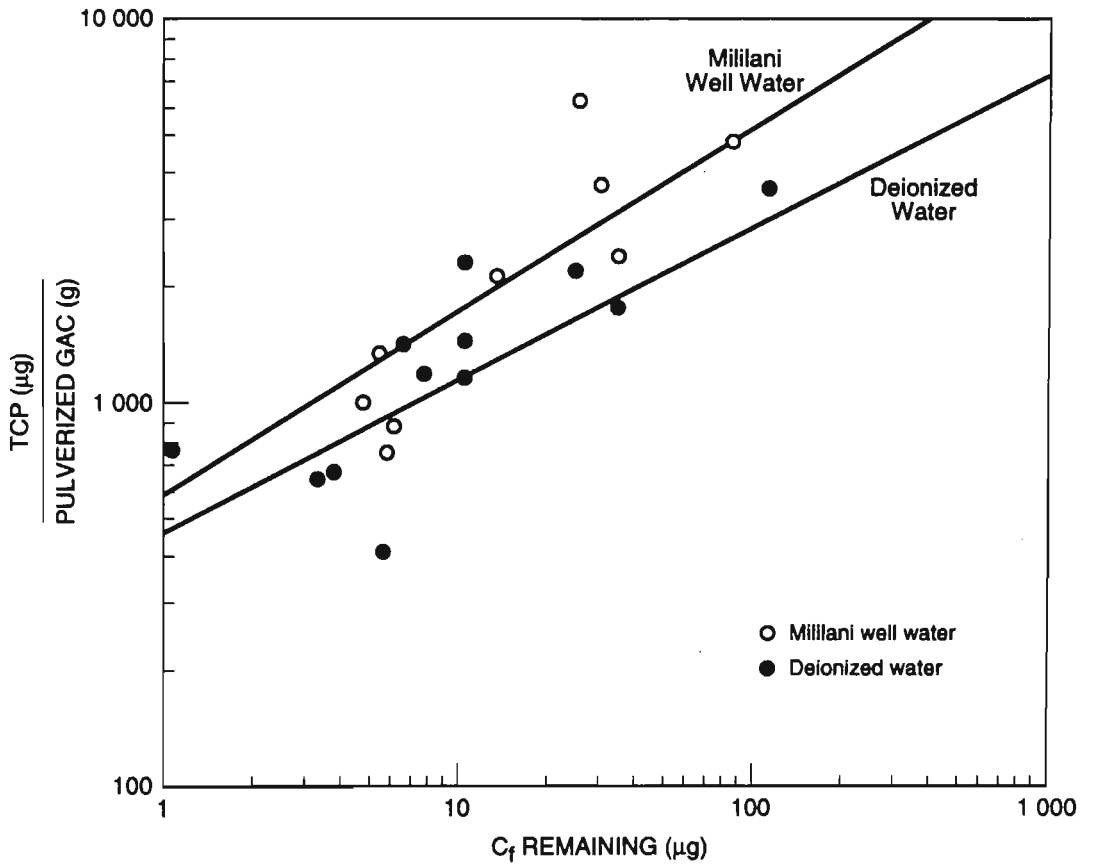


FIGURE 2. Schematic of system used for continuous-flow aeration experiments



From Chu 1992

FIGURE 3. TCP equilibrium time determination



From Chu 1992

FIGURE 4. TCP isotherms for deionized water and Millilani well water

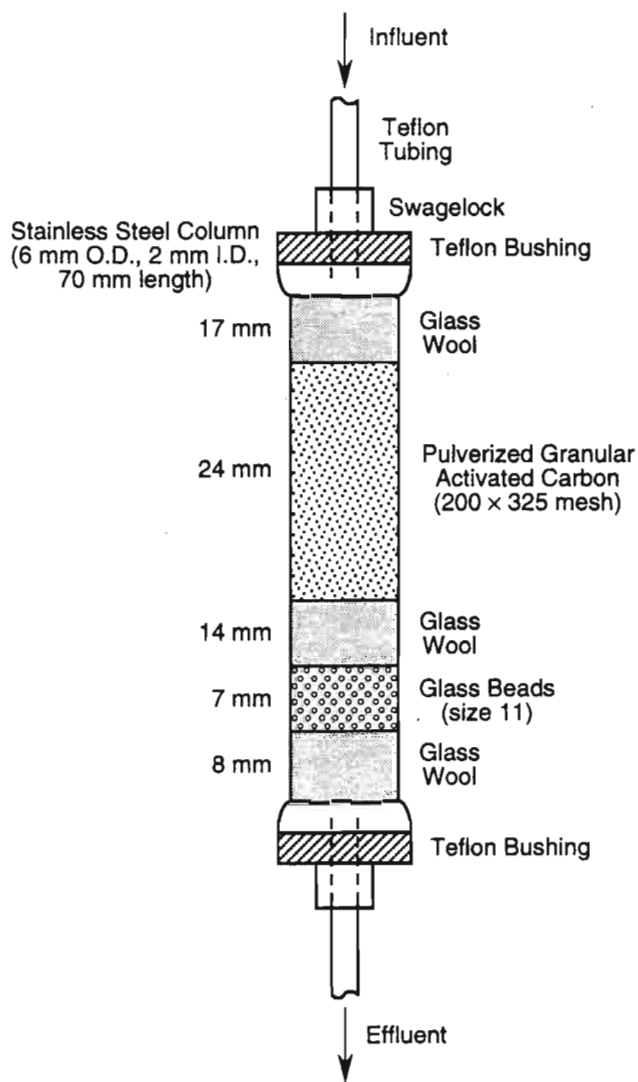


FIGURE 5. Cross section of minicolumn

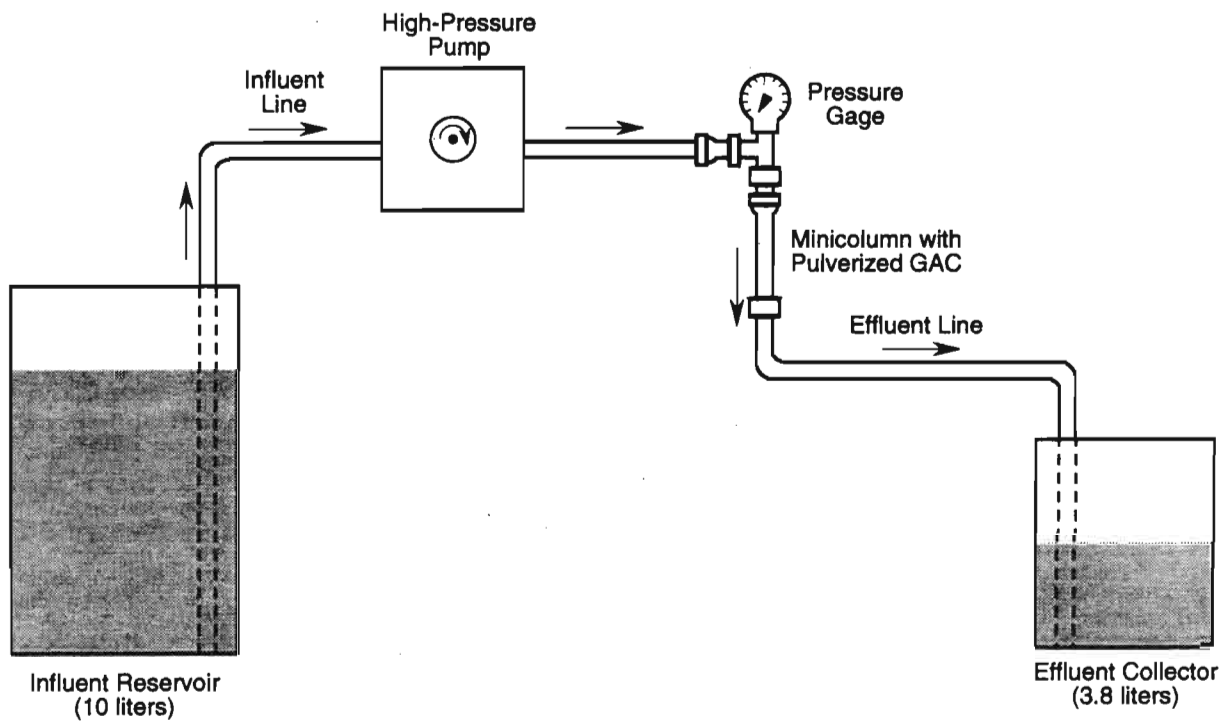


FIGURE 6. Schematic of the minicolumn testing system

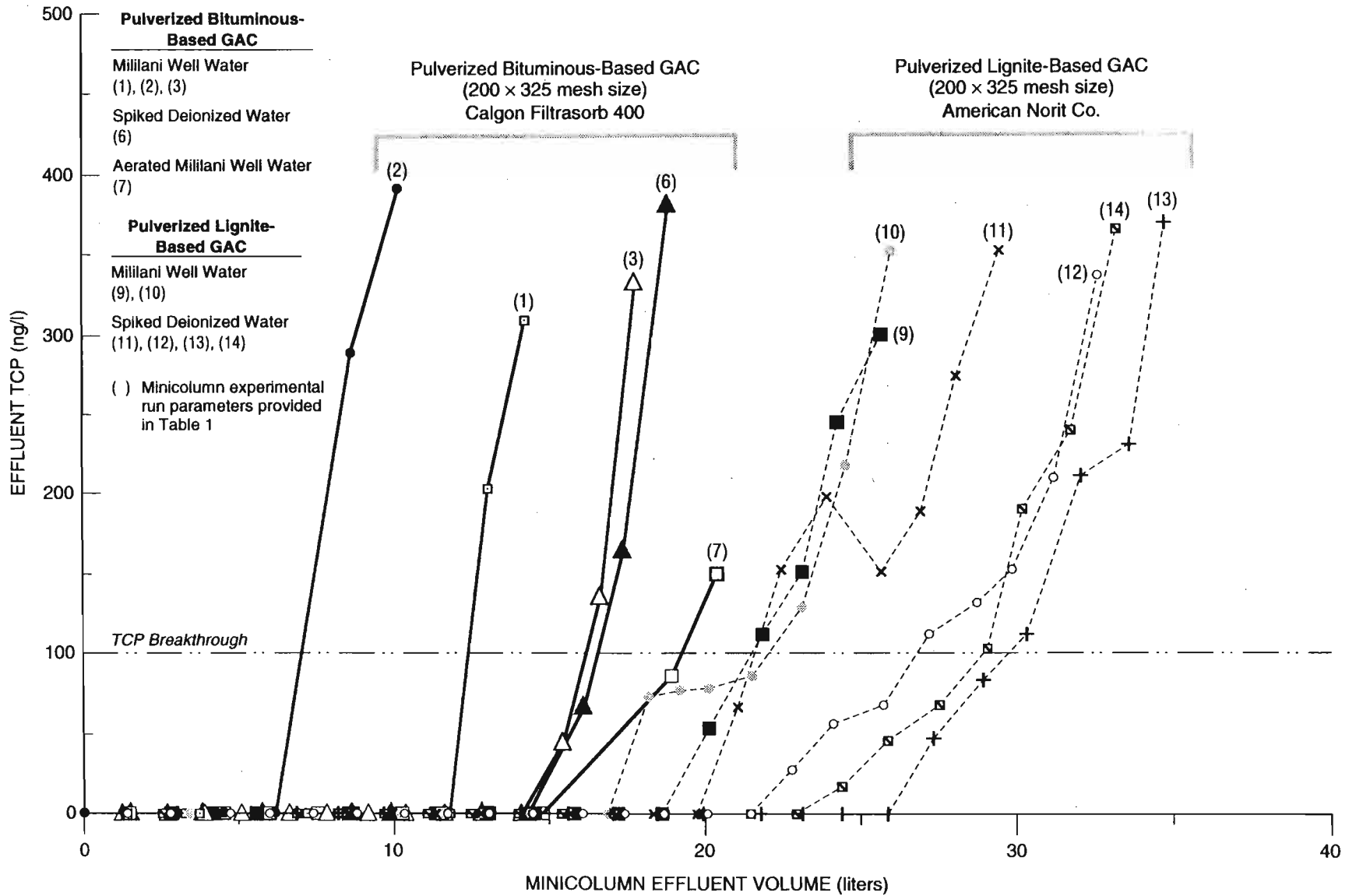


FIGURE 7. Effluent TCP concentrations versus minicolumn effluent volume

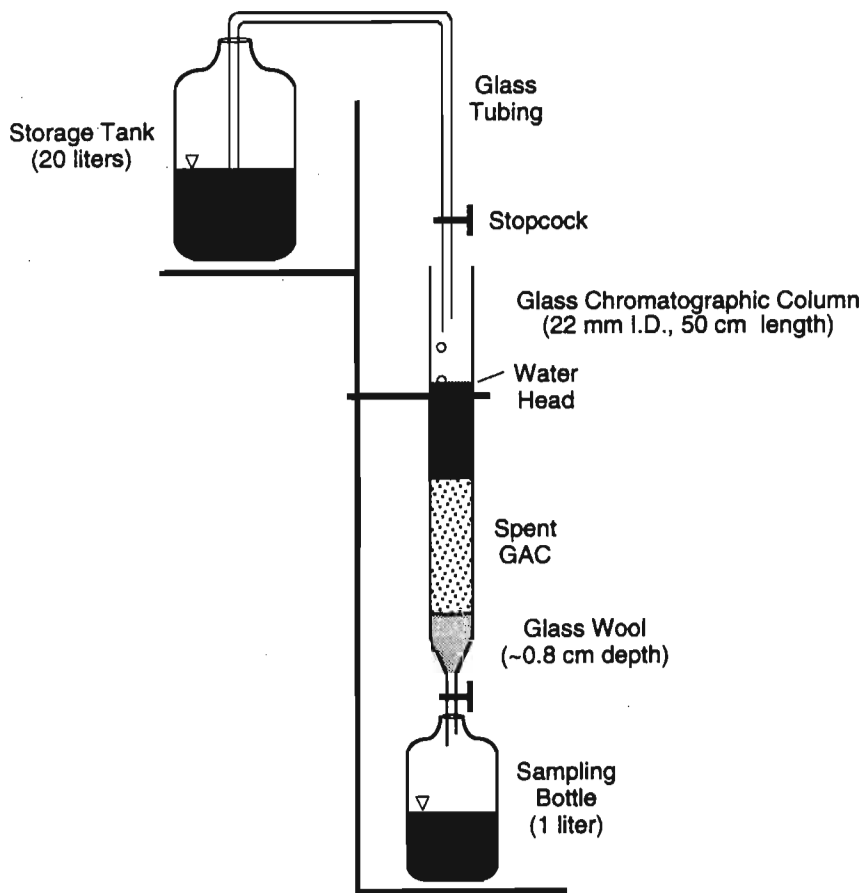


FIGURE 8. Schematic of laboratory GAC desorption system

TEXT TABLES

TABLE 1. Summary of Minicolumn Experiments Involving TCP Breakthrough (≥ 100 ng/l)

Run No.	Influent Water	Time Period	Breakthrough Characteristics				Basic Data (App. Table No.)	Plotted Data (Fig. No.)	
			GAC Type ^a	Time (days)	Volume (liters)	Carbon Usage (kg/m ³) ^b			TCP Adsorbed (ng)
1	Mililani Well Water	September 1991	Bit	11	12.4	0.00402	19 616	C.1	D.1
2	Mililani Well Water	January 1992	Bit	6	7.0	0.00711	7 692	C.2	D.2
3	Mililani Well Water	March 1992	Bit	14	16.2	0.00310	18 934	C.3	D.3
4	Autoclaved Mililani Well Water	April 1992	Bit	13	12.1	0.00416	2 565	C.4	D.4
5	Spiked Deionized Water	April 1992	Bit	14	19.5	0.00258	29 429	C.5	D.5
6	Spiked Deionized Water	May 1992	Bit	12	16.6	0.00304	35 140	C.6	D.6
7	Aerated Mililani Well Water	April 1992	Bit	14	19.6	0.00257	13 103	C.7	D.7
8	Aerated Mililani Well Water	May 1992	Bit	14	19.6	0.00258	11 838	C.8	D.8
9	Mililani Well Water	July 1992	Lig	16	21.5	0.00233	20 363	C.9	D.9
10	Mililani Well Water	August 1992	Lig	18	22.5	0.00223	30 543	C.10	D.10
11	Spiked Deionized Water	July 1992	Lig	17	21.8	0.00230	31 462	C.11	D.11
12	Spiked Deionized Water	August 1992	Lig	20	27.0	0.00186	39 998	C.12	D.12
13	Spiked Deionized Water ^c	September 1992	Lig	21	30.0	0.00167	40 916	C.13	D.13
14	Spiked Deionized Water ^d	September 1992	Lig	20	29.0	0.00173	40 893	C.14	D.14
—	GMP—Mililani Well Water	March 1984	Bit ^e	—	18.1	0.00276	42 250	—	—

^aBit = Pulverized bituminous-based GAC (200 × 325 mesh size) — Calgon Filtrasorb 400.

Lig = Pulverized lignite-based GAC (200 × 325 mesh size) — American Norit Co.

^bConversion: kg/m³ × 8.346 = lb/1,000 gal.

^cPulverized lignite-based GAC received a flow of deionized water for 72 hours prior to start of test.

^dPulverized lignite-based GAC received a flow of Pacific Palisades water for 72 hours prior to start of test.

^ePowdered activated carbon, Darco H 90.

TABLE 2. Summary of Average GAC Characteristics in Minicolumn Experiments Involving TCP Breakthrough (100 ng/l)

Influent Water	Run No. ^a	Average GAC Usage (kg/m ³) (lb/1,000 gal)		Carbon Adsorptive Capacity (mg GAC/mg TCP)
Pulverized Bituminous-Based GAC (200 × 325 mesh) — Calgon Filtrasorb 400				
Mililani Well Water ^b	1, 3	0.00350	0.0292	2 599
Spiked Deionized Water	5, 6	0.00279	0.0233	1 560
Autoclaved Mililani Well Water	4	0.00416	0.0347	19 610
Aerated Mililani Well Water	7, 8	0.00257	0.0214	4 038
Pulverized Lignite-Based GAC (200 × 325 mesh) — American Norit Co.				
Mililani Well Water	9, 10	0.00228	0.0190	1 968
Spiked Deionized Water	11, 12	0.00206	0.0172	1 404
Spiked Deionized Water Presoaked for 72 hours				
with Deionized Water	13	0.00167	0.0139	1 227
with Pacific Palisades Water	14	0.00173	0.0144	1 230

^aSee Table 1 for minicolumn experimental run parameters.

^bExcluding Run No. 2 in which short-circuiting was suspected.

TABLE 3. Results of Spent GAC Desorption Tests Using Mililani Well Composited Water Samples

Eluant No.	10 g Spent GAC, Bed Depth 3.8 cm, in Glass Chromatographic Column					100 g Spent GAC, Bed Depth 30.0 cm, in Glass Chromatographic Column				
	Elution Rate (ml/min)	(22 mm I.D., 50 cm length)		(22 mm I.D., 50 cm length)		Elution Rate (ml/min)	(22 mm I.D., 50 cm length)		(22 mm I.D., 50 cm length)	
		TCP Desorption		DBCP Desorption			TCP Desorption		DBCP Desorption	
		Concentration (ng/l)	Accumulation (ng)	Concentration (ng/l)	Accumulation (ng)		Concentration (ng/l)	Accumulation (ng)	Concentration (ng/l)	Accumulation (ng)
1	13.5	3 816.8	3 816.8	58.0	58.0	4.5	3 737.2	3 737.2	42.1	42.1
2	12.3	3 476.5	7 293.3	48.0	106.0	16.7	3 281.5	7 018.7	43.0	85.1
3	11.5	1 864.0	9 157.3	24.5	130.5	12.8	1 672.5	8 691.2	17.2	102.3
4	12.2	2 042.1	11 199.4	29.8	160.3	11.1	2 339.4	11 030.6	23.4	125.7
5	13.7	1 943.6	13 143.0	28.9	189.2	4.5	2 009.0	13 039.6	17.8	143.5
6	13.5	2 168.2	15 311.2	23.6	212.8	2.3	2 083.8	15 123.4	20.4	163.9
7	14.3	2 118.9	17 430.1	22.2	235.0	3.2	1 586.0	16 709.4	12.9	176.8
8	13.3	1 478.8	18 908.9	22.0	257.0	3.0	2 108.1	18 817.5	18.2	195.0
9	12.5	1 516.3	20 425.2	18.0	275.0	2.5	1 635.4	20 452.9	11.9	206.9
10	13.5	1 305.4	21 730.6	16.2	291.2					
11	14.1	1 491.2	23 221.8	21.3	312.5					
12	13.2	1 229.2	24 451.0	12.9	325.4					
13	13.5	1 412.7	25 863.7	19.2	344.6					
14	13.5	1 420.3	27 284.0	16.7	361.3					
15	13.5	1 398.0	28 682.0	13.1	374.4					
16	14.3	998.2	29 680.2	11.4	385.8					
17	14.3	1 035.9	30 716.1	11.4	397.2					
18	13.2	1 384.7	32 100.8	14.7	411.9					
19	13.9	1 510.8	33 611.6	12.7	424.6					
20	13.7	1 194.6	34 806.2	14.6	439.2					
21	13.9	738.8	35 545.0	8.2	447.4					
22	13.3	1 054.8	36 599.8	13.7	461.1					
23	13.5	1 151.0	37 750.8	12.0	473.1					
24	14.3	891.1	38 641.9	9.8	482.9					
25	13.9	946.1	39 588.0	12.8	495.7					
Average	13.5	1 583.5		19.8		6.7	2 272.5		23.0	
Total (ng)		39 588.0		495.7			20 452.9		206.9	

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Appendix A. Reduction of TCP and DBCP in Aeration Experiments

TABLE A.1. Reduction of TCP and DBCP in Mechanical Aeration Experiments of Primary Pesticide Constituents

Sample Detention Time (hr)	% Reduction		Relative Speed of Mixing ^a (rpm)
	TCP	DBCP	
0.5 C ^b	32.1	37	5
0.5 C	25	19.7	5
0.5 C	17.8	9.1	5
0.5	38.5	37.4	5
0.5	—	—	5
0.5	54.7	48.1	5
1	52.8	56.2	5
1	32.8	20.6	5
1	54.9	42.6	5
2 C	46.6	45.3	5
2 C	8.5	0	5
2 C	47.6	57.8	5
2 C	47.8	56.1	2
2 C	56.1	24	8
2	56.5	55.8	5
2	65.2	58.7	5
2	54.7	50.8	5
2	43.2	53	2
2	73.6	73.7	2
2	36.3	49.7	8
2	61.9	52.7	8
5 C	41.1	40.6	5
5 C	8.5	0	5
5 C	53.6	55.9	5
5	81.9	83.2	5
5	80.3	71.5	5
5	83.2	75.7	5

^aMinimum speed setting 2 = 58 rpm.

^bControl; no stirring.

TABLE A.2. Reduction of TCP and DBCP in Batch Diffused Aeration Experiments

Air Flow (ml/min)	Sample Detention Time (hr)	Water Height (in.)	% Reduction		Water Temperature (°C)
			TCP	DBCP	
400	0.167	19	0	0	20
400	0.5	19	52.09	42.06	20
400	1	19	24.25	0	20
400	2	19	5.59	13.36	19.75
400	0.33	13.5	17.888	0	20
400	1	13.5	43.14	29.61	20.25
400	2	13.5	40.336	6.09	20
2124	0.33	13.5	62.2	50.27	19.75
2124	1	13.5	84.54	65.57	19.875
2124	2	13.5	93.55	66.48	19
2124	5	13.5	99.93	100	20
400	0.33	13.5	0	0	21
400	1	13.5	17.3	0	21.5
400	2	13.5	61.43	39.82	20.25
400	5	13.5	76.29	25.08	21.5
2124	0.33	19	28.27	21.27	20.5
2124	1	19	78.53	58.52	20.5
2124	2	19	80.41	11.09	20.5
2124	3.5	19	99.99	99.99	20.5
2124	0.33	8	52.52	9.45	21.25
2124	1	8	87.48	54.73	21.25
2124	2	8	97.79	77.79	21
2124	1.5	8	93.95	69.91	21.25
400	0.33	8	51.62	51	20
400	1	8	50.07	30.03	20
400	2	8	77.68	63.59	20
400	2.5	8	75.28	41.19	20

TABLE A.3. Reduction of TCP and DBCP in Continuous-Flow Aeration Experiments

Air:Water (ml/min:ml/min)	Detention Time (hr)	Water Height (in.)	% Reduction		Water Temperature (°C)
			TCP	DBCP	
106.2:1	34.75	13.5	54.8	49.07	20
20:01	34.75	13.5	55.2	62.7	19
20:01	34.75	13.5	20.12	20.88	20
106.2:1	34.75	13.5	37.47	8.06	20.75
106.2:1	34.75	13.5	50.5	38.1	20
20:01	34.75	13.5	36.25	36.31	19.75
0	34.75	13.5	6.61	13.99	19
20:01	10.3	8	37.2	50.4	19.5
106.2:1	10.3	8	23.3	0	19.5
106.2:1	65.21	19	53.63	23.74	19.75
20:01	65.21	19	8.71	0	19.75
106:1	34.75	13.5	72.05	65.15	21.5
106:1	34.75	13.5	65.88	63.67	21.5
177:1	34.32	8	79.41	73.6	22
33.3:1	34.32	8	55.93	57.12	22
75.9:1	34.93	19	42.58	39.5	21
14:01	34.32	19	8.8	20.13	21.5
75.9:1	34.93	19	43.77	32.89	21.5
75.9:1	34.93	19	68.6	20.05	20.5
75.9:1	34.93	19	35.8	13.49	21
43.3:1	34.67	33	26.5	15.4	20.25
8:01	34.67	33	54.71	54.83	20.25
75.9:1	34.93	13.5	56.21	42.51	20
75.9:1	34.93	19	39.93	26.3	19.5
106.2:1	84.94	33	60.29	47.65	19.5
20:01	84.94	33	48.08	46.14	19.5
75.9:1	34.93	19	52.86	37.57	21

Appendix B. Laboratory Experimental Methods

CARBON PREPARATION

The bituminous-based GAC (Calgon Filtrasorb 400, lot 2119-N) was obtained on 24 February 1992 from bags containing carbon stored for future replacement at the Mililani Treatment Plant site. The lignite-based GAC (American Norit Co.) was provided by the Board of Water Supply. Both types of GAC were stored in an opaque glass container and placed in a desiccator in the Water Resources Research Center's Toxic Chemistry Laboratory.

The GAC was placed in a blender with the grinding attachment set on low speed for approximately 5 minutes. The carbon was then shaken through a size 200 ASTM sieve and retained on a size 325 sieve as pulverized GAC. Deionized water was poured through the sieves to eliminate fine-sized material. The oversized carbon was returned to the grinder for further crushing until the required quantity was obtained.

The 200 × 325 mesh size carbon was placed in a 500-ml beaker and filled with deionized water, followed by stirring. The particles were allowed to settle for 15 minutes. Then the supernatant was drained off in a washing procedure that was repeated until no particles could be removed from the solution.

The beaker was covered with aluminum foil perforated with small holes at the top for evaporation and then placed in an oven at 105°C overnight. The washing procedure was repeated. The beaker was again placed in an oven at 105°C for several hours until the contents were dry. After that, the beaker was placed in an oven at 180°C for 2 hours and slowly cooled in a desiccator.

The carbon sample was transferred to an opaque 50-ml glass bottle with a teflon-lined cap and then stored in a desiccator kept in darkness.

PACKING THE PULVERIZED GRANULAR ACTIVATED CARBON COLUMN

The columns used in the experiment were stainless steel tubes (6 mm O.D. × 70 mm length) which were previously rinsed with acetone, dried in an oven at 105°C, and cooled to room temperature. The mass of these empty steel columns was measured. An approximate amount of the packing materials—glass wool, glass beads (size 11), and pulverized GAC (200 × 325 mesh size)—were also measured in separate containers before packing. A sample amount of the packing materials and the order in which they were placed in the column are shown in Figure 5. The glass wool at the bottom was tightly packed by pushing the end of the steel rod against it at the bottom of the column. The glass beads, being breakable, were packed

by evenly tapping the column against the table top. A layer of glass wool was gently packed to prevent the glass beads from breaking into smaller pieces. Then, the pulverized GAC was added in fractions tapping the column evenly until the desired bed height was attained. The small piece of glass wool at the top of the carbon was just loosely packed. The actual mass of each of the materials packed in the column was measured and their corresponding height in the column determined.

PREPARATION OF SPIKED DEIONIZED WATER INFLUENT

The influent was 18 Mohm-cm deionized water spiked with a known concentration and volume of TCP and DBCP. The TCP and DBCP spiking solutions were first prepared by diluting 1 ml of each of the stock solutions (3.56 mg/ml for TCP, 92 µg/ml for DBCP) and adding enough methanol to the individual volumetric flask to reach a volume of 100 ml. For an 8-liter influent stock, an aliquot of the spiking solution (0.8 ml for TCP, 1.0 ml for DBCP) was transferred into a 1-liter volumetric flask and diluted to the 8-liter volume with deionized water. The solution was further diluted to 8 liters in a 10-liter nalgene jar and then mixed well by shaking for about 3 minutes. The TCP and DBCP concentrations were measured at the time the influent was prepared and analyzed again before the influent was used. The 8-liter influent, which lasted for four nights, had an initial concentration of 1500 ng/l for TCP and 45 ng/l for DBCP by gas chromatography analysis. The influent concentrations were kept at a range of 1200 to 2500 ng/l for TCP and 30 to 90 ng/l for DBCP, similar to the concentration levels of these target compounds in the Mililani influent.

ANALYSIS OF PULVERIZED GAC COLUMN INFLUENT AND EFFLUENT

Carbon Analysis

The column influent and effluent were analyzed for total organic carbon using a Shimadzu Model TOC-5000 Total Organic Carbon Analyzer.

One hundred milliliters of the influent and effluent were separately collected in 125-ml Erlenmeyer flasks which were thoroughly rinsed first with the water to be analyzed. For good results, the effluent to be analyzed must be freshly collected from the column to avoid contamination from exposure to the air during the collection. The sample was analyzed for total carbon first, followed by analysis for TOC, or, specifically, the nonpurgeable organic carbon analysis of the sample was undertaken. In the NPOC analysis the carbon dioxide from the carbonate and the bicarbonate ions were removed by first acidifying the solution with

2.0 M HCL to pH 2 and then purging it with ultra-pure air for at least 15 minutes. The sample was analyzed for NPOC at least once before and once after TCP breakthrough in the column.

Pesticide Analysis

The concentrations of the target compounds, TCP and DBCP, in the influent and effluent were analyzed on the day the influent was prepared and were periodically checked thereafter for changes in concentration. At each water change, the new influent water concentration was also determined. The effluent was likewise monitored regularly to detect for breakthrough of TCP, and possibly DBCP, to determine whether the column had already reached the saturation or desorption point.

Six hundred milliliters of the influent or effluent were placed in a 1-liter round-bottom boiling flask with 24/40 ground joint. Ten milliliters of hexane and a few grains of boiling chips were added to the flask. The boiling flask was attached to a Barret distilling receiver, which was connected to an Allihn condenser. The solution was heated with a heating mantle to distill over the hexane and associated desorbed organic compounds. The recovered hexane was dried over anhydrous sodium sulfate. Five microliters of the extract were injected into the gas chromatograph equipped with an electron capture detector for pesticide analysis.

GAS CHROMATOGRAPHY

The column effluent and influent were analyzed for pesticides using a Hewlett-Packard Model 5700A gas chromatograph equipped with a nickel 63-electron capture detector. One J&W Scientific DB-624 megabore capillary column ($\phi = 0.53$ mm I.D. \times 75 m) was installed in the gas chromatograph. Injector and detector temperatures were set at 250°C and 300°C, respectively. Oven temperature was set at 135°C for TCP and DBCP analysis. The carrier gas used was 95% argon and 5% methane maintained at a flow rate of 35 ml/min at 4.1 bar (60 psi). Chromatograms were plotted on a Hewlett-Packard Model 3390A integrator.

Appendix C. Data for 14 Minicolumn Experiments

TABLE C.1. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 1

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
09/06/91	0	1 116	—	52	—	Influent: Mililani well water Date minicolumn packed: 5 September 1991 Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.0 mg, 200 × 325 mesh size carbon, 2.5 cm bed length Total volume of water to breakthrough = 12 400 ml TCP to breakthrough = 19 616 ng/l DBCP to breakthrough = 592 ng/l Total C usage = 0.00402 kg/m ³ (0.0335 lb/1,000 gal)
09/07/91	1 530	<i>1 189</i>	<i>0</i>	<i>44</i>	<i>0</i>	
09/09/91	1 710	<i>1 271</i>	<i>0</i>	<i>36</i>	<i>0</i>	
09/09/91	0	<i>1 866</i>	—	<i>56</i>	—	
09/09/91	490	<i>1 866</i>	<i>0</i>	<i>56</i>	<i>0</i>	
09/10/91	2 030	<i>1 866</i>	<i>0</i>	<i>56</i>	<i>0</i>	
09/10/91	0	<i>1 552</i>	—	<i>43</i>	—	
09/11/91	1 425	<i>1 771</i>	<i>0</i>	<i>51</i>	<i>0</i>	
09/12/91	1 720	<i>2 035</i>	<i>0</i>	<i>61</i>	<i>0</i>	
09/13/91	1 070	<i>2 199</i>	<i>0</i>	<i>67</i>	<i>0</i>	
09/13/91	0	<i>1 371</i>	—	<i>33</i>	—	
09/13/91	270	<i>1 352</i>	<i>0</i>	<i>33</i>	<i>0</i>	
09/17/91	1 570	<i>1 244</i>	<i>0</i>	<i>31</i>	<i>0</i>	
09/18/91	1 240	<i>1 159</i>	<i>203</i>	<i>29</i>	<i>0</i>	
09/18/91	0	<i>2 583</i>	—	<i>99</i>	—	
09/19/91	1 190	<i>2 447</i>	<i>308</i>	<i>92</i>	<i>0</i>	
09/20/91	1 920	<i>2 228</i>	<i>478</i>	<i>81</i>	<i>0</i>	
09/21/91	1 430	<i>2 065</i>	<i>604</i>	<i>73</i>	<i>0</i>	
09/21/91	810	<i>1 973</i>	<i>588</i>	<i>68</i>	<i>0</i>	
09/22/91	1 430	<i>1 654</i>	<i>697</i>	<i>54</i>	<i>0</i>	
09/23/91	1 000	<i>1 431</i>	<i>774</i>	<i>44</i>	<i>0</i>	
09/23/91	0	<i>1 672</i>	—	<i>50</i>	—	
09/24/91	2 290	<i>1 672</i>	<i>2 886</i>	<i>50</i>	<i>70</i>	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.2. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 2

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
01/27/92	0	1 529	0	53	0	Influent: Mililani well water
01/28/92	1 340	<i>1 342</i>	0	45	0	Date minicolumn packed: 23 January 1992
01/29/92	1 475	1 136	0	36	0	Pulverized bituminous-based GAC: Calgon Filtrasorb 400
01/30/92	1 726	982	0	30	0	Total C = 50.1 mg, 200 × 325 mesh size carbon,
01/31/92	1 650	834	0	25	0	1.9 cm bed length
02/01/92	—	—	—	—	—	
02/02/92	2 459	<i>613.5</i>	289	17	0	Total volume of water to breakthrough = 7 042 ml
02/02/92	0	1 096	—	33	—	
02/03/92	1 570	1 539	390	58	0	TCP to breakthrough = 7 692 ng/l
02/04/92	1 332	981	419	33	0	DBCP to breakthrough = 246 ng/l
02/05/92	1 645	963	646	33	0	
02/06/92	1 793	199	959	7	0	Total C usage = 0.00700 kg/m ³ (0.0593 lb/1,000 gal)
02/06/92	0	1 410	—	45	—	
02/07/92	1 680	1 649	729	73	0	
02/08/92	—	—	—	—	—	
02/09/92	3 050	<i>1 366</i>	<i>1 132</i>	55	0	
02/10/92	1 725	1 274	1 370	52	0	
02/11/92	1 675	<i>1 103</i>	938	44	2.7	
02/12/92	1 102	991	1 110	39	3.3	
02/13/92	1 200	869	1 155	33	3.6	
02/13/92	0	1 508	—	66	—	
02/14/92	1 200	738	712	34	1.9	
02/15/92	—	—	—	—	—	
02/16/92	3 185	<i>1 200</i>	880	35	3.7	
02/17/92	1 133	1 839	967	37	4.7	
02/18/92	1 230	<i>1 000</i>	1 406	35	8.1	
02/19/92	1 593	<i>1 000</i>	1 582	30	14	
02/20/92	1 044	—	652	—	4.3	Begin tap water influent
02/21/92	1 095	0	954	0	10.2	
02/22/92	1 445	—	880	—	9.1	
02/23/92	910	—	654	—	6.3	
02/24/92	935	—	435	—	5.4	
02/25/92	1 130	—	648	—	7.3	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.3. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 3

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
03/09/92	0	1 255.6	—	42.8	—	Influent: Mililani well water
03/10/92	1 245	966.2	0	29.1	0	Date minicolumn packed: 8 March 1992
03/11/92	1 470	<i>956.04</i>	0	<i>28.54</i>	0	Pulverized bituminous-based GAC: Calgon Filtrasorb 400
03/12/92	1 200	<i>947.74</i>	0	<i>28.08</i>	0	Total C = 50.2 mg, 200 × 325 1.9 mesh size carbon,
03/13/92	1 250	939.1	0	27.6	0	3.3 cm bed length
03/14/92	1 500	<i>939.1</i>	0	27.6	—	
03/14/92	0	1 452.6	—	36.4	—	Total volume of water to breakthrough = 16 202 ml
03/15/92	1 200	<i>1 410.1</i>	0	35.7	0	
03/16/92	1 320	<i>1 363.4</i>	0	<i>34.94</i>	0	TCP to breakthrough = 18 934 ng/l
03/17/92	1 220	<i>1 320.2</i>	0	<i>34.23</i>	0	DBCP to breakthrough = 514 ng/l
03/18/92	1 255	1 275.7	0	33.5	0	
03/19/92	1 180	<i>1 275.7</i>	0	33.5	0	Total C usage = 0.00310 kg/m ³ (0.0259 lb/1,000 gal)
03/20/92	1 320	<i>1 275.7</i>	0	33.5	0	
03/20/92	0	1 161.4	—	27.8	—	
03/21/92	1 310	<i>1 119.4</i>	44.3	27.8	0	
03/22/92	1 200	<i>1 080.9</i>	135.6	27.8	0	
03/23/92	1 155	1 043.8	332	29.9	0	
03/24/92	1 240	1 071.8	481.2	28.2	0	
03/25/92	1 285	1 250.4	781.1	33.1	0	
03/26/92	1 380	<i>1 250.4</i>	1 107.1	<i>33.1</i>	0	
03/26/92	0	1 284.2	—	38.3	—	
03/27/92	1 180	1 164.3	1 050.6	34	0	
03/28/92	1 200	<i>1 250.2</i>	1 531	33.82	0	
03/29/92	1 100	<i>1 234.5</i>	1 137	<i>31.74</i>	0	
03/30/92	1 100	<i>1 202</i>	1 205.4	27.45	0	
03/31/92	940	<i>1 205.4</i>	1 318.4	27.9	0	
04/01/92	1 270	825.7	1 177.9	23.5	0	
04/02/92	1 000	825.7	1 442.1	23.5	0	
04/02/92	0	1 173.8	—	32.8	—	
04/03/92	1 073	1 179.8	1 603	28.8	0	
04/04/92	1 615	<i>1 025</i>	1 120.6	22.37	0	
04/05/92	950	933.98	1 698.3	18.59	0	
04/06/92	750	862.1	1 201.2	15.6	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.4. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 4

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
03/20/92	0	288.1	—	7.34	—	Influent: Autoclaved Mililani well water Date minicolumn packed: 19 March 1992 Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.3 mg, 200 × 325 mesh size carbon, 2.4 cm bed length Total volume of water to breakthrough = 12 095 ml TCP to breakthrough = 2 565 ng/l DBCP to breakthrough = 61 ng/l Total C usage = 0.00416 kg/m ³ (0.0347 lb/1,000 gal)
03/21/92	1 490	<i>286.13</i>	—	<i>7.21</i>	—	
03/22/92	1 200	<i>284.54</i>	—	<i>7.11</i>	—	
03/23/92	1 210	<i>282.94</i>	0	7	0	
03/24/92	—	—	—	7	—	
03/25/92	2 370	279.8	0	6.8	0	
03/26/92	1 260	<i>279.8</i>	—	6.8	—	
03/26/92	0	116.1	—	3	—	
03/27/92	1 240	<i>104.77</i>	—	2.5	—	
03/29/92	1 645	<i>89.75</i>	—	2	—	
03/30/92	—	—	—	—	—	
03/31/92	—	—	—	—	—	
04/01/92	720	<i>83.17</i>	NQ	1	0	
04/02/92	960	74.4	70.3	NQ	0	

NOTE: Calculated values in italics; "not measured" indicated by dashes (—); NQ = not quantifiable.

TABLE C.5. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 5

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
04/08/92	0	875.3	0	30.1	0	Influent: Deionized water (18 Mohm-cm) spiked with TCP and DBCP Date minicolumn packed: 7 April 1992 Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.3 mg, 200 × 325 mesh size carbon, 2.7 cm bed length Total volume of water to breakthrough = 19 493 ml TCP to breakthrough = 29 429 ng/l DBCP to breakthrough = 995 ng/l Total C usage = 0.00258 kg/m ³ (0.0215 lb/1,000 gal)
04/09/92	1 570	772.2	0	27.5	0	
04/09/92	0	2 448.4	0	109.8	0	
04/10/92	1 500	1 582.4	0	127.7	0	
04/10/92	0	1 281.9	0	41.6	0	
04/11/92	1 500	<i>1 246</i>	0	39.8	0	
04/12/92	1 500	<i>1 210.2</i>	0	38	0	
04/13/92	1 600	1 171.9	0	36.1	0	
04/13/92	0	1 099.4	0	34.2	0	
04/14/92	1 350	1 533.1	0	63.6	0	
04/14/92	0	1 825.2	0	72.1	0	
04/15/92	1 560	<i>1 666.2</i>	0	<i>60.3</i>	0	
04/16/92	1 540	1 509.2	0	48.6	0	
04/17/92	1 580	<i>1 509.2</i>	0	48.6	0	
04/17/92	0	1 824.8	0	49.1	0	
04/18/92	1 930	<i>1 688.1</i>	0	46.4	0	
04/19/92	1 520	1 580.5	0	44.2	0	
04/20/92	1 500	1 474.3	38.8	42.1	0	
04/20/92	0	1 512.6	—	45.1	—	
04/21/92	1 520	<i>1 389.4</i>	149.1	<i>43.1</i>	0	
04/22/92	1 390	<i>1 246.8</i>	484.6	41.2	0	
04/23/92	1 600	1 147.2	536.6	39.1	0	
04/24/92	1 570	<i>1 147.2</i>	978.6	<i>39.1</i>	0	
04/24/92	0	1 592.3	—	47.2	—	
04/25/92	1 870	<i>1 575.8</i>	1 243.1	47.2	0	
04/26/92	1 595	<i>1 561.8</i>	1 807.7	47.2	0	
04/27/92	970	<i>1 553.2</i>	2 180.9	47.2	0	
04/28/92	1 395	1 540.9	1 747.2	49.6	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.6. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 6

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
05/19/92	0	1 804.9	—	65.44	—	Influent: Deionized water (18 Mohm-cm) spiked with TCP and DBCP Date minicolumn packed: 18 May 1992 Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.4 mg, 200 × 325 mesh size carbon, 2.8 cm bed length Total volume of water to breakthrough = 16 560 ml TCP to breakthrough = 35 140 ng/l DBCP to breakthrough = 1 301 ng/l Total C usage = 0.00304 kg/m ³ (0.0254 lb/1,000 gal)
05/20/92	1 520	<i>1 660.9</i>	0	58.5	0	
05/22/92	2 350	<i>1 438.25</i>	0	47.87	0	
05/22/92	0	<i>1 780.1</i>	—	59.84	—	
05/23/92	1 940	<i>1 688.6</i>	0	58.5	0	
05/25/92	2 885	<i>1 551.6</i>	0	56.6	0	
05/26/92	1 250	<i>1 492 .25</i>	0	55.78	0	
05/26/92	0	<i>2 107.75</i>	—	92.35	—	
05/27/92	1 420	<i>2 054.2</i>	—	88.4	—	
05/28/92	1 520	<i>1 996.8</i>	0	84.1	0	
05/29/92	1 460	<i>1 941.7</i>	0	80	0	
05/29/92	0	<i>2 197.3</i>	—	74.4	—	
05/30/92	1 759	<i>2 056.1</i>	66.19	71.5	0	
05/31/92	1 315	<i>1 950.6</i>	163.78	69.4	0	
06/01/92	1 440	<i>1 835</i>	380.57	67.1	0	
06/02/92	1 390	<i>1 723.5</i>	851.35	64.8	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.7. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 7

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
04/29/92	0	614.5	—	20.45	—	Influent: Mililani aerated well water Date minicolumn packed: 28 April 1992
04/30/92	1 500	<i>521.39</i>	0	<i>19.79</i>	0	
05/01/92	1 350	437.6	0	19.2	0	Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.3 mg, 200 × 325 mesh size carbon, 2.6 cm bed length
05/01/92	0	713.1	0	28.3	—	
05/02/92	1 655	<i>666.48</i>	0	<i>26.16</i>	0	Total volume of water to breakthrough = 19 554 ml
05/03/92	1 500	<i>624.22</i>	0	<i>24.22</i>	0	
05/04/92	1 550	<i>580.56</i>	0	<i>22.22</i>	0	TCP to breakthrough = 13 103 ng/l DBCP to breakthrough = 513 ng/l
05/05/92	1 410	<i>540.84</i>	0	<i>20.4</i>	0	
05/06/92	1 549	497.2	0	18.4	0	Total C usage = 0.00257 kg/m ³ (0.0214 lb/1,000 gal)
05/07/92	1 300	<i>497.2</i>	0	<i>18.4</i>	0	
05/07/92	0	834.8	—	31.7	—	
05/08/92	1 450	<i>809.77</i>	0	<i>31.2</i>	0	
05/09/92	1 831	<i>778.17</i>	0	<i>30.6</i>	0	
05/10/92	0	<i>778.17</i>	—	<i>30.6</i>	—	
05/11/92	2 750	730.7	NQ	29.7	0	
05/11/92	0	902.5	—	39.3	—	
05/12/92	1 380	776.24	85.6	32.92	0	
05/13/92	1 450	<i>643.58</i>	149.1	<i>26.21</i>	0	
05/14/92	1 365	<i>518.7</i>	461.9	<i>19.9</i>	0	
05/15/92	1 390	531.2	477.2	22.3	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—); NQ = not quantifiable.

TABLE C.8. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 8

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
05/16/92	0	319.6	—	14.3	—	Influent: Mililani aerated well water Date minicolumn packed: 15 May 1992 Pulverized bituminous-based GAC: Calgon Filtrasorb 400 Total C = 50.4 mg, 200 × 325 mesh size carbon, 2.4 cm bed length Total volume of water to breakthrough = 19 552 ml TCP to breakthrough = 11 838 ng/l DBCP to breakthrough = 549 ng/l Total C usage = 0.00258 kg/m ³ (0.0215 lb/1,000 gal)
05/18/92	2 750	<i>319.6</i>	0	<i>14.3</i>	0	
05/19/92	1 415	<i>578.5</i>	—	<i>26.6</i>	—	
05/20/92	1 375	<i>578.5</i>	0	<i>26.6</i>	0	
05/21/92	1 390	<i>557.5</i>	—	<i>24.3</i>	—	
05/22/92	1 605	<i>535.9</i>	0	<i>21.9</i>	0	
05/23/92	1 515	<i>513.4</i>	—	<i>19.4</i>	—	
05/25/92	2 920	<i>472.8</i>	0	<i>14.9</i>	0	
05/25/92	0	<i>1 010.3</i>	—	<i>44.6</i>	—	
05/26/92	1 210	<i>1 010.3</i>	0	<i>44.6</i>	0	
05/27/92	1 532	<i>905.2</i>	—	<i>44.6</i>	—	
05/28/92	1 240	<i>820.2</i>	0	<i>44.6</i>	0	
05/29/92	1 495	<i>723.1</i>	NQ	<i>46.9</i>	0	
05/30/92	1 335	<i>569.8</i>	120.8	<i>34.2</i>	0	
05/31/92	1 085	<i>451.7</i>	181.9	<i>24.4</i>	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—); NQ = not quantifiable.

TABLE C.9. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 9

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
07/17/92	0	1 087.7	—	44.8	—	Influent: Mililani well water
07/18/92	1 430	<i>1 024.6</i>	0	<i>41.1</i>	0	Date minicolumn packed: 16 July 1992
07/19/92	1 400	<i>961.6</i>	0	<i>37.5</i>	0	Pulverized lignite-based GAC: American Norit Co.
07/20/92	1 330	<i>898.5</i>	0	<i>33.9</i>	0	Total C = 50.0 mg, 200 × 325 mesh size carbon,
07/21/92	1 490	<i>835.4</i>	0	<i>30.2</i>	0	2.9 cm bed length
07/22/92	1 465	<i>772.3</i>	0	<i>26.6</i>	0	
07/23/92	1 450	<i>709.2</i>	0	<i>23.0</i>	0	Total volume of water to breakthrough
07/23/92	0	<i>1 003.3</i>	—	<i>40.7</i>	—	(100 ng/l TCP) = 21 500 ml
07/24/92	1 450	<i>990.7</i>	0	<i>40.0</i>	0	
07/25/92	1 340	<i>978.1</i>	0	<i>39.3</i>	0	TCP to breakthrough = 20 363 ng/l
07/26/92	1 690	<i>965.5</i>	0	<i>38.6</i>	0	DBCP to breakthrough = >1 579 ng/l
07/27/92	1 510	<i>952.9</i>	0	<i>37.9</i>	0	
07/28/92	1 250	<i>940.3</i>	0	<i>37.2</i>	0	Total C usage = 0.00233 kg/m ³ (0.0194 lb/1,000 gal)
07/29/92	1 400	<i>927.7</i>	0	<i>36.5</i>	0	
07/30/92	1 415	<i>915.1</i>	0	<i>35.8</i>	0	
07/30/92	0	<i>1 173.8</i>	—	<i>41.3</i>	—	
07/31/92	1 520	<i>1 164.4</i>	54.0	<i>39.8</i>	0	
08/01/92	1 715	<i>1 154.9</i>	111.8	<i>38.3</i>	0	
08/02/92	1 260	<i>1 145.4</i>	150.7	<i>36.8</i>	0	
08/03/92	1 150	<i>1 135.9</i>	244.9	<i>35.3</i>	0	
08/04/92	1 385	<i>1 126.4</i>	300.1	<i>33.8</i>	0	
08/05/92	1 390	<i>1 116.9</i>	406.8	<i>32.3</i>	0	
08/06/92	1 390	<i>1 107.5</i>	610.0	<i>30.8</i>	0	
08/06/92	0	<i>1 643.4</i>	—	<i>91.2</i>	—	
08/07/92	1 345	<i>1 550.2</i>	658.9	<i>91.2</i>	0	
08/08/92	1 610	<i>1 457.1</i>	771.3	<i>82.8</i>	0	
08/09/92	1 430	<i>1 363.9</i>	1 087.3	<i>74.4</i>	0	
08/10/92	1 080	<i>1 270.8</i>	850.1	<i>65.9</i>	0	
08/11/92	650	<i>1 177.7</i>	972.5	<i>57.5</i>	0	
08/12/92	1 360	<i>1 084.5</i>	1 460.1	<i>49.1</i>	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.10. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 10

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
08/19/92	0	1 591.5	—	66.0	—	Influent: Mililani well water Date minicolumn packed: 18 August 1992 Pulverized lignite-based GAC: American Norit Co. Total C = 50.2 mg, 200 × 325 mesh size carbon, 3.3 cm bed length Total volume of water to breakthrough (100 ng/l TCP) = 22 500 ml TCP to breakthrough = 30 543 ng/l DBCP to breakthrough = >1 728.1 ng/l Total C usage = 0.00223 kg/m ³ (0.0188 lb/1,000 gal)
08/20/92	1 450	1 535.5	0	62.7	0	
08/21/92	1 970	1 479.6	0	59.4	0	
08/22/92	1 230	1 423.7	0	56.1	0	
08/23/92	1 410	1 367.7	0	52.8	0	
08/24/92	1 180	1 311.8	0	49.5	0	
08/25/92	1 570	1 255.9	0	46.2	0	
08/25/92	0	1 404.4	—	57.2	—	
08/26/92	1 410	1 402.1	0	55.7	0	
08/27/92	1 320	1 399.8	0	54.2	0	
08/28/92	1 320	1 397.5	0	52.6	0	
08/29/92	1 570	1 395.2	0	51.1	0	
08/30/92	1 260	1 392.9	0	49.5	0	
08/31/92	1 170	1 390.6	0	48.0	0	
09/01/92	1 370	1 388.3	73.0	46.5	0	
09/01/92	0	1 172.6	—	41.4	—	
09/02/92	940	1 148.0	76.3	39.5	0	
09/03/92	960	1 123.4	77.8	37.6	0	
09/04/92	1 390	1 098.9	85.6	35.7	0	
09/05/92	1 630	1 074.3	128.8	33.8	0	
09/06/92	1 360	1 049.7	217.0	31.9	0	
09/07/92	1 470	1 025.1	352.2	30.1	0	
09/08/92	1 070	1 000.6	487.5	28.2	0	
09/09/92	1 250	976.0	499.8	26.3	0	
09/10/92	1 330	951.4	571.8	24.4	0	
09/10/92	0	1 291.2	—	47.2	0	
09/11/92	1 550	1 284.7	725.5	46.7	0	
09/12/92	No Collection (Hurricane)		—	—	—	
09/13/92	1 450	1 271.6	879.3	45.6	0	
09/14/92	990	1 265.1	956.1	45.1	0	
09/15/92	1 410	1 258.6	1 033.0	44.6	0	
09/16/92	1 420	1 252.0	1 358.3	44.0	0	
09/17/92	1 330	1 245.5	1 508.2	43.5	NQ (3.9)	

NOTE: Calculated values in italics; "not measured" indicated by dash (—); NQ = not quantifiable.

TABLE C.11. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 11

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
07/14/92	0	1 384.3	—	51.0	—	Influent: Deionized water (18Mohm-cm) spiked with TCP and DBCP Date minicolumn packed: 13 July 1992 Pulverized lignite-based GAC: American Norit Co. Total C = 50.1 mg, 200 × 325 mesh size carbon, 2.8 cm bed length Total volume of water to breakthrough (100 ng/l TCP) = 21 750 ml TCP to breakthrough = 31 462 ng/l DBCP to breakthrough = >1 780 ng/l Total C usage = 0.00230 kg/m ³ (0.0192 lb/1,000 gal)
07/15/92	1 420	1 358.5	0	48.9	0	
07/16/92	1 490	1 332.8	0	46.8	0	
07/17/92	1 350	1 307.1	0	44.7	0	
07/17/92	0	1 494.1	—	48.2	—	
07/18/92	1 400	1 466.4	0	46.2	0	
07/19/92	1 330	1 438.6	0	44.2	0	
07/20/92	1 520	1 410.9	0	42.2	0	
07/21/92	1 390	1 533.1	0	50.1	0	
07/21/92	0	1 903.2	—	78.1	—	
07/22/92	1 410	1 883.4	0	71.1	0	
07/23/92	1 480	1 678.0	0	64.2	0	
07/24/92	1 310	1 472.5	0	57.4	0	
07/24/92	0	1 228.2	0	47.2	0	
07/25/92	1 595	1 205.4	0	45.3	0	
07/26/92	1 500	1 182.6	0	43.3	0	
07/27/92	1 120	1 159.8	0	41.3	0	
07/28/92	1 395	1 378.9	0	52.6	0	
07/28/92	0	1 724.1	—	73.8	—	
07/29/92	1 345	1 614.5	67.0	65.0	0	
07/30/92	1 400	1 505.0	152.8	56.2	0	
07/31/92	1 450	1 395.4	197.3	47.5	0	
07/31/92	0	1 629.3	—	49.9	—	
08/01/92	1 740	1 563.5	150.7	48.9	0	
08/02/92	1 280	1 497.6	188.3	47.9	0	
08/03/92	1 170	1 431.7	273.1	46.9	0	
08/04/92	1 385	1 365.9	352.2	45.9	0	
08/05/92	1 390	1 300.0	453.1	44.9	0	
08/06/92	1 370	1 234.1	761.1	43.9	0	

TABLE C.11—Continued

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
08/07/92	1 365	1 168.3	823.5	42.9	0	
08/07/92	0	2 102.4	—	53.1	—	
08/08/92	1 560	1 998.8	1 313.7	52.1	0	
08/09/92	1 435	1 895.1	2 441.0	51.0	0	
08/10/92	1 110	1 791.4	2 485.3	50.0	0	
08/11/92	1 400	1 687.7	—	48.9	—	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.12. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 12

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
08/18/92	0	1 314.7	—	45.1	—	Influent: Deionized water (18 Mohm-cm) spiked with TCP and DBCP Date minicolumn packed: 17 August 1992 Pulverized lignite-based GAC: American Norit Co. Total C = 50.2 mg, 200 × 325 mesh size carbon, 3.0 cm bed length Total volume of water to breakthrough (100 ng/l TCP) = 27 000 ml TCP to breakthrough = 39 998 ng/l DBCP to breakthrough = >2 309 ng/l Total C usage = 0.00186 kg/m ³ (0.0155 lb/1,000 gal)
08/19/92	1 380	1 278.0	0	43.7	0	
08/20/92	1 420	1 241.4	0	42.4	0	
08/20/92	0	1 542.7	—	52.4	—	
08/21/92	1 920	1 511.1	0	50.6	0	
08/22/92	1 260	1 479.5	0	48.8	0	
08/23/92	1 430	1 447.9	0	47.0	0	
08/24/92	1 400	1 416.3	0	45.2	0	
08/25/92	1 500	1 384.7	0	43.4	0	
08/25/92	0	1 712.6	—	73.3	—	
08/26/92	1 440	1 560.9	0	64.7	0	
08/27/92	1 320	1 409.2	0	56.0	0	
08/28/92	1 390	1 257.5	0	47.4	0	
08/28/92	0	1 190.6	—	39.4	—	
08/29/92	1 610	1 174.2	0	38.1	0	
08/30/92	1 330	1 157.9	0	36.8	0	
08/31/92	1 260	1 141.6	0	35.5	0	
09/01/92	1 410	1 125.2	0	34.2	0	
09/01/92	0	1 674.5	—	55.4	—	
09/02/92	1 370	1 617.4	0	54.3	0	
09/03/92	1 370	1 560.3	27.3	53.3	0	
09/04/92	1 330	1 503.2	56.5	52.3	0	
09/04/92	0	1 896.0	—	64.1	—	
09/05/92	1 590	1 845.4	67.2	62.8	0	
09/06/92	1 440	1 794.7	111.9	61.5	0	
09/07/92	1 550	1 744.0	131.9	60.2	0	
09/08/92	1 140	1 693.3	151.9	58.9	0	
09/09/92	1 350	1 642.7	209.3	57.3	0	
09/09/92	0	2 260.1	—	91.4	—	
09/10/92	1 390	2 166.1	335.5	85.7	0	
09/11/92	1 380	2 072.2	408.6	80.0	0	

TABLE C.12—Continued

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
09/12/92	No collection (Hurricane Iniki)	—	—	—	—	
09/13/92	1 570	<i>1 884.2</i>	554.8	68.6	0	
09/14/92	1 200	<i>1 790.2</i>	627.9	62.9	0	
09/15/92	1 490	<i>1 696.2</i>	879.5	57.2	0	
09/15/92	0	<i>1 431.4</i>	—	49.6	—	
09/16/92	1 450	<i>1 390.9</i>	1 141.7	48.1	0	
09/17/92	1 450	<i>1 350.3</i>	1 401.2	46.7	0	
09/18/92	1 380	<i>1 061.6</i>	1 350.3	45.3	0	

NOTE: Calculated values in italics; “not measured” indicated by dash (—).

TABLE C.13. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 13

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
09/19/92	—	0	—	0	—	Influent: Deionized water (18 Mohm-cm) spiked with TCP and DBCP presoaked for 72 hours with distilled water Date minicolumn packed: 18 September 1992 Pulverized lignite-based GAC: American Norit Co. Total C = 50.2 mg, 200 × 325 mesh size carbon, 3.2 cm bed length Total volume of water to breakthrough (100 ng/l TCP) = 30 000 ml TCP to breakthrough = 40 916 ng/l DBCP to breakthrough = >2 185 ng/l Total C usage = 0.00167 kg/m ³ (0.0140 lb/1,000 gal)
09/20/92	3 000	—	0	—	0	
09/21/92	1 120	—	—	—	—	
09/22/92	1 250	1 452.4	0	39.4	0	
09/23/92	1 470	1 436.8	0	38.7	0	
09/24/92	1 390	1 421.3	0	37.9	0	
09/24/92	—	1 664.9	—	41.0	—	
09/25/92	1 450	1 620.9	0	40.6	0	
09/26/92	—	—	—	—	—	
09/27/92	—	—	—	—	—	
09/28/92	4 400	1 532.8	0	39.7	0	
09/29/92	1 525	1 444.6	0	38.9	0	
09/29/92	—	1 865.1	—	60.1	—	
09/30/92	1 430	1 727.5	0	52.5	0	
10/01/92	1 440	1 589.9	0	45.0	0	
10/02/92	1 470	1 452.4	0	37.4	0	
10/02/92	—	1 803.6	—	47.9	—	
10/03/92	1 865	1 748.9	0	45.2	0	
10/04/92	1 300	1 694.3	0	42.6	0	
10/05/92	1 280	1 639.6	0	39.9	0	
10/05/92	—	1 820.6	0	46.9	—	
10/06/92	1 470	1 763.1	0	45.0	0	
10/07/92	1 500	1 705.5	47.1	43.1	0	
10/08/92	1 560	1 648.0	82.8	41.2	0	
10/09/92	1 440	1 590.4	112.5	39.4	0	
10/09/92	—	1 752.4	—	49.2	—	
10/10/92	1 710	1 714.0	211.4	47.7	0	
10/11/92	1 500	1 675.7	230.2	46.2	0	
10/12/92	1 150	1 637.3	368.9	44.8	0	

TABLE C.13—Continued

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
10/13/92	1 465	<i>1 599.0</i>	<i>685.0</i>	<i>43.3</i>	<i>0</i>	
10/14/92	1 490	<i>1 560.6</i>	<i>706.8</i>	<i>41.8</i>	<i>0</i>	
10/15/92	1 460	<i>1 522.3</i>	<i>728.7</i>	<i>40.3</i>	<i>0</i>	
10/15/92	—	<i>2 231.5</i>	—	<i>79.8</i>	—	
10/16/92	1 520	<i>2 058.3</i>	<i>1 183.6</i>	<i>72.4</i>	<i>0</i>	
10/17/92	1 690	<i>1 885.1</i>	<i>856.1</i>	<i>65.1</i>	<i>0</i>	
10/18/92	1 550	<i>1 711.9</i>	<i>925.8</i>	<i>57.7</i>	<i>0</i>	
10/19/92	1 175	<i>1 538.7</i>	<i>1 194.7</i>	<i>50.3</i>	<i>0</i>	
10/20/92	1 480	<i>1 365.5</i>	<i>1 140.3</i>	<i>43.0</i>	<i>0</i>	
10/20/92	—	<i>1 948.7</i>	—	<i>75.4</i>	—	
10/21/92	1 500	<i>1 890.8</i>	<i>2 471.7</i>	<i>73.3</i>	<i>0</i>	
10/22/92	1 500	<i>1 832.9</i>	<i>1 920.1</i>	<i>71.2</i>	<i>0</i>	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

TABLE C.14. Analysis of TCP and DBCP in Minicolumn Experimental Run No. 14

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
09/29/92	1 300	0	—	0	—	Influent: Deionized water (18 Mohm-cm) spiked with TCP and DBCP presoaked for 72 hours with Pacific Palisades water Date minicolumn packed: 28 September 1992 Pulverized lignite-based GAC: American Norit Co. Total C = 50.3 mg, 200 × 325 mesh size carbon, 3.3 cm bed length Total volume of water to breakthrough (100 ng/l TCP) = 29 000 ml TCP to breakthrough = 40 895 ng/l DBCP to breakthrough = >2 342 ng/l Total C usage = 0.00173 kg/m ³ (0.0145 lb/1,000 gal)
09/30/92	1 250	—	0	—	0	
10/01/92	1 357	—	—	—	—	
10/02/92	1 390	1 590.4	—	43.8	—	
10/03/92	1 585	1 520.7	0	40.1	0	
10/04/92	1 585	1 450.9	0	36.5	0	
10/05/92	1 210	1 381.2	0	32.8	0	
10/05/92	—	2 156.5	—	57.5	—	
10/06/92	1 390	2 021.3	0	51.8	0	
10/07/92	1 425	1 886.0	0	46.1	0	
10/08/92	1 500	1 750.7	0	40.3	0	
10/09/92	1 400	1 615.5	0	34.6	0	
10/09/92	—	1 967.1	—	56.9	—	
10/10/92	1 705	1 884.4	0	53.1	0	
10/11/92	1 560	1 801.7	0	49.3	0	
10/12/92	1 240	1 719.0	0	45.5	0	
10/12/92	—	1 946.2	—	56.9	—	
10/13/92	1 560	1 920.8	0	54.9	0	
10/14/92	1 500	1 895.4	0	53.0	0	
10/15/92	1 450	1 870.0	17.0	51.1	0	
10/16/92	1 490	1 844.6	45.6	49.2	0	
10/16/92	—	1 293.2	—	38.9	—	
10/17/92	1 640	1 258.9	67.8	38.3	0	
10/18/92	1 560	1 224.7	102.7	37.7	0	
10/19/92	1 130	1 190.5	190.3	37.1	0	
10/20/92	1 530	1 156.2	239.7	36.5	0	
10/21/92	1 420	1 122.3	365.0	35.8	0	
10/21/92	—	1 556.9	—	46.5	—	
10/22/92	1 250	1 463.4	491.4	44.5	0	

TABLE C.14—Continued

Date	Volume (ml)	TCP (ng/l)		DBCP (ng/l)		Experimental Data
		Influent	Effluent	Influent	Effluent	
10/23/92	1 350	1 369.8	464.6	42.5	0	
10/23/92	—	1 832.9	—	71.2	—	
10/24/92	1 640	<i>1 800.4</i>	479.3	<i>68.0</i>	0	
10/25/92	1 440	<i>1 767.9</i>	494.0	<i>64.8</i>	0	
10/26/92	1 140	<i>1 735.3</i>	523.3	<i>61.6</i>	0	
10/27/92	1 410	<i>1 702.8</i>	737.8	<i>58.4</i>	0	
10/28/92	1 420	1 670.3	920.8	55.2	0	
10/28/92	—	1 770.4	—	55.3	—	
10/29/92	1 422	<i>1 749.9</i>	1 077.0	53.5	0	
10/30/92	1 400	<i>1 729.3</i>	941.7	<i>51.6</i>	0	
10/31/92	—	—	—	—	—	
11/01/92	—	—	—	—	—	
11/02/92	4 076	<i>1 667.7</i>	1 358.7	46.2	(7.6)	
11/03/92	—	—	—	—	—	
11/04/92	2 790	1 626.6	1 423.4	42.5	0	
11/05/92	1 440	1 643.4	1 728.4	46.3	0	

NOTE: Calculated values in italics; "not measured" indicated by dash (—).

**Appendix D. Graphs Depicting TCP and DBCP Behavior
in 14 Minicolumn Experiments**

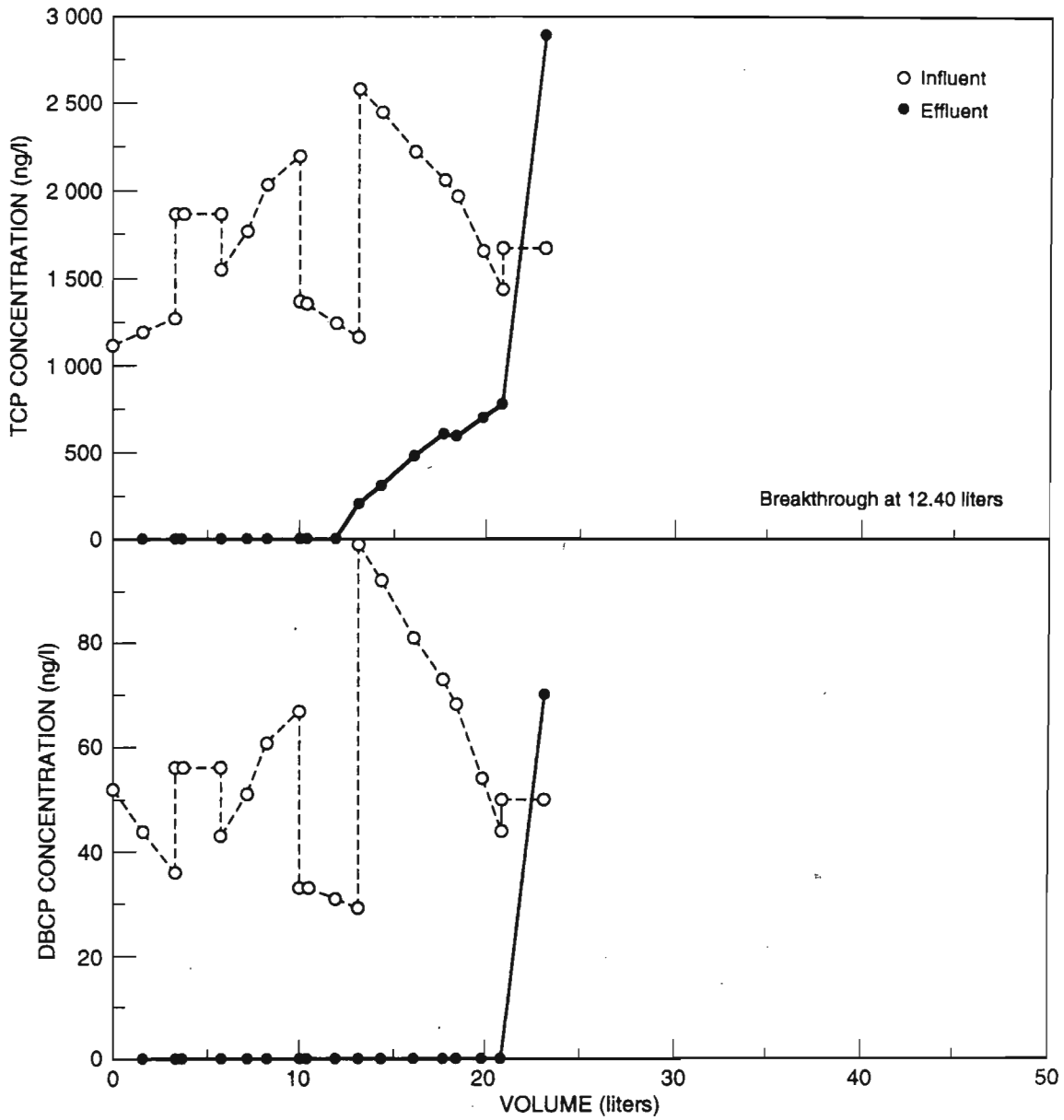
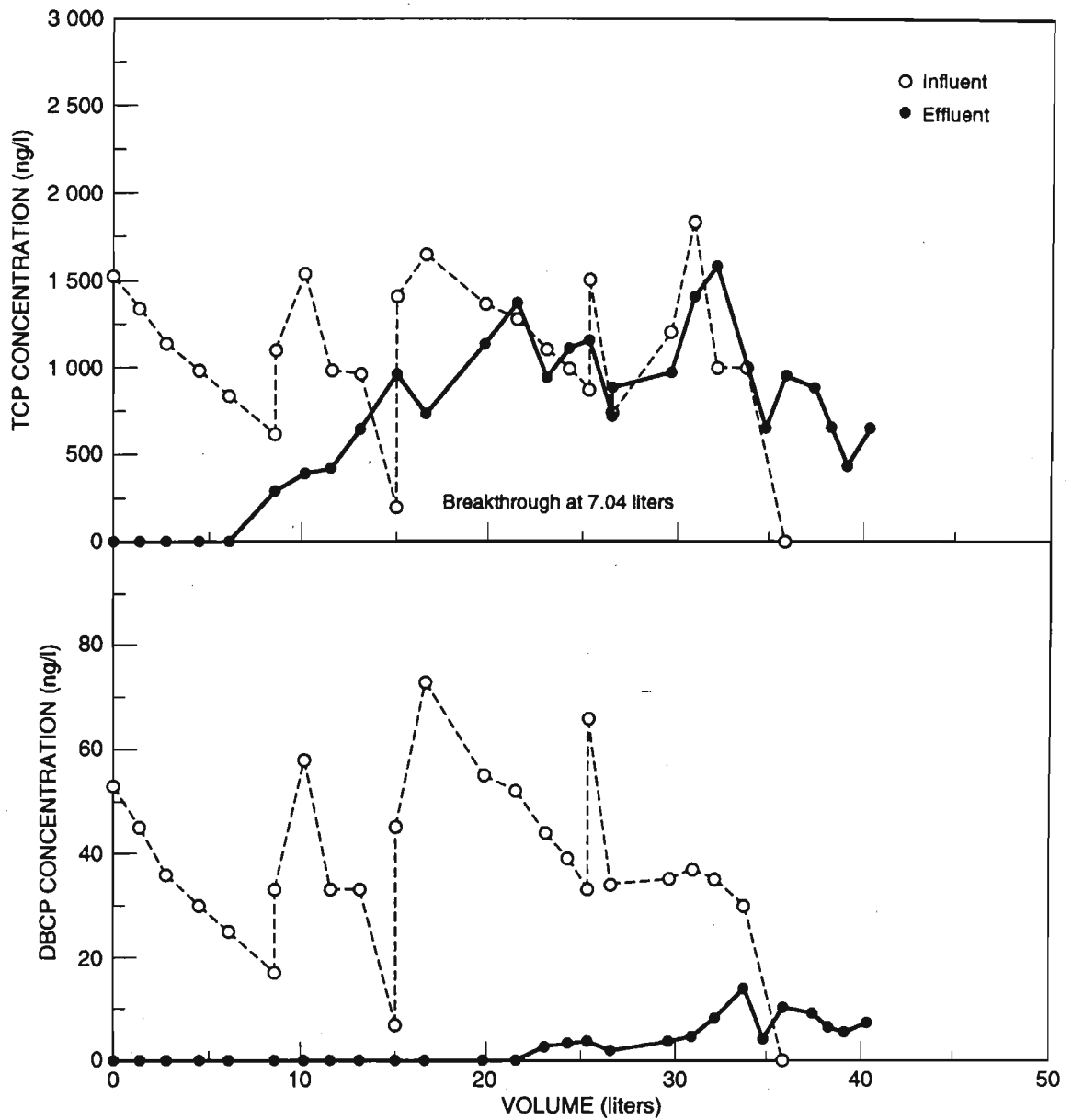


FIGURE D.1. Behavior of TCP and DBCP in minicolumn experimental Run No. 1 conducted in September 1991 using Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)



NOTE: Deionized water ran after 35 liters.

FIGURE D.2. Behavior of TCP and DBCP in minicolumn experimental Run No. 2 conducted in January 1992 using Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

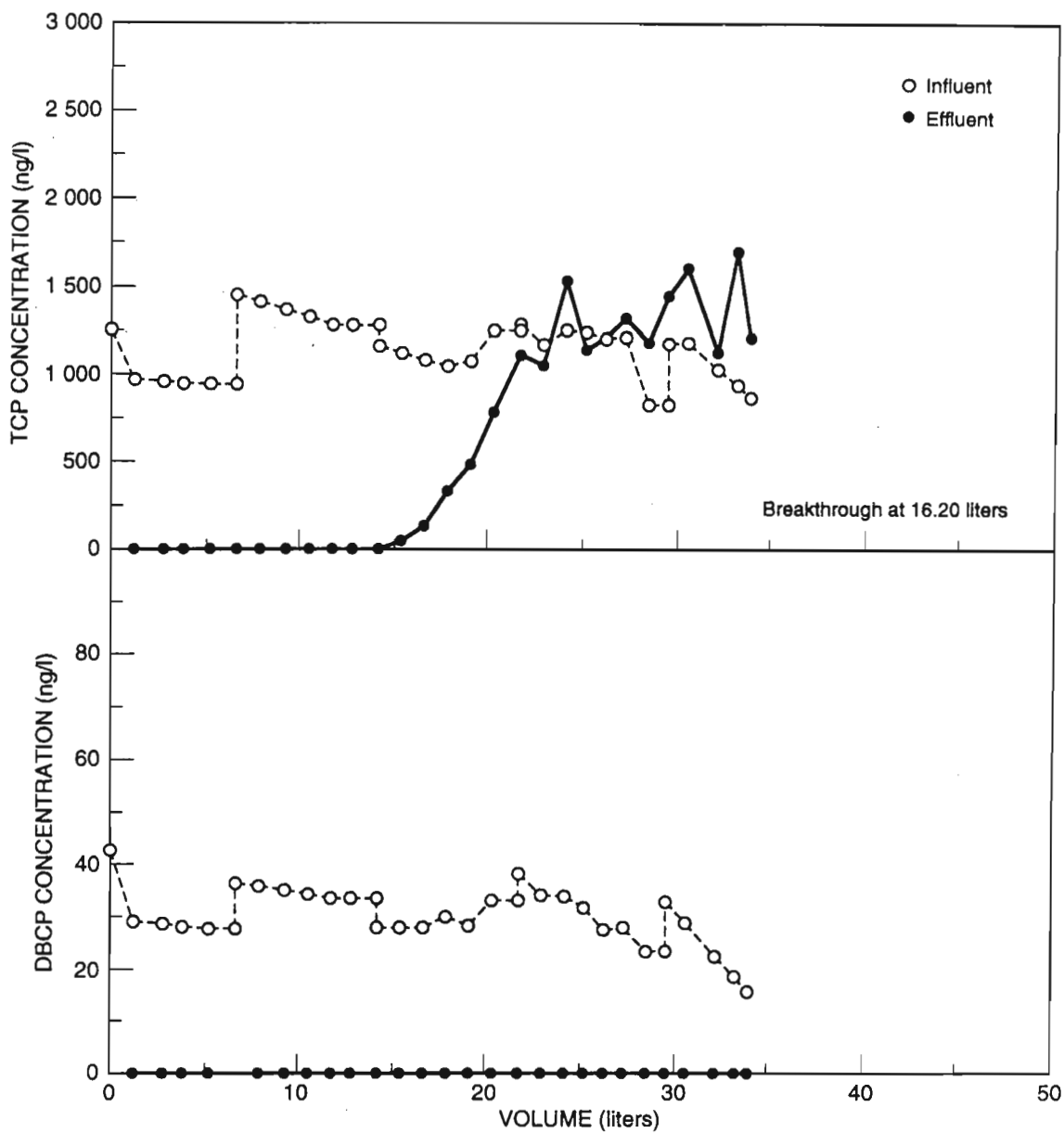


FIGURE D.3. Behavior of TCP and DBCP in minicolumn experimental Run No. 3 conducted in March 1992 using Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

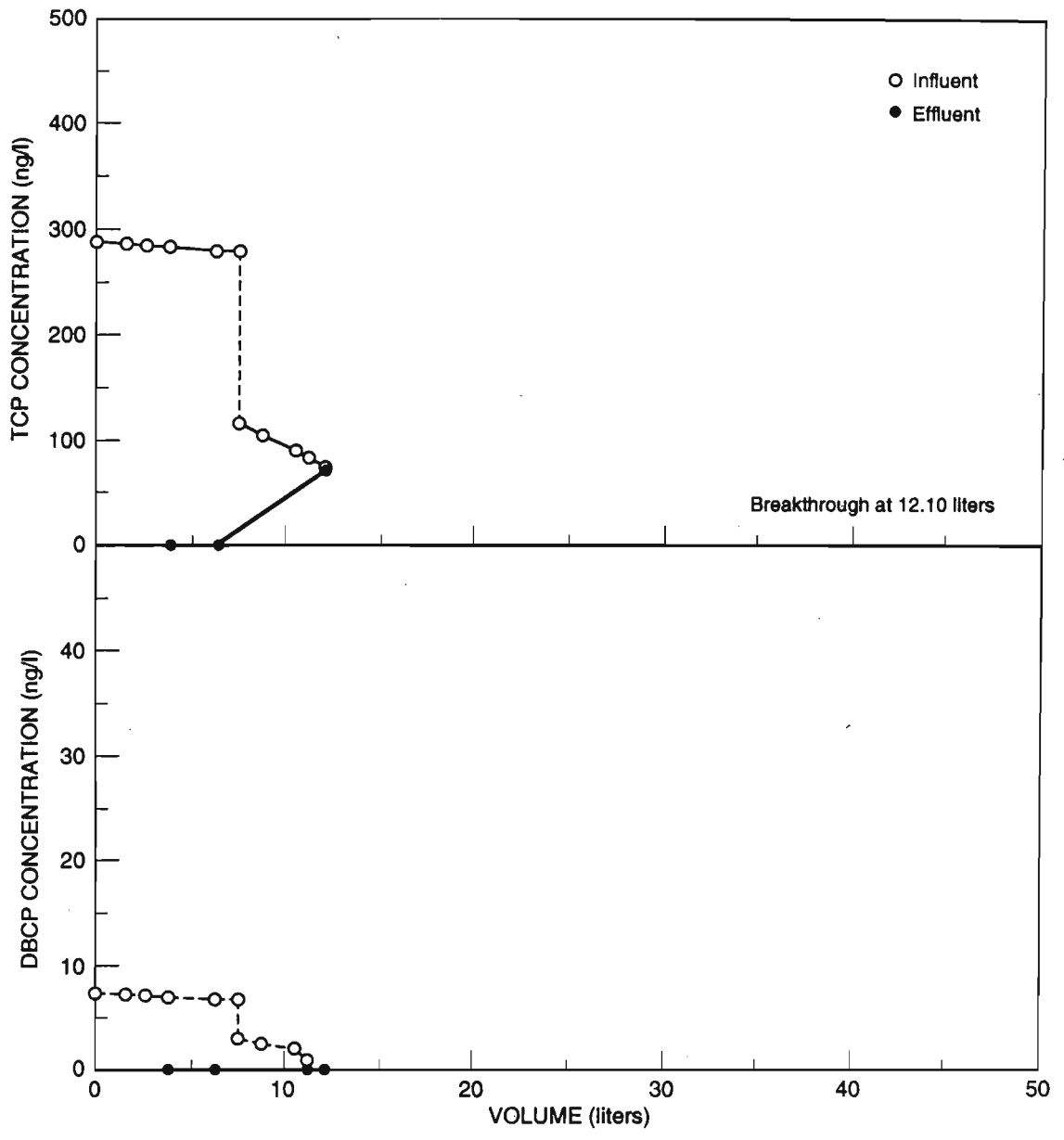


FIGURE D.4. Behavior of TCP and DBCP in minicolumn experimental Run No. 4 conducted in March 1992 using autoclaved Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

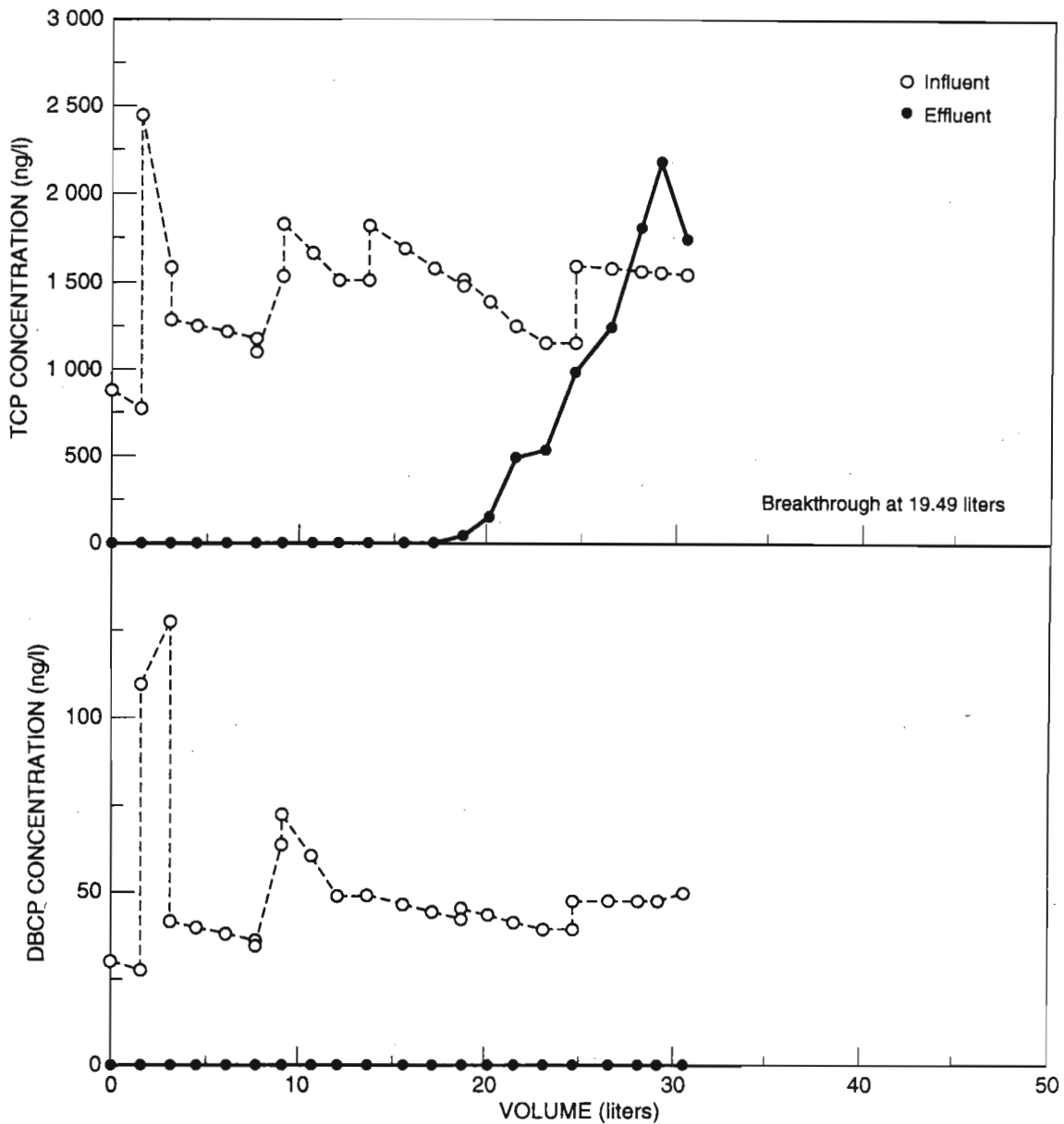


FIGURE D.5. Behavior of TCP and DBCP in minicolumn experimental Run No. 5 conducted in April 1992 using deionized water spiked with TCP and DBCP and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

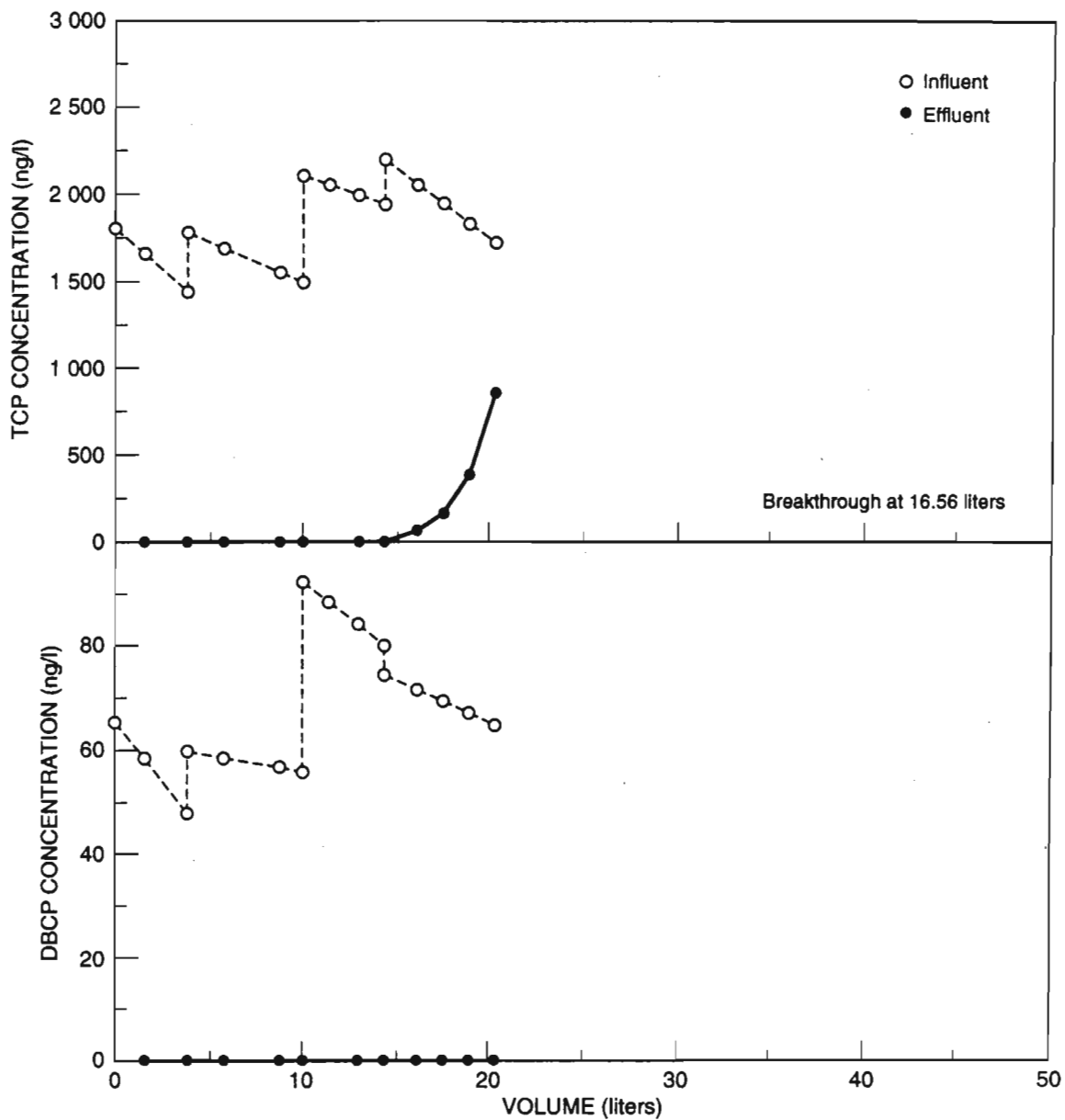


FIGURE D.6. Behavior of TCP and DBCP in minicolumn experimental Run No. 6 conducted in May 1992 using deionized water spiked with TCP and DBCP and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

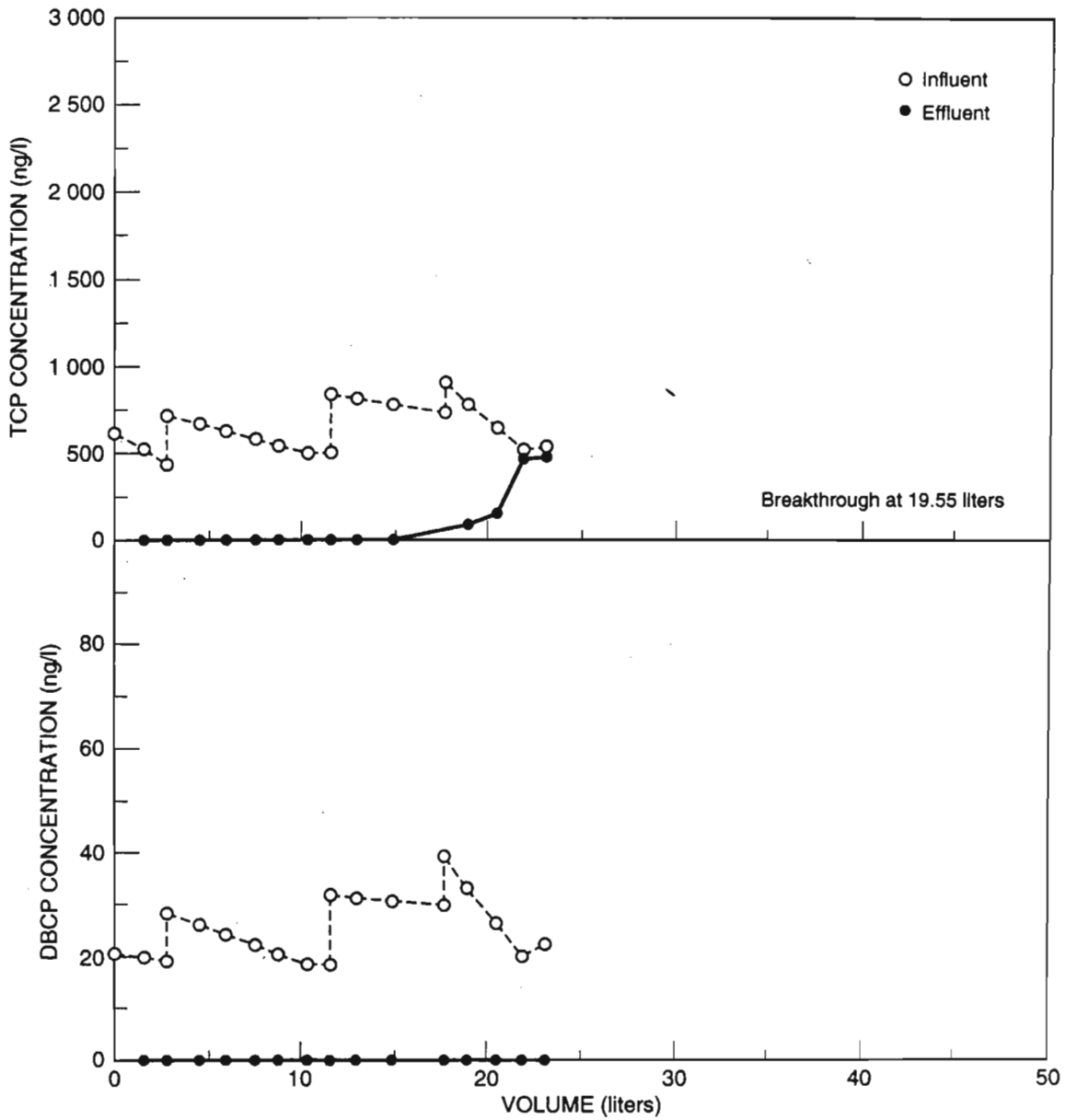


FIGURE D.7. Behavior of TCP and DBCP in minicolumn experimental Run No. 7 conducted in April 1992 using aerated Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

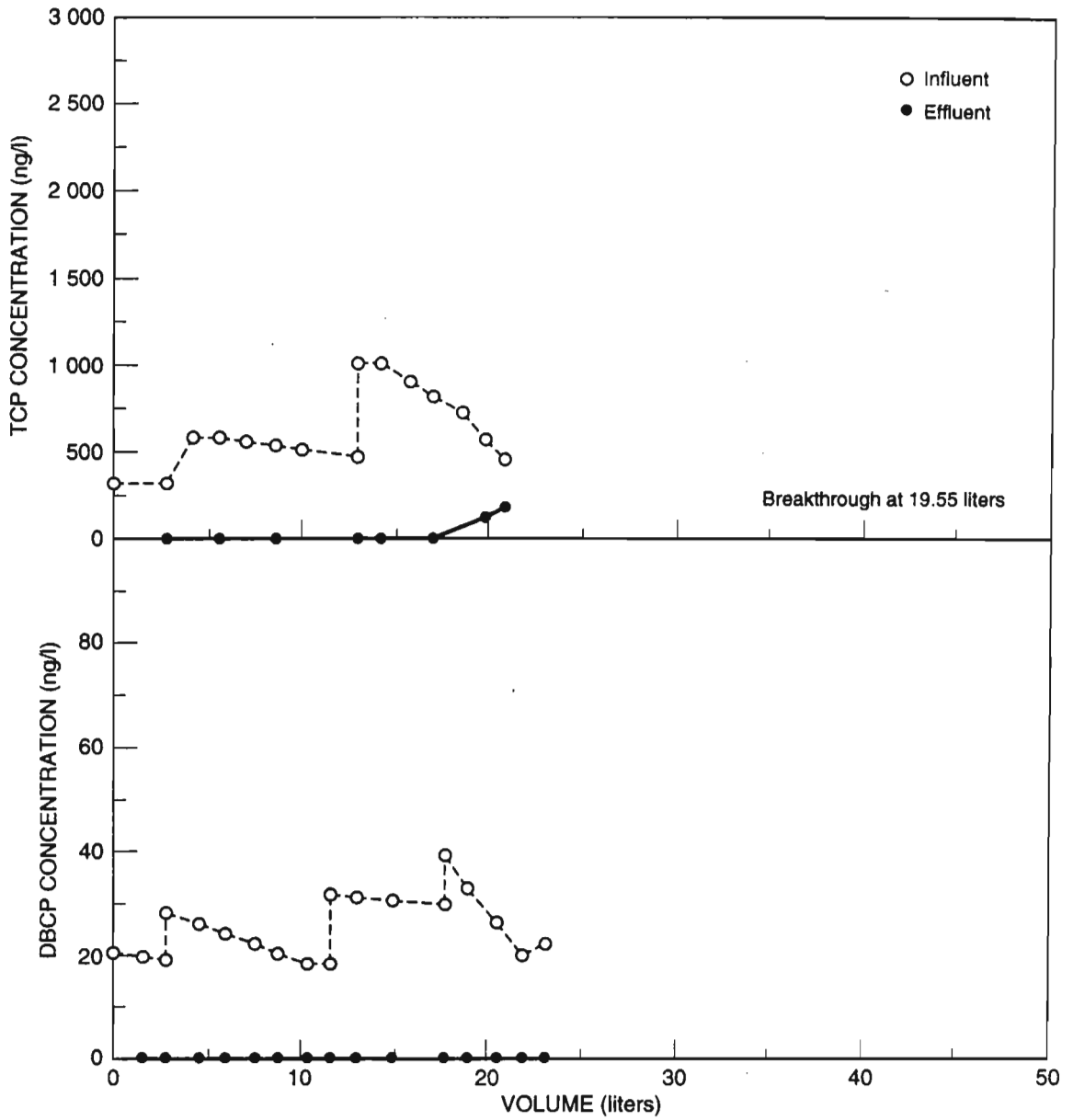


FIGURE D.8. Behavior of TCP and DBCP in minicolumn experimental Run No. 8 conducted in May 1992 using aerated Mililani well water and pulverized bituminous-based GAC (Calgon Filtrasorb 400)

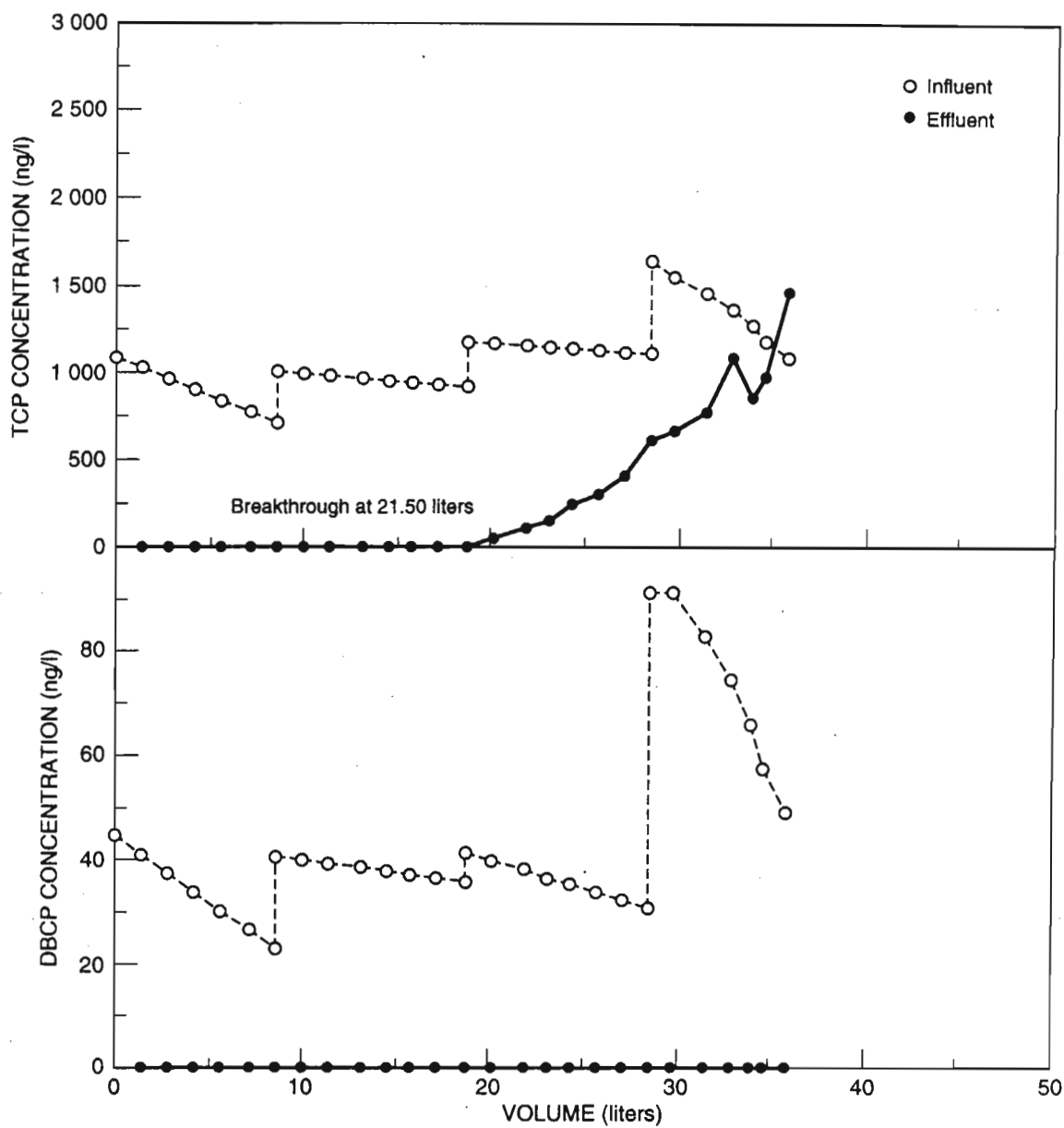


FIGURE D.9. Behavior of TCP and DBCP in minicolumn experimental Run No. 9 conducted in July 1992 using Mililani well water and pulverized lignite-based GAC (American Norit Co.)

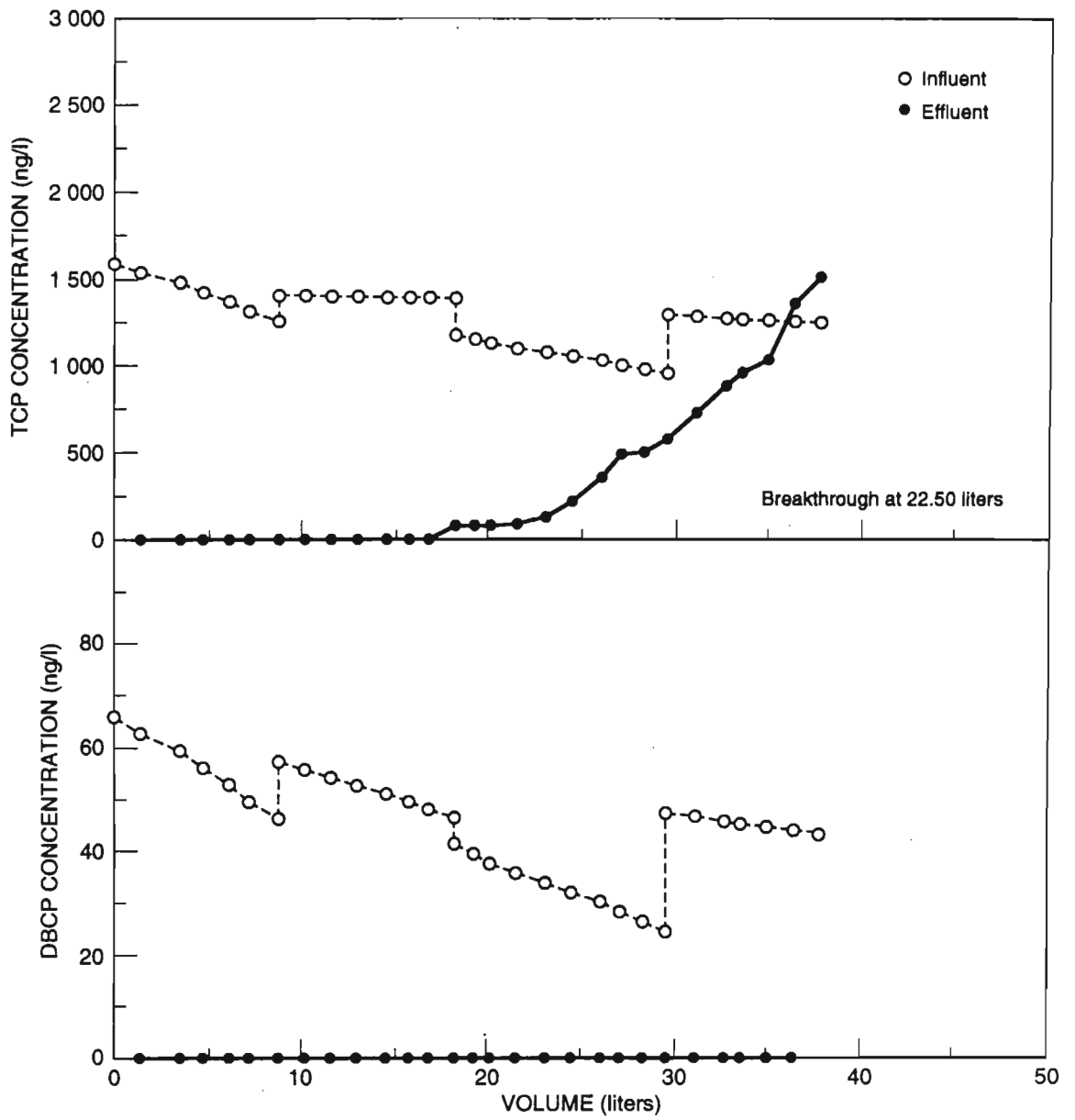


FIGURE D.10. Behavior of TCP and DBCP in minicolumn experimental Run No. 10 conducted in August 1992 using Mililani well water and pulverized lignite-based GAC (American Norit Co.)

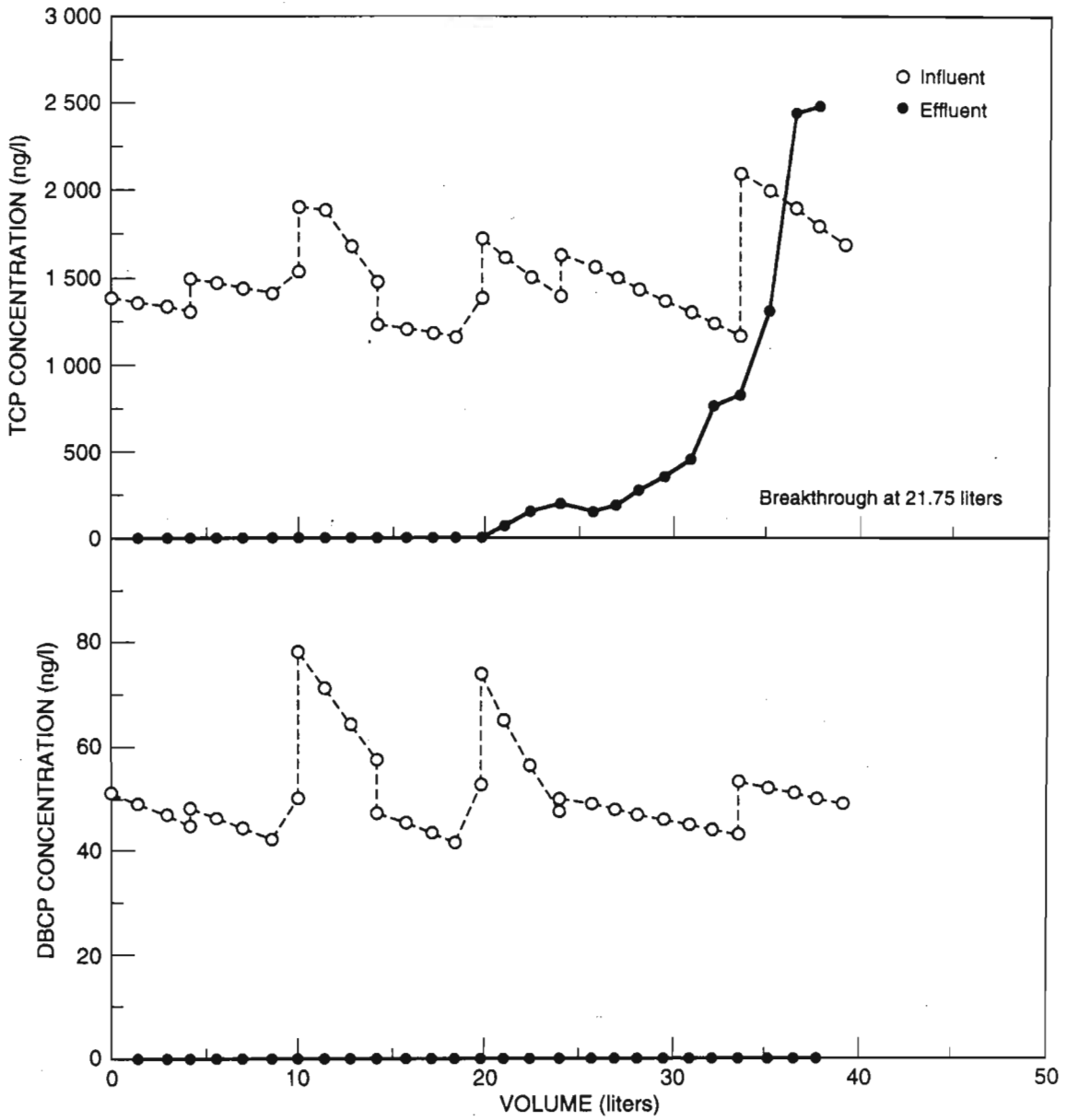


FIGURE D.11. Behavior of TCP and DBCP in minicolumn experimental Run No. 11 conducted in July 1992 using deionized water spiked with TCP and DBCP and pulverized lignite-based GAC (American Norit Co.)

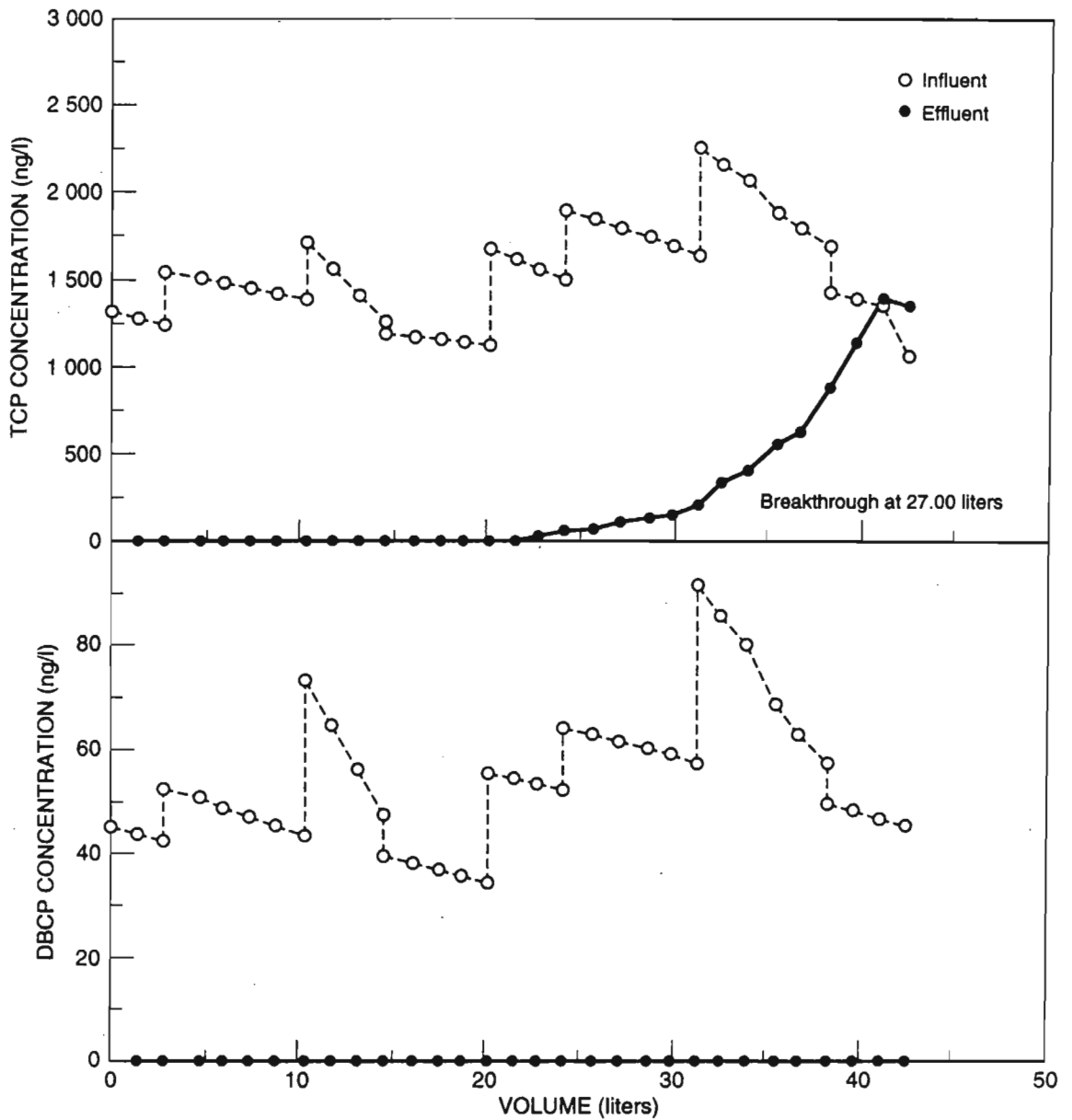


FIGURE D.12. Behavior of TCP and DBCP in minicolumn experimental Run No. 12 conducted in August 1992 using deionized water spiked with TCP and DBCP and pulverized lignite-based GAC (American Norit Co.)

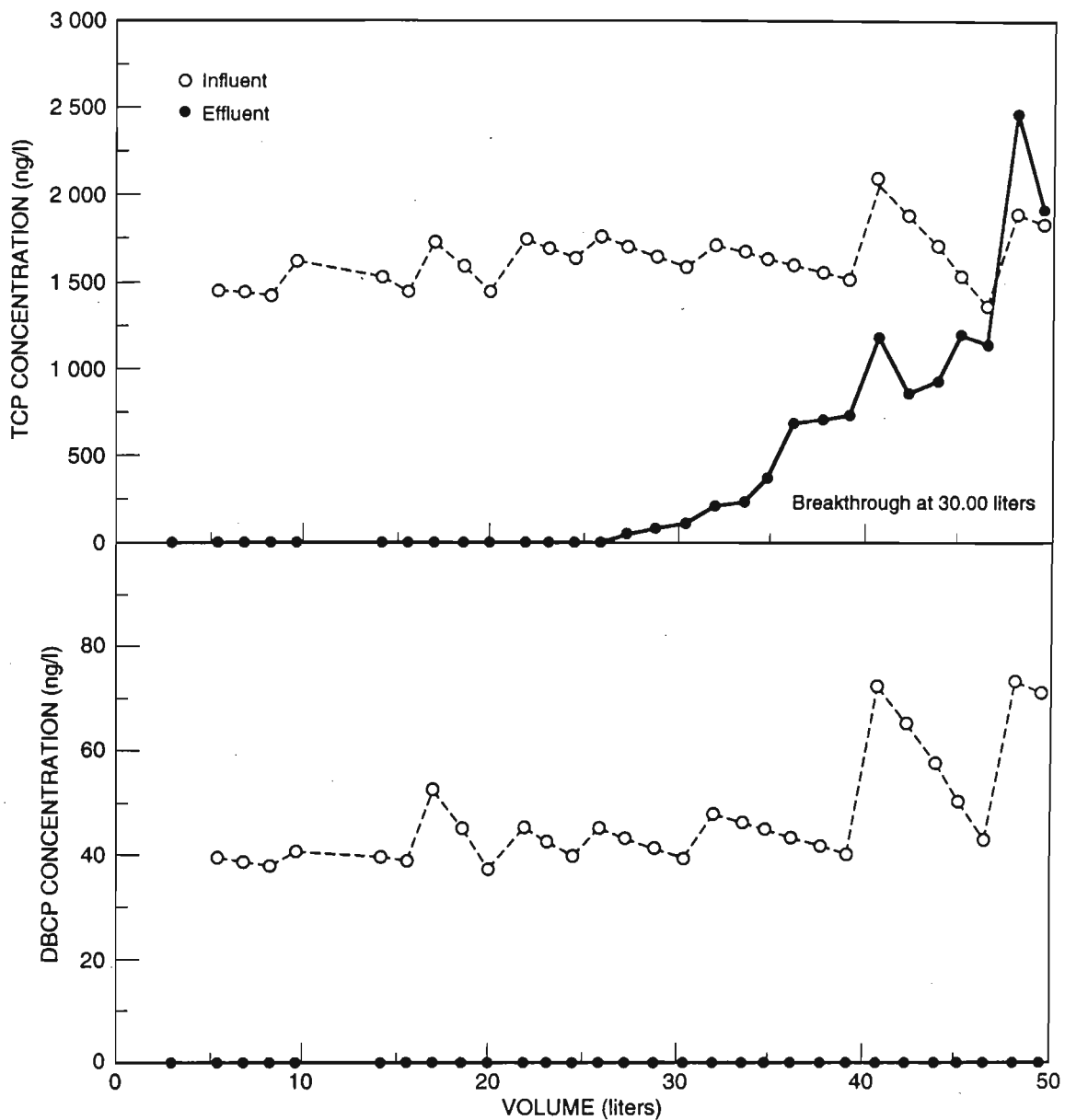


FIGURE D.13. Behavior of TCP and DBCP in minicolumn experimental Run No. 13 conducted in September 1992 using deionized water spiked with TCP and DBCP presoaked for 72 hours with distilled water and pulverized lignite-based GAC (American Norit Co.)

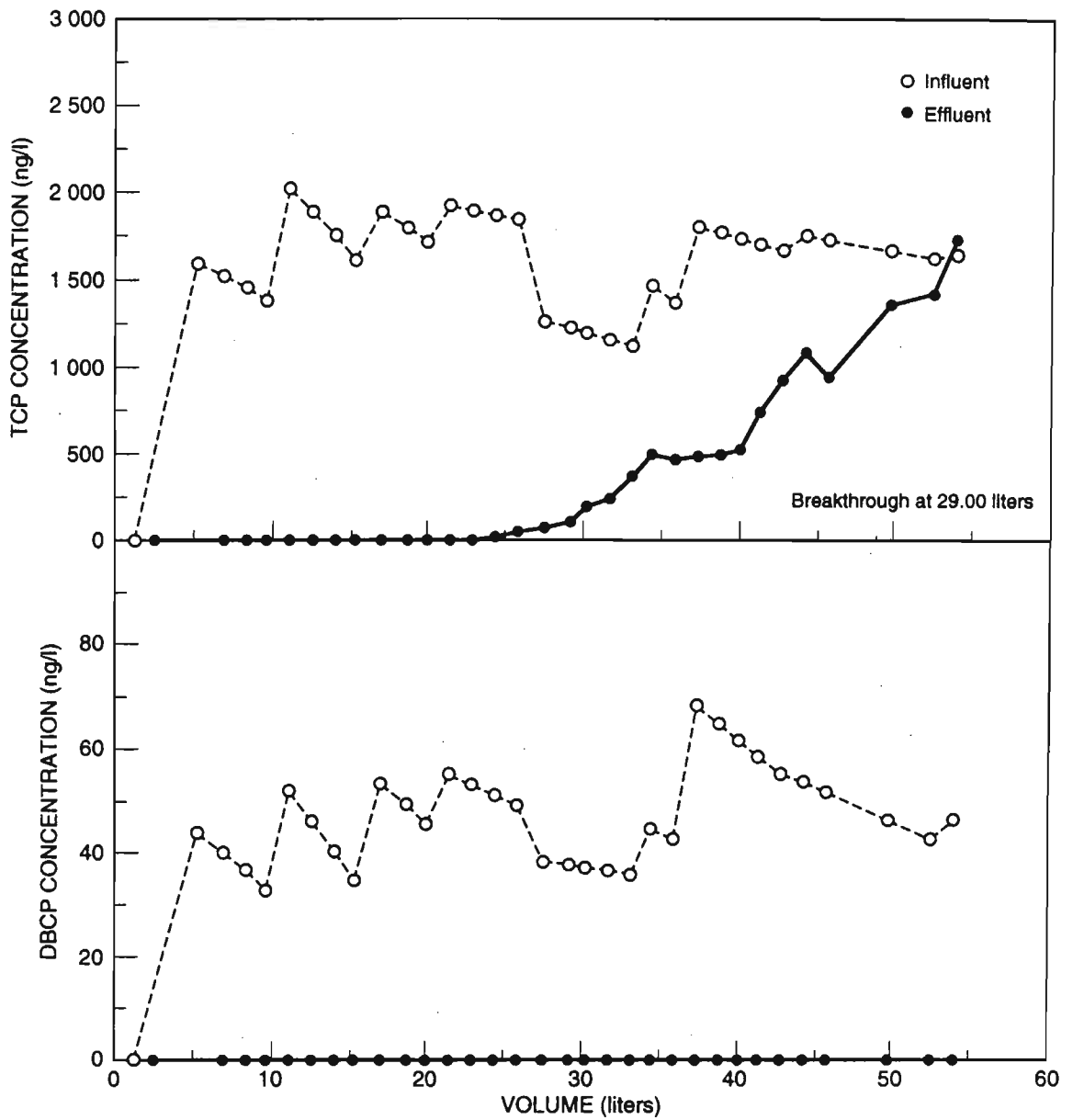


FIGURE D.14. Behavior of TCP and DBCP in minicolumn experimental Run No. 14 conducted in September 1992 using deionized water spiked with TCP and DBCP presoaked for 72 hours with Pacific Palisades water and pulverized lignite-based GAC (American Norit Co.)

Appendix E. Carbon Analysis from Minicolumn Experiments

TABLE E.1. Summary of Carbon Analysis Data from Minicolumn Experiments (Influent and Effluent) Using Bituminous-Based GAC^a

Sample	Date Collected/Analyzed	TC (mg/l)	NPOC (mg/l)
Minicolumn Influent: Mililani Well Water			
Influent	03-25-92	10.563	0.5553
Effluent	03-25-92	11.063	0.7132
Influent	04-02-92	11.172	0.5556
Effluent (kept in refrigerator)	03-29-92/04-02-92	overscale	overscale
Effluent (freshly collected)	04-02-92	13.574	3.0979
Influent	04-03-92	11.546	1.6957
Effluent	04-03-92	13.210	2.9097
Minicolumn Influent: Deionized Water Spiked with TCP and DBCP in Methanol			
Influent	04-15-92	73.831	68.798
Effluent (freshly collected)	04-15-92	74.818	66.686
Effluent (overnight collection)	04-15-92	70.427	67.315
Effluent (kept in refrigerator)	04-14-92/04-15-92	62.680	58.442
Deionized Water	04-10-92/04-15-92	0.342	0.251
Deionized Water + 1 drop methanol	04-15-92	41.017	38.962
Influent	04-20-92/04-21-92	64.291	64.291
Effluent	04-21-92	63.929	63.929
Minicolumn Influent: Aerated Mililani Well Water			
Influent	04-28-92/04-30-92	10.624	0.4525
Effluent (overnight collection)	04-30-92	10.512	0.5328
Effluent (freshly collected)	04-30-92	10.750	0.4271
Influent	04-30-92	11.460	1.0088
Influent	04-28-92/05-01-92	10.411	0.6377
Effluent (freshly collected)	05-01-92	10.513	0.4176
Influent (new 05-01-92)	05-01-92/05-04-92	10.697	0.6537
Influent (freshly collected)	05-04-92	10.691	0.3821
Influent	05-01-92/05-06-92	10.556	0.3658
Influent (repeated)	05-01-92/05-06-92	10.862	
Effluent	05-06-92	10.680	0.3791
Influent	05-07-92	10.586	0.4196
Effluent (overnight collection)	05-07-92	11.283	1.0863
Effluent (freshly collected)	05-07-92	10.431	0.3090
Influent	05-06-92/05-11-92	10.518	
Influent	05-06-92/05-11-92	10.518	0.6161
Effluent (2-night collection)	05-11-92	10.406	0.3090
Effluent (freshly collected)	05-11-92	10.437	0.4271
Influent (new 05-11-92)	05-08-92/05-11-92	10.737	0.5995
Influent	05-08-92/05-13-92	10.434	0.6668
Effluent (overnight collection)	05-13-92	11.953	1.8883
Effluent (freshly collected)	05-13-92	10.354	0.3085
Influent	05-14-92	10.429	0.3298
Effluent (overnight collection)	05-14-92	10.885	0.5384
Effluent (freshly collected)	05-14-92	10.327	0.7174

NOTE: TC = total carbon, NPOC = nonpurgeable organic carbon.

^aCalgon Filtrasorb 400.