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THIS DOCUMENT EXPLAINS THE INSTALLATION RESTORATION PHILOSOPHY OF MONITORING, CONTAMINATION MIGRATION CONTROL, AND ELIMINATION OF CONTAMINATION SOURCES. IT ALSO DISCUSSES THE HISTORY OF RMA CONTAMINATION, HYDROLOGY OF THE AREA, CONTAMINATION PATTERNS, THE AQUIFER RESTORATION PROGRAM, AND DISPOSAL ALTERNATIVES.

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Ground-Water Contamination and Aquifer Reclamation at the Rocky Mountain Arsenal, Colorado

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Ground-Water Contamination and Aquifer Reclamation at the Rocky Mountain Arsenal, Colorado

Abstract

Ground-water contamination at the Rocky Mountain Arsenal, Colorado, is related to the disposal of liquid industrial wastes and to industrial leaks and spills that have occurred during the 40-year history of operation of the Arsenal. From 1943 to 1956 the liquid wastes were discharged into unlined ponds, which resulted in contamination of part of the underlying alluvial aquifer. Since 1956, disposal has been accomplished by discharge into an asphalt-lined reservoir, which significantly reduced the volume of contaminants entering the aquifer. In the mid-1970's toxic organic chemicals were detected off the Arsenal in the alluvial aquifer, and the Colorado Department of Health issued Cease and Desist Orders, which called for (1) a halt to unauthorized discharges, (2) cleanup, and (3) ground-water monitoring. Subsequently, a management commitment was made to mitigate the problem. A pilot ground-water containment and treatment system was constructed in 1978; it consists of (1) a bentonite barrier and several withdrawal wells to intercept contaminated ground-water along a 1500-ft length of the northern Arsenal boundary, (2) treating the water with an activated carbon process, and (3) reinjecting the treated water on the downgradient side of the barrier through several recharge wells. Because of the success of the pilot operation, it is being expanded at present to intercept most of the contaminated underflow crossing the entire north boundary. However,

boundary interception alone cannot achieve aquifer restoration at the Arsenal. It is anticipated that the overall final program will also have to include elements of source containment and isolation, source elimination, process modification to reduce the volume of wastes generated, and development of alternative waste-disposal procedures that are nonpolluting. A variety of alternatives have been generated and are currently being evaluated to determine the most feasible for implementation. The research, planning, and design studies that are necessary to achieve the reclamation goal at the Arsenal illustrate that an effective aquifer restoration program is difficult to design and expensive to implement.

INTRODUCTION

The contamination of a ground-water resource is a serious problem that can have long-term economic and physical consequences. Because in most cases the problem is neither easily nor quickly remedied, Wood (1972) concluded, "The most satisfactory cure for ground-water pollution is prevention." Serious ground-water contamination problems have already occurred at numerous sites throughout the Nation. The magnitude of the problem is reflected by the results of several recent surveys of municipal and industrial waste-disposal sites in the United States (U.S. Environmental Protection Agency, 1980); they indicate that (1) 32,000 to 50,000 disposal sites may contain hazardous wastes; (2) of the approximately 57 million tons of hazardous liquid and solid industrial wastes generated in 1978, about 80 percent were disposed improperly in landfills or lagoons and pose a threat of ground-water contamination; (3) there may be as many as 100,000 abandoned industrial landfill sites; and (4) there are over 25,000 industrial surface impoundments and most of them are unlined. Pollution at a single site may be localized or may spread over a large area, depending on the nature and source of the pollutant and on the nature of the ground-water system. In many cases the single most important remedial action that can be taken is to eliminate the source of contamination. But even then, contaminants already in the aquifer will continue to migrate and spread unless some action is taken to immobilize, neutralize, or remove them.

The "restorability" of a contaminated aquifer is dependent on the hydrogeologic and geochemical properties of the affected aquifer and on the chemical and physical properties of the contaminant. Restoration of a contaminated aquifer is neither technically nor economically feasible in many cases. Factors frequently hindering restoration include: (1) the slow diffusive nature of ground-water flow; (2) the difficulty of defining secondary permeability effects; (3) the generally low oxygen content and lack of biologic reactivity in ground water; (4) the retention of some chemicals in the aquifer because they tend to be sorbed by minerals in the rocks making up the aquifer; (5) the lack of transferability of some restoration techniques from one site to another; and (6) the lack of knowledge about the source of the contamination.

Effective aquifer restoration programs, if technically feasible, are both difficult to design and expensive to implement. Nevertheless, in response to public or governmental demands for positive action in clearly documented cases where ground-water contamination threatens public health, aquifer clean-up programs are being required and instituted more frequently. Some programs are being financed and operated by the Federal Government. Examples include the Rocky Mountain Arsenal, Colorado, where irrigation and domestic water supply wells in adjacent areas have been contaminated from industrial wastes stored at the arsenal, and also Wurtsmith Air Force Base, Michigan, where toxic organic solvents used in aircraft maintenance have entered and spread through the underlying aquifer. Other programs may be implemented because of violations of Federal regulations. For example, a recent Justice Department suit was filed in North Carolina under the imminent hazard provision of the Resource Conservation and Recovery Act; the suit asks that the defendants "... permanently restore the aquifer to a condition commensurate with safe human use" (Hazardous Waste News, v. 2, no. 2, Jan. 21, 1980, p. 12). As an example of an aquifer restoration program being initiated because of State regulations, a chemical company in northern Michigan has come to an agreement with the State of Michigan to remove the contaminants from the soil and ground water at their former dump site; the projected cost is $12 million to $15 million (The Wall Street Journal, Sept. 25, 1981, p. 48).

General management options for restoring water quality in aquifers presently available include: (1) eliminate the source of contamination but allow restoration to proceed only through natural flushing, dilution, and geochemical or biological reactions; (2) accelerate removal of contaminants through withdrawal wells, drains, or trenches; (3) accelerate flushing with artificial recharge; (4) install "impermeable" barriers to contain a contaminated area; (5) induce *in situ* chemical or biologic reactions that would neutralize or immobilize the contaminant; and (6) excavate and remove the contaminated part of the aquifer. The selection of the best approach for a particular situation requires the ability to predict changes in flow and chemical concentration in the aquifer for each possible management alternative. This in turn requires both adequate field data to describe the aquifer systems and the development of accurate simulation models to define the ground-water flow system, pollutant-transport mechanisms, and nature and rate of chemical or biological reactions.

This report focuses on the ground-water contamination problem at at the Rocky Mountain Arsenal, which is located near Denver, Colorado (see figure 1). (Note that the boundaries shown in figure 1 do not reflect recent changes in the boundaries of Denver and the Rocky Mountain Arsenal.) This area is well suited for serving as a case study to illustrate data requirements, investigative approaches, and management options related to the reclamation of contaminated aquifers because (1) the 40-year history of ground-water contamination is relatively well documented in the scientific and engineering literature, (2) the geology and hydrology of the area are fairly well known, (3) adequate, though limited, water-quality data are available to calibrate numerical simulation models, (4) the locations and strengths of contaminant sources can be approximately reconstructed, (5) a management commitment has been made to aquifer reclamation, and (6) construction, operation, and evaluation of a pilot reclamation system at the arsenal have been completed.

DESCRIPTION OF STUDY AREA

History of Contamination

The Rocky Mountain Arsenal has been operating since 1942, primarily manufacturing and processing chemical warfare products and pesticides. These operations have produced liquid wastes that contain complex organic and inorganic chemicals, including a characteristically high chloride concentration that apparently ranged up to about 5,000 mg/L (milligrams per liter).

The liquid wastes were disposed into several unlined ponds (fig. 2), resulting in the contamination of the underlying alluvial aquifer. On the basis of available records it is assumed that contamination first occurred at the beginning of 1943. From 1943 to 1956 the primary disposal was into pond A. Alternate and overflow discharges were collected in ponds B, C, D, and E.

Much of the area north of the Arsenal is irrigated, both with surface water diverted from one of the irrigation canals, which are also unlined, and with ground water pumped from irrigation wells. Some damage to crops irrigated with shallow ground water was observed in 1951, 1952, and 1953 (Walton, 1961). Severe crop damage was reported during 1954, a year when the annual precipitation was about one-half the normal amount, and ground-water use was heavier than normal (Petri, 1961).

Several investigations have been conducted since 1954 to determine both the cause of the problem and how to prevent further damages. Petri and Smith (1956) showed that an area of contaminated ground water of several square miles existed north and northwest of the disposal ponds. These data clearly indicate that the liquid wastes seeped out of the unlined disposal ponds, infiltrated the underlying alluvial aquifer, and migrated downgradient toward the South Platte River. To prevent additional contaminants from entering the aquifer, a 100-acre (0.045 km^2) evaporation pond (Reservoir F) was constructed with an asphalt lining in 1956 to hold all subsequent liquid wastes (Engineering New-Record, Nov. 22, 1956). However, even if the lining were to remain totally impervious, this new disposal pond in itself would not eliminate the contamination problem because such a large mass of contaminants were already present in and slowly migrating through the aquifer.

From about 1968 or 1969 through about 1974, pond C was maintained full most of the time by diverting water from the freshwater reservoirs to the south. This resulted in the infiltration of about 1.0 ft^3/s (0.03 m^3/s) of fresh water into the alluvial aquifer. This artificial recharge had the effect of diluting and flushing the contaminated ground water away from pond C faster than would have occurred otherwise. By 1972 the areal extent and magnitude of contamination, as indicated by chloride concentration, had significantly diminished. source of this info. Chloride concentrations were then above 1,000 mg/L in only two relatively small parts of the contaminated area and were almost at normal background levels in the middle of the affected area (immediately downgradient from pond C).

In 1973 and 1974 there were new claims of crop and livestock damages allegedly caused by ground water that was contaminated at the Arsenal (The Denver Post, Jan. 22, 1973; May 12, 1974; May 23, 1974). Data collected by the Colorado Department of Health (Shukle, 1975) show that DIMP (Diisopropylmethylphosphonate), a nerve-gas byproduct, has been detected at a concentration of 0.57 ppb (parts per billion) in a well located approximately 8 miles (12.9 km) downgradient from the disposal ponds and 1 mile (1.6 km) upgradient from 2 municipal water-supply wells of the City of Brighton. A DIMP concentration of 48 ppm (parts per million), which is nearly 100,000 times higher, was measured in a ground-water sample collected near the disposal ponds. Other contaminants detected in wells or springs in the area include DCPD (Dicyclopentadiene), endrin, aldrin, dieldrin, and several organo-sulfur compounds.

The detection of these chemicals, which were manufactured or used at the Arsenal, in areas off the Arsenal property led the Colorado Department of Health to issue three Cease and Desist Orders in April, 1975 against the Rocky Mountain Arsenal and Shell Chemical Company, which was leasing industrial facilities on the site. The Cease and Desist Orders called for (1) a halt to unauthorized discharges, (2) cleanup, and (3) ground-water monitoring. Consequently, a program that included ground-water monitoring and studies to determine a means to intercept contaminants flowing across the north boundary of the Arsenal was established by the U.S. Army.

As a result of continued monitoring, additional contaminants have been identified either qualitatively or quantitatively in the ground water at the Arsenal. The most widespread of those found are Nemagon (Dibromochloropropane) and various industrial solvents. Nemagon contamination has been identified as probably resulting from Arsenal-related activities while the industrial solvents identified are not unique to Arsenal activities. Extremely low concentrations of Nemagon (F2 ppb) have been found in wells located immediately west of the Arsenal boundary. Other-organic contaminants associated with pesticide manufacturing have been found in wells located in a centrally-located manufacturing plant area known as the South Plants area. These contaminants probably entered the aquifer from accidental spills and leaks and appear to be migrating from this area very slowly.

Hydrogeology

The records of several hundred observation wells, test holes, irrigation wells, and domestic wells were compiled and analyzed to describe the hydrogeologic characteristics of the alluvial aquifer in and adjacent to the Rocky Mountain Arsenal. Konikow (1975) presented four maps that show the configuration of bedrock surface, generalized water-table configuration, saturated thickness of alluvium, and transmissivity of the aquifer. These maps show that the alluvium forms a complex, nonuniform, sloping, discontinuous, and heterogeneous aquifer system.

A map showing the general water-table configuration for 1955-71 is presented in figure 3. The assumptions and limitations of figure 3 are discussed in more detail by Konikow (1975). The areas in which the alluvium either is absent or is unsaturated most of the time form internal barriers that significantly affect ground-water flow patterns within the aquifer and, hence, significantly influence solute transport.

The general direction of ground-water movement is from regions of higher water-table altitudes to those of lower water-table altitudes and is approximately perpendicular to the water-table contours. Deviations from the general flow pattern inferred from water-table contours may occur in some areas because of local variations in aquifer properties, recharge, or discharge. The nonorthogonality at places between water-table contours and aquifer boundaries indicates that the approximate limit of the saturated alluvium does not consistently represent a no-flow boundary, but that, at some places, there may be significant flow across this line. Such a condition can readily occur in areas where the bedrock possesses significant porosity and hydraulic conductivity, or where recharge from irrigation, unlined canals, or other sources is concentrated. Because the hydraulic conductivity of the bedrock underlying the alluvium is generally much lower than that of the alluvium, ground-water flow and contaminant transport through the bedrock is assumed to be a secondary consideration compared to flow and transport in the alluvial aquifer. Ground-water withdrawals in the area are predominantly from wells tapping the alluvial aquifer.

Contamination Pattern

Since 1955 several hundred observation wells and test holes have been constructed to monitor changes in water quality and water levels in the alluvial aquifer. The areal extent of contamination has been mapped on the basis of chloride concentrations in wells, which ranged from normal background concentrations of about 40 to 150 mg/L to about 5,000 mg/L in contaminated ground water near pond A. Data collected during 1955-56 indicate that one main plume of contaminated water extended beyond the northwestern boundary of the Arsenal and that a small secondary plume extended beyond the northern boundary (see fig. 4). The contamination pattern shown in figure 4 clearly indicates that the migration of contaminants in this aquifer is also significantly constrained by the aquifer boundaries.

The extent of contamination as indicated by chloride concentration reflects a dilution ratio of about 33:1 from the contaminant source to the definable downgradient limit of contamination. However, the extent of contamination as indicated by some of the organic compounds, such as DIMP, is much greater because they have a zero background concentration and can be detected to trace concentrations that reflect a dilution ratio of about 100,000:1. Other organic contaminants exhibit a much smaller plume, or migration distance, than does the chloride because of reactions that cause them to decay or to be adsorbed. Other differences among shapes and locations of plumes of different contaminants arise because they entered the aquifer at significantly different times and (or) locations within the Arsenal. For example, the Nemagon plume occurs west of the chloride plume because the source of the Nemagon was not from the disposal ponds, but apparently from a spill that occured west of the ponds.

Contaminants have also been detected in several shallow bedrock wells in or near the arsenal. However, at present there are inadequate data to define the areal extent, depth of penetration, or rate of spreading of contaminants in the bedrock.

APPLICATION OF SIMULATION MODELS

The reliable assessment of hazards or risks arising from ground-water contamination problems and the design of efficient and effective techniques to mitigate them require the capability to predict the behavior of chemical contaminants in flowing ground water. Reliable and quantitative predictions of contaminant movement can only be made if the processes controlling convective transport, hydrodynamic dispersion, and chemical, physical, and biological reactions that affect solute concentrations in the ground are understood. These processes, in turn, must be expressed in precise mathematical equations having defined parameters. The theory and development of the equations describing ground-water flow and solute transport have been well documented in the literature. Perhaps the most important technical advancement in the analysis of ground-water contamination problems during the past 10 years has been the development of deterministic numerical simulation models that efficiently solve the governing flow and transport equations for the properties and boundaries of a specific field situation. Although many of the processes that affect waste movement are individually well understood, their complex interactions in a heterogeneous environment may not be understood well enough for the net outcome to be reliably predicted. Thus, the analysis of ground-water contamination problems can be greatly aided by the application of deterministic numerical simulation models that solve the equations describing ground-water flow and solute transport.

The solute-transport model described by Konikow and Bredehoeft (1978) was used to simulate the movement of chloride through the alluvial aquifer in an effort to reproduce the 30-year (1943-72) history of contamination, to help test hypotheses concerning governing processes and parameters in order to develop an improved conceptual model of the problem, to aid in setting priorities for the collection of additional data, and to evaluate possible management alternatives (Konikow, 1977). The stringent data requirements for applying the solute-transport model pointed out deficiencies in the data base available at the start of the study. Specifically, it was found that the velocity distribution determined from the water-table configuration mapped in 1956 (see Petri and Smith, 1956) was in part inconsistent with the observed pattern of contaminant spreading. The subsequent quantitative analysis and reinterpretation of available hydrogeologic data, based partly on feedback from the numerical simulation model, led to a revised conceptual model of the aquifer properties and boundaries that incorporated the strong influence of the internal barriers within the alluvial aquifer.

The solute-transport model of Konikow (1977) was calibrated mainly on the basis of the chloride concentration pattern that was observed in 1956 (figure 4). Computed chloride patterns agreed closely with observed patterns, which during the 30-year history were available only for 1956, 1961, 1969, and 1972. The calibrated model was then used to analyze the effects of future and past changes in stresses and boundary conditions. For example, comparative analyses illustrated that it would probably take at least many decades for this contaminated aquifer to naturally recover its original water-quality characteristics. But it was also inferred that appropriate water-management policies for aquifer reclamation can help to reduce this restoration time to the order of years, rather than decades, for the relatively mobile contaminants. Konikow (1974) also noted that the simulation results showed that a reclamation scheme using a network of interceptor wells would aid in containing and removing the contaminated ground water.

To more fully evaluate the range of engineering approaches or alternatives that would be feasible for construction along the north boundary of the Arsenal, Warner (1979) modeled a smaller part of the aquifer in that area in much finer detail. He predicted the impact on DIMP concentration of implementing a variety of interception schemes that incorporated variants of a basic plan that included elements of ground-water withdrawal, a barrier, and reinjection of treated water. Among other findings, Warner (1979) showed that a properly operated hydraulic barrier, consisting of a line of pumping wells, would be just as effective as a bentonite barrier in stopping the movement of DIMP-contaminated ground water across the northern boundary of the Arsenal.

AQUIFER RESTORATION PROGRAM

Reponse to Cease and Desist Orders

As a result of the Cease and Desist Orders, an Installation Restoration program was established at the Rocky Mountain Arsenal under the direction of the Program Manager for Chemical Demilitarization and Installation Restoration, Aberdeen Proving Ground, Maryland. This office was later reorganized into the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA), which currently directs the Installation Restoration program at the Arsenal. The main objective of this program is to limit the migration of contaminants from the Arsenal to the degree required by applicable Federal and State regulations. The program is primarily concerned with contamination problems resulting from historical activities on the Arsenal as opposed to ongoing operations.

The Installation Restoration program consists of three major subprograms, each of which addresses a particular requirement of the Cease and Desist Orders. These subprograms include regional ground-water monitoring, contaminant migration control, and elimination of contaminant sources. This division of the program and associated activities has allowed for a phased approach in developing and implementing contaminant control systems at the Arsenal, thereby accelerating the reduction of potential environmental hazards.

A comprehensive ground-water monitoring program was developed based on historical contaminant distribution information and initiated late in 1975. It included sample collection from both onsite and adjacent offsite wells. This monitoring program has been continually updated since that time to include additional wells and analytical parameters as required. Currently, this program involves the collection and analysis of samples from 90 to 100 wells on a quarterly basis. Samples from other wells on the Arsenal are periodically collected and analyzed as required to generate data in support of individual studies or operations. The information generated from the monitoring program is used to define the distribution and track the migration of the various known contaminants, identify new contaminants, develop design criteria for proposed contamination control and treatment systems, and evaluate the operation of existing systems.

The subprogram concerning contaminant migration control at the Arsenal boundaries was initiated in late 1975 with the goal of rapidly eliminating the migration of contaminants off the Arsenal. Boundary control was the only viable option available to meet this goal because of the already wide distribution of contaminants, the long travel times associated with contaminant migration from the sources to the boundaries, and the lack of precise definition of all source areas. This subprogram has resulted in the development and implementation of both pilot and full scale boundary control systems at the northern Arsenal boundary and planned development of boundary control systems to be constructed along the northwestern Arsenal boundary. These systems will be discussed in more detail later in this paper.

The subprogram concerning control and elimination of contaminant sources evolved several years after the other subprograms as additional data became available on specific source areas. The goal of this subprogram is to control or eliminate the contaminant sources on the Arsenal and thereby eliminate the need for boundary control in the future. This subprogram consists of studies aimed at further identification and definition of contaminant sources, development of feasible source control and elimination alternatives, and development of design criteria for proposed control and treatment systems. A summary of the status of this subprogram will be given at the end of this paper.

Contaminant Migration Control at Arsenal Boundaries

Because the contamination that resulted in the issuance of the Cease and Desist Orders was detected in surface water and ground water immediately north of the Arsenal, the primary focus of the Installation Restoration program during 1976 and 1977 was the northern Arsenal boundary. A dike was constructed to stop the off-post discharge of contaminated surface water. Studies were initiated to determine a feasible alternative for stopping the off-post flow of contaminated ground water without significantly altering the normal ground-water flow pattern in the area. The concept selected involved interception of the ground water a short distance south of the northern Arsenal boundary, treatment of the water to remove the contaminants, and reinjection of the treated water at the boundary.

Two methods were proposed for intercepting or "cutting off" the flow of ground water. The first method involved the use of a hydraulic barrier, one or two lines of closely spaced pumping wells that would provide for dewatering of the aquifer along or between the lines. The permeability in the area is sufficiently high for this concept to have worked, but the gradient is shallow and concern was expressed over the potential for excessive recycling of water from the reinjection wells back to the withdrawal wells. As a result of this concern and to provide an additional safety factor, a second method was selected that involved the use of a slurry cut-off wall to form an impermeable barrier between the withdrawal and reinjection wells.

Treatment Process

Late in 1975, a laboratory treatability study was initiated on representative ground-water samples from the area. Treatment processes investigated included granular activated carbon adsorption, powdered activated carbon adsorption, chemical oxidation using ultraviolet light (UV) and ozone, and anionic exchange resins. Key chemical parameters for analysis included DIMP and DCPD. Extensive laboratory studies were conducted using standard isotherm tests for evaluating the carbons and resins and using batch reactor tests for evaluating the UV/ozone process. The anionic exchange resins were dropped from further consideration because of their low efficiencies and high costs. A series of field studies were initiated on the carbon adsorption and UV/ozone oxidation processes to permit further evaluation.

Powdered activated carbon adsorption tests incorporating a polymeric coagulant were conducted using a standard Army Erdlator water treatment unit (chemical addition, mixing, upflow clarification) (Sweder, 1977). Granular activated carbon adsorption tests were conducted using a dynamic flow, multi-column system (Sweder, 1977). UV/ozone oxidation tests were conducted using a continuous flow, mechanically mixed reactor (Buhts, Malone, and Thompson, 1978). Granular activated carbon was found to be more efficient (110 mg carbon/liter of water) in removing the contaminants than was the powdered activated carbon (200 mg carbon/liter of water). Cost estimates were developed for the carbon adsorption and UV/ozone oxidation processes based on treating 10,000 gallons of water per hour (37,850 liters/hour). The estimated cost of granular activated carbon treatment was approximately $2 per 1000 gallons (3785 liters); powdered activated carbon was approximately $4 per 1000 gallons; and UV/ozone oxidation was approximately $3 per 1000 gallons. As a result of these studies and the immediate availability of proven process equipment, granular activated carbon was selected for use in the proposed treatment system.

Installation and Operation of Pilot Containment System

The information obtained from both the historical data base and the ongoing monitoring subprogram indicated that the highest concentrations of contaminants were crossing the northern Arsenal boundary in the alluvial aquifer in an area associated with a buried channel in the relatively impermeable bedrock of the Denver Formation. This area is located approximately one mile east of the northwest boundary and has a width of approximately 1000 feet (305 meters). Because very litte historical operational information was available on ground-water contamination control systems similar to the one proposed, the Army decided to install a limited pilot containment system in the narrow area of high contaminant concentrations to evaluate the feasibility of the overall approach. If the pilot system proved successful, the containment system would be extended to intercept and treat contaminated ground water crossing the entire affected part of the northern boundary.

The North Boundary Pilot System (NBPS) was constructed and placed in operation in July 1978. The NBPS was composed of the following subsystems:

(1) Barrier
(2) Dewatering wells
(3) Reinjection wells
(4) Treatment plant
(5) Monitoring wells

A schematic diagram of the system is provided in Figure 5.

The barrier was constructed by filling a 3-foot-wide (0.91 meters), 1500-foot-long (457 meters) trench, averaging 25 feet (7.6 meters) in depth, with a mixture of soil and bentonite clay. The barrier was anchored approximately 2 feet into the bedrock all along the alignment.

The dewatering subsystem was installed south (upgradient) of the barrier and consisted of six 8-inch (20.3 cm) diameter wells placed within 30-inch (76.2 cm) diameter gravel-packed holes. The wells were placed approximately 225 feet (68.6 meters) apart on a straight line parallel to the barrier. Each well was screened throughout the entire saturated portion of the alluvial aquifer. A submersible pump and flow control system were installed at each well site. Water from the wells was pumped through an underground manifold to a single sump at the treatment plant.

The reinjection subsystem was installed north (downgradient) of the barrier. It consisted of twelve 18-inch (45.7 cm) diameter wells approximately 100 feet (30 meters) apart on a straight line between the barrier and the northern Arsenal boundary. They were installed in 36-inch (91.4 cm) diameter gravel-packed holes. The recharge wells were screened to a point somewhat above the water table. Treated water was continuously injected into the recharge wells by gravity flow through an underground manifold system. Sensors and flow control valves were installed in the wells to prevent overflow or surface discharge in the event that a well experienced an excessively high buildup of hydraulic head because of clogging of well screens or other factors.

The treatment plant subsystem was designed to treat 10,000 gallons of water per hour. It consisted of two mixed-media pressure filters, each four feet (1.2 meters) in diameter; two adsorber vessels (or columns) each 10 feet (3.1 meters) in diameter and 11 feet (3.4 meters) high, designed to contain about 20,000 pounds (9100 kilograms) of granular activated carbon; and assorted pumps, controllers, piping, and valves. Water from the collection sump was pumped through the filters in parallel to remove suspended material, then through the carbon adsorbers, and finally to the reinjection wells. Only one carbon adsorber was in operation at any one time. The alternate was used when it became necessary to remove exhausted carbon from the adsorber vessel and replace it with fresh carbon. The treatment system was designed to be largely automatic and simple to operate by incorporating automatic back-washing of the filters and sensors for control of pumps and valves. Only one intermittent operator was needed to monitor the system. The concentration of DIMP in the effuent from the treatment system was used to determine when the carbon in the adsorber required replacement. When the DIMP concentration approached 50 ppb, the carbon was replaced. During 1978-81, replacement was required approximately once every 9 months. The exhausted carbon was transported offsite for regeneration by a commercial vendor.

The monitoring well subsystem consisted of ten observation wells installed both upgradient and downgradient of the pilot containment system. They were cased with small diameter PVC pipe and screened in the alluvial aquifer. Water levels and chemical quality were monitored periodically to provide information on the effectiveness of the operation of the system.

The cost of the barrier and the well subsystems as constructed in 1978 was $450,000. The facility for housing the treament system cost approximately $40,000. The treatment equipment was obtained under a lease/service contract agreement with a commercial vendor with an upfront cost of approximately $100,000 and a yearly fee ranging from $135,000 to $150,000.

The NBPS operated successfully for a period of approximately 3 years. For example, during FY 1979, downtime was less than one percent of operating time based on a 365-day operating schedule. The granular activated carbon effectively removed the organic contaminants from the ground water, as illustrated by a comparison of typical GC/MS analyses of the influent (Figure 6) and effluent (Figure 7) of the treatment system. Final carbon usage rates ranged from 100 to 150 mg of carbon per liter of water. The flow of ground water downgradient from the NBPS was essentially unchanged (D'Appolonia Consulting Engineers, Inc., 1979).

Expanded Containment System

As a result of the successful operation of the pilot containment system, construction of the expanded containment system was begun in early 1981. The expanded system consists of a 6800-foot (2070-meter) barrier ranging from 25 to 50 feet (7.6 to 15.2 meters) deep, 54 withdrawal wells, and 38 reinjection wells. The expanded barrier effectively intercepts all the contaminated ground water flowing across the northern Arsenal boundary in the alluvial aquifer. The expanded treatment system is designed to treat 36,000 gallons (136,000 liters) of water per hour. The adsorbers used in the pilot operation have been replaced with three pulsed-bed adsorbers designed to contain 30,000 pounds (13,600 kilograms) of carbon each. The new adsorbers should be much more efficient than the old ones because the anticipated carbon usage rate is only 25 to 30 mg of carbon per liter of water. The mixed-media filters have been replaced with cartridge filters, which are easier to maintain. The whole system is highly automated and will require only intermittent monitoring by a single operator. The estimated cost for the expanded system is approximately $6,000,000. The expanded system is scheduled to be operational early in 1982.

Other Contaminant Migration Control Systems

Concepts have been developed for two additional boundary contaminant migration control systems located along the northwestern Arsenal boundary (Figure 8). One system will be located at the southern end of that boundary and the other midway along that boundary. Both systems have been developed primarily to control the migration of low concentrations of Nemagon across the boundary. Both systems will be similar in size to the NBPS and will incorporate granular activated carbon treatment of the ground water. The system to be located on the southern end of the boundary (Irondale System) is being constructed under the direction of Shell Chemical Company and will incorporate a hydraulic barrier for interception of the ground water, along with the reinjection wells. It is scheduled to be in operation in 1982. The other system, to be constructed by the Army, will incorporate a slurry cut-off wall, withdrawal wells, and reinjection wells, similar to the NBPS. It is scheduled to be operational in 1985.

Control and Elimination of Contaminant Sources

Contaminant migration control at the boundaries of the Rocky Mountain Arsenal was initiated to stop or severely limit the migration of contaminants off the Arsenal as soon as possible. Due to the size of the Arsenal and extent of the source areas, the boundary control systems could be required to operate for an indefinite period of time. The only way to limit this requirement and the associated cost is to control or eliminate the contaminant sources. As a result, a subprogram was initiated to define and assess source control and elimination strategies.

In 1980, a study was initiated to identify existing and innovative control or elimination alternatives for contaminant source areas. The study objectives stipulated that the selected alternatives should be capable of bringing the Arsenal into compliance with all applicable Federal and state environmental laws and regulations. Another study objective was to develop preliminary cost data and technical data for use in a subsequent detailed evaluation and comparison of alternatives. A study team comprised of twelve government and independent scientists and engineers was established to conduct and manage the study.

A review of historical operations, past study reports, and data from ongoing studies was made to identify, where possible, potential sources of contaminant migration problems. The sources identified were categorized as primary sources or potential or unknown sources (unpub. report, Rocky Mountain Arsenal Contamination Control Study Team, August 1981). The latter sources were included in a prioritized list of areas requiring further problem definition.

The next phase of the study involved the development of control strategies. Guidelines and criteria for development of the strategies were required because of the complexity of and relationships between the contaminant sources and migration characteristics. In addition, some degree of commonality of structure or organization among the strategies was needed to enable a comparison and ranking of the alternatives to be developed. As a result, a hierarchical approach and structure for generation and classification of control strategies was developed incorporating five levels of detail ranging from concept to unit operation (unpub. report, Rocky Mountain Arsenal Contamination Control Study Team, August 1981). At this point, each team member individually developed a number of strategies using the hierarchical approach and determined the problem definition and technical data-base deficiencies associated with each scheme. The schemes were then submitted to the group as a whole for integration and evaluation.

At the same time that scheme development was being pursued, screening criteria were developed for use in evaluating and comparing the alternative schemes. The goal was to produce a set of criteria that could be applied at the various hierarchical levels, thereby enabling the screening of the schemes without doing a detailed evaluation of each one. The major criteria selected for use are as follows:

(1) Availability of technology
(2) Amount of additional data required
(3) Cost and time needed to fill data gaps
(4) Life cycle costs - capital and O&M
(5) Compatibility between systems
(6) Degree of risk - environmental and technological
(7) Compliance with regulatory requirements

The schemes developed by the study group members were integrated, evaluated, and screened by the study group as a whole. This work resulted in the presentation of fourteen alternative schemes that were recommended for detailed evaluation by the Contamination Control Study Team. The schemes incorporate various aspects of the technologies listed in Table 1. The schemes address only the known contaminant sources at the Arsenal and therefore may have to be expanded if additional sources are identified in the future.

In addition to the development of the alternative schemes, the study group identified a number of data gaps concerning both problem definition and technology development that must be filled before final section of a control or elimination alternative can be made. Studies have been included in the overall Installation Restoration program to fill these data gaps. They include additional hydrogeological definition of certain areas on the Arsenal, surface-water hydrology definition, water treatment technology development, and contaminated soil and residue disposal technology development. As the data from these additional studies become available, the study team will further evaluate and revise the alternatives as required with the goal of selecting one alternative for implementation.

The implementation of the selected alternative will be conducted using a phased approach. As soon as a particular part of the alternative is defined and design criteria are developed, construction will be initiated. For example, the elimination of Basin F will probably be one of the first major actions initiated because it has been ascertained that it is leaking and because the extent and nature of the contamination associated with this area of the Arsenal has been better defined than elsewhere. The control and elimination of known contaminant sources at the Rocky Mountain Arsenal is currently expected to involve a five-year construction program that is scheduled to start in 1985. A final cost estimate for the construction program has not been developed, but preliminary estimates range from $50 to $100 million.

TABLE 1. CONTAMINANT SOURCE CONTROL AND ELIMINATION TECHNOLOGIES

Ground-water Interception

a. Hydraulic barrier
b. Slurry trench
c. Dewatering trench (French drain)

Water Treatment

a. Adsorption (carbon and resin)
b. Chemical addition/coagulation/precipitation
c. Filtration
d. Membrane separation
e. Chemical oxidation
f. Activated sludge
g. Volatile stripping
h. Ion exchange

Contaminated Soil and Residue Treatment

a. Incineration
b. Fixation/stabilization
c. *In situ* forced leaching
d. Excavation and disposal.

SUMMARY AND CONCLUSIONS

Removing pollutants from a contaminated aquifer may seem to be an almost impossible task. While this may be true for some contaminated aquifers, others may be amenable to one or more plans for artificial reclamation that could significantly accelerate the rate of water-quality improvement in the aquifer. The feasibility of any such reclamation plan would be strongly dependent on the hydraulic and chemical properties of the aquifer, on the type and source of contamination, and on the duration and areal extent of contamination. Because a variety of reclamation plans can be proposed for any one problem, an accurate model of flow and contaminant transport in the aquifer could be in invaluable tool for planning an efficient and effective program.

The control and elimination of contaminant migration and contaminant sources at the Rocky Mountain Arsenal represents a large, complex, and costly undertaking. In excess of $25 million has been expended to date in the Installation Restoration program, excluding the costs associated with construction of the control systems. An extensive monitoring well program has been required to define the extent of the contamination and the relationships between the sources and contaminant migration patterns. Control of contaminant migration at the Arsenal boundaries has proved feasible using a system involving ground-water interception, treatment, and reinjection. Such a system was operated successfully without adversely affecting the flow and distribution of ground water downgradient from the treatment system.

Although boundary control systems can be used successfully to stop or restrict the migration of contaminants off the Arsenal, they can not solve the problem of continued contaminant migration from the source areas to the environment. The overall solution thus involves the control or elimination of the contamination at the sources. A program has been successfully initiated at the Rocky Mountain Arsenal to develop and assess source control and elimination strategies. Through additional data collection and feasibility studies, a single strategy will be selected and implemented using a phased construction approach. The ultimate goal of these activities is to bring the Arsenal into compliance with all applicable Federal and state environmental laws and regulations.

The great difficulty and great expense involved in mitigating ground-water contamination problems does not lessen the need to do so; it does illustrate the long-term benefits of planning and designing waste-disposal activities to prevent or minimize future contamination hazards.

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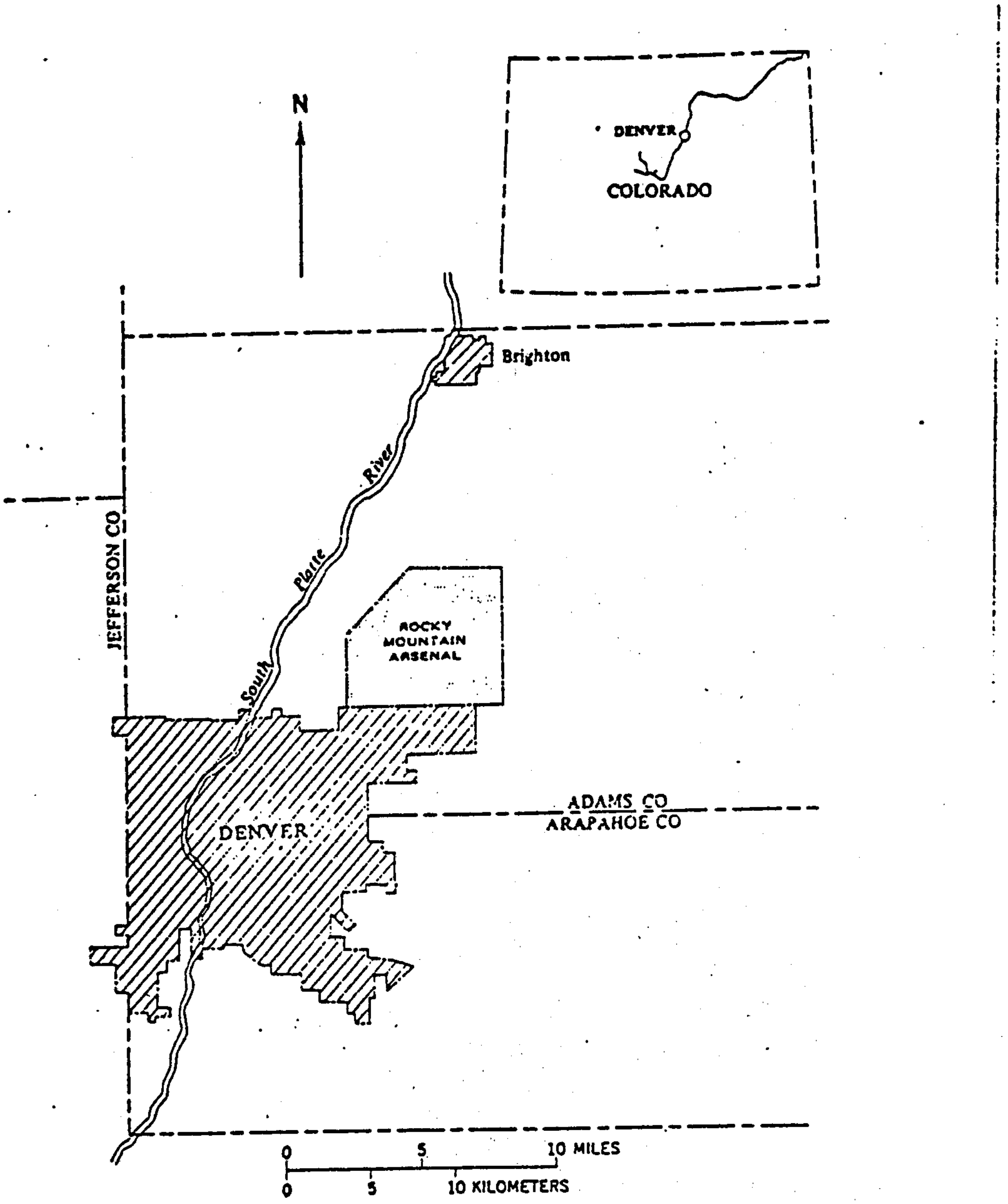

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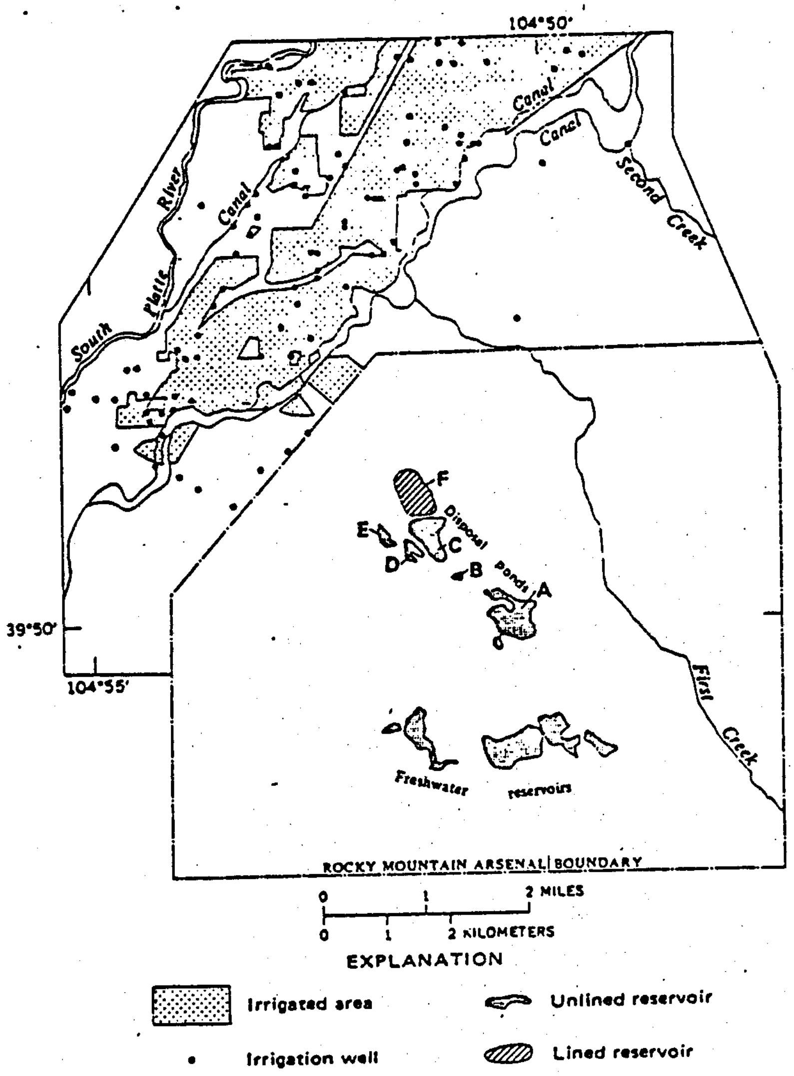

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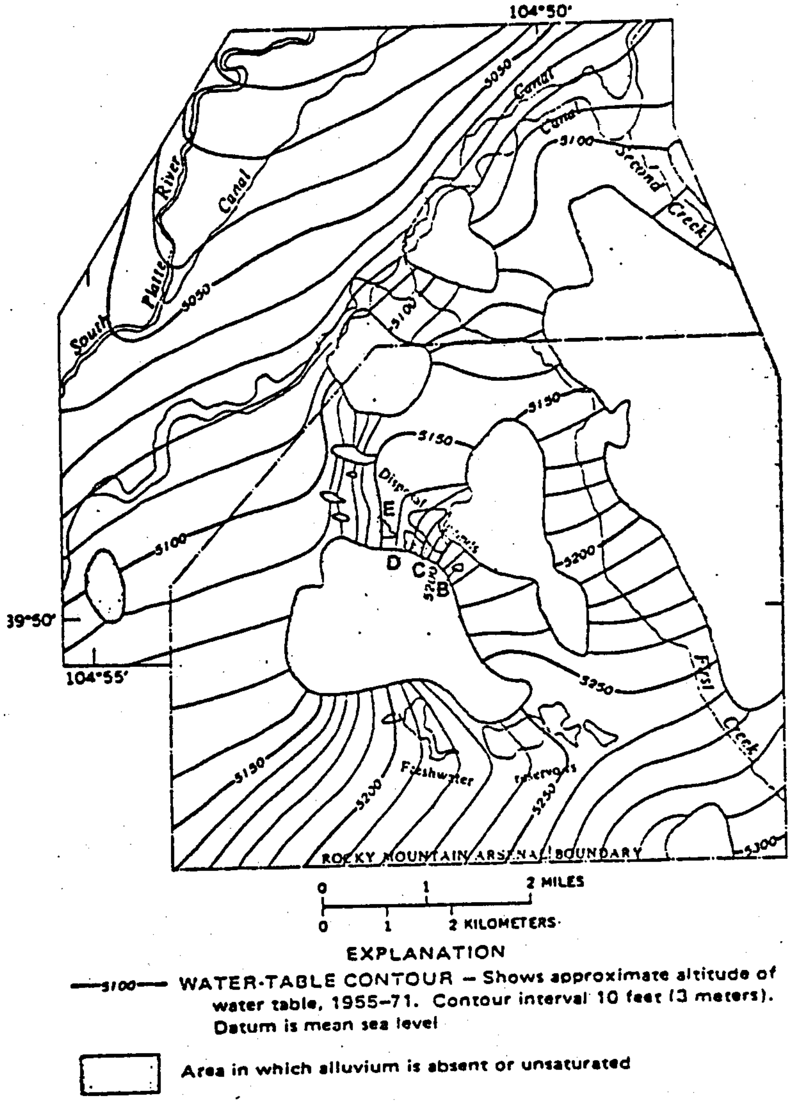

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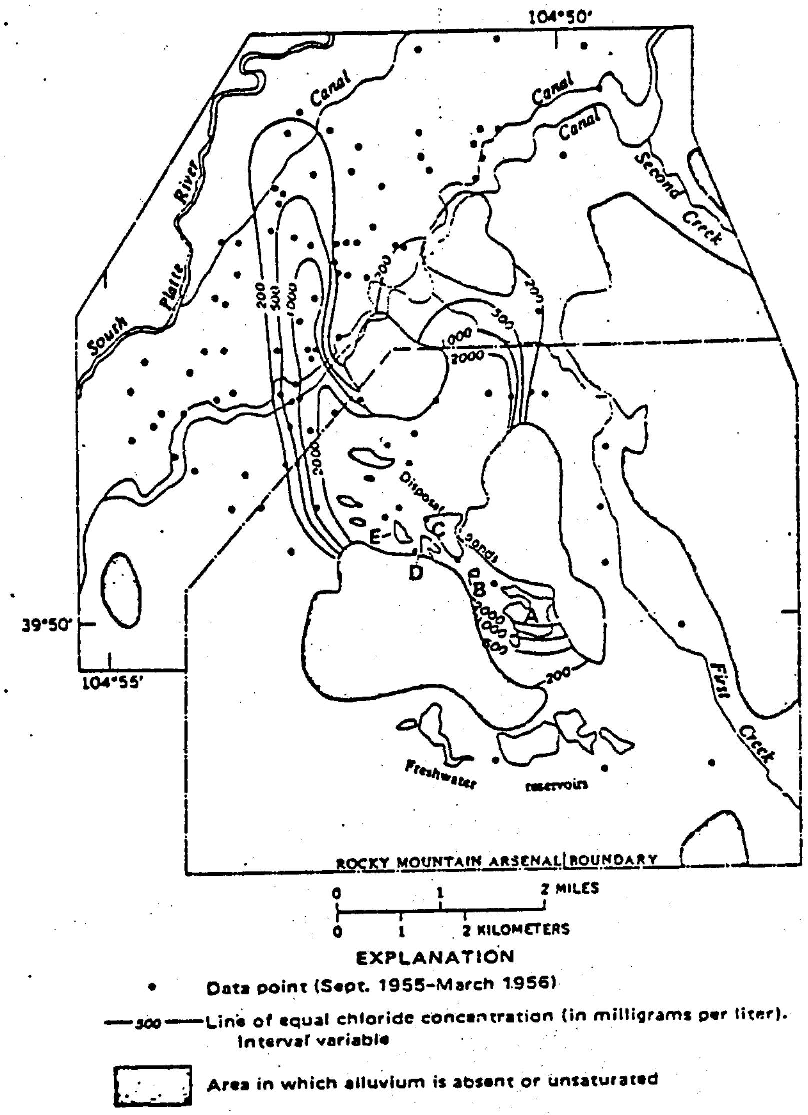
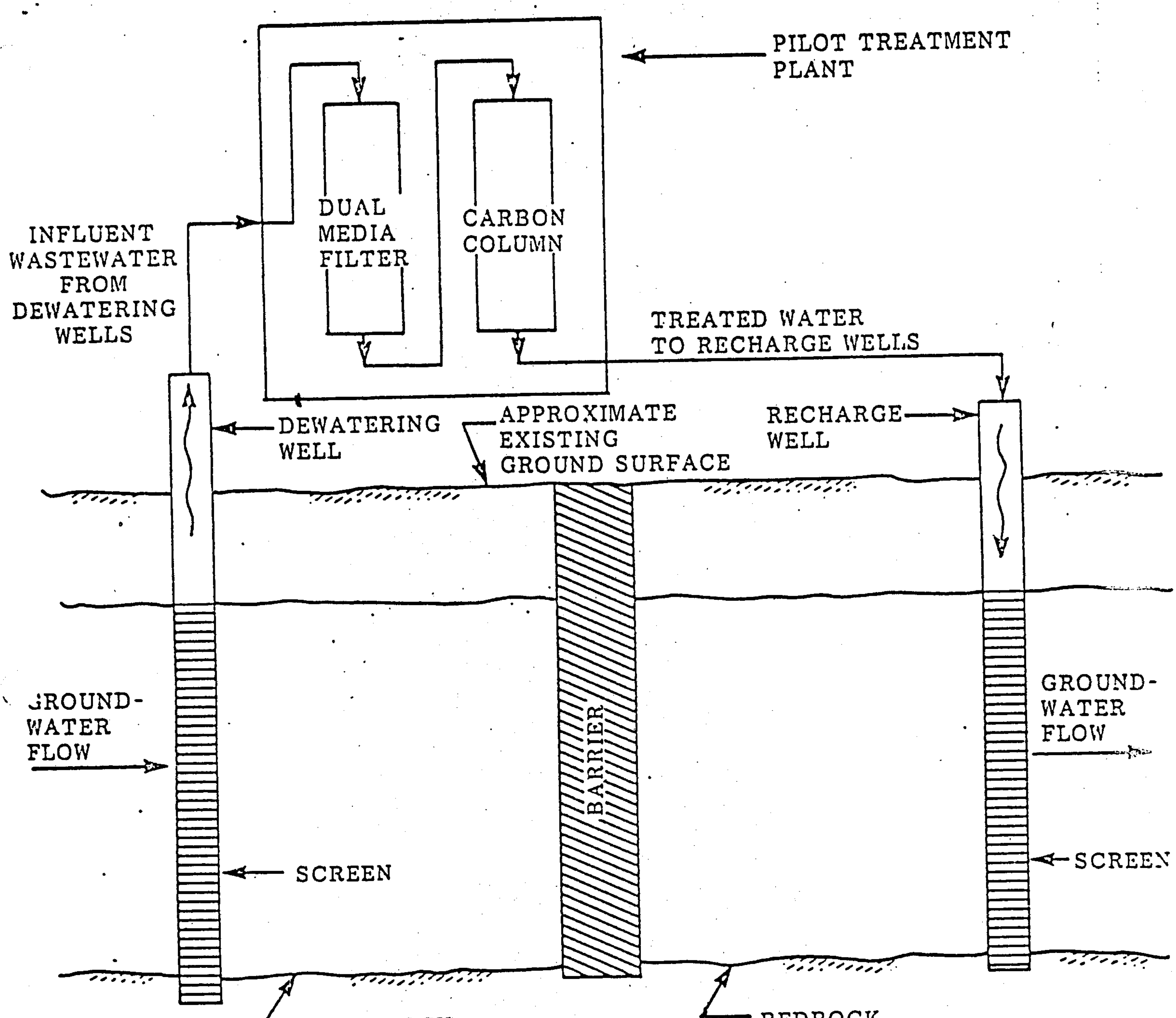


Figure 4.--Observed chloride concentration, 1956 (Konikow, 1977).



(Not to scale)

Figure 5. Schematic Diagram of North Boundary Contamination Control Pilot System

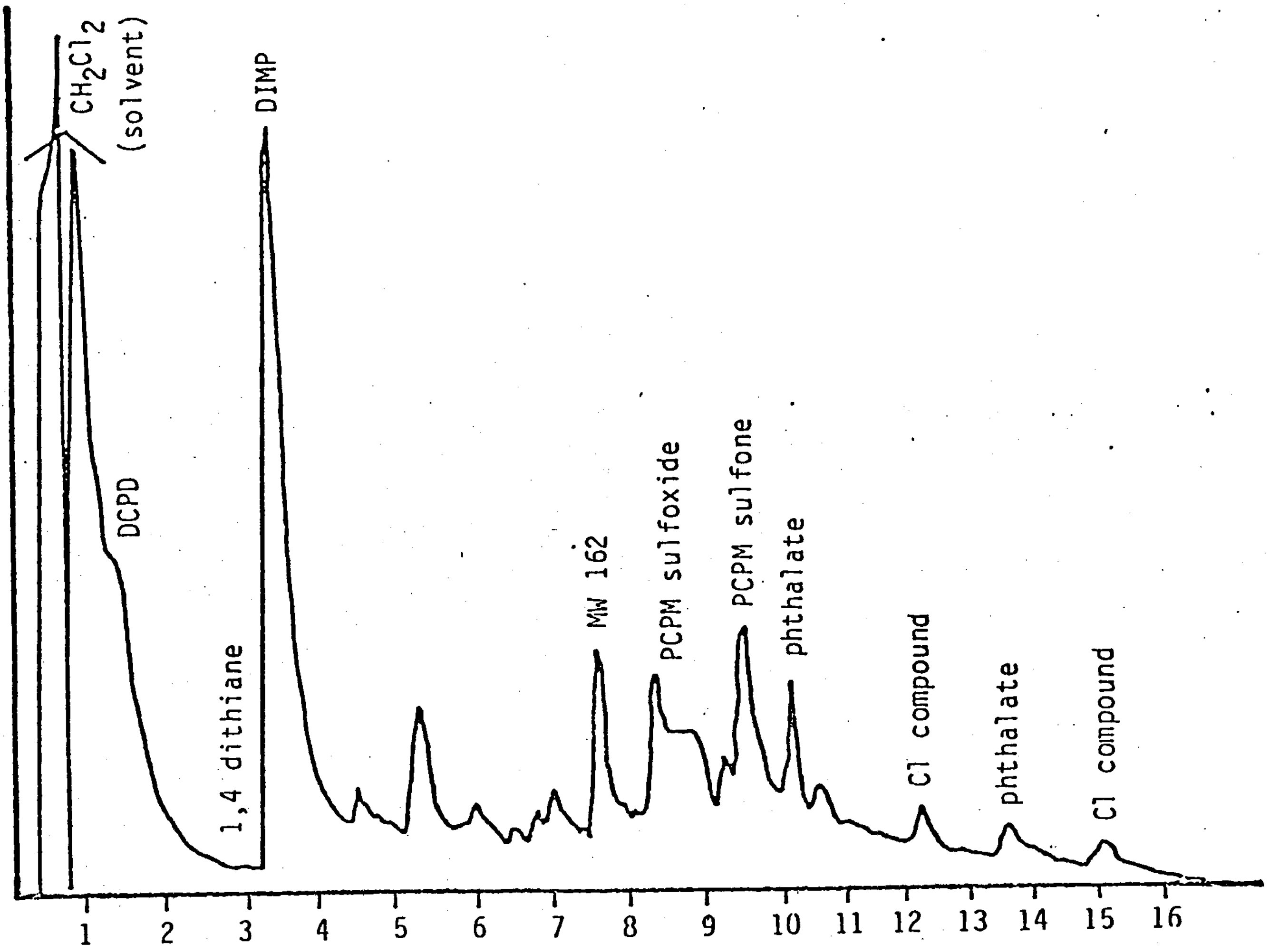


FIGURE 6. Typical GC/MS SCAN OF [redacted] North Boundary Pilot TREATMENT SYSTEM INFLUENT

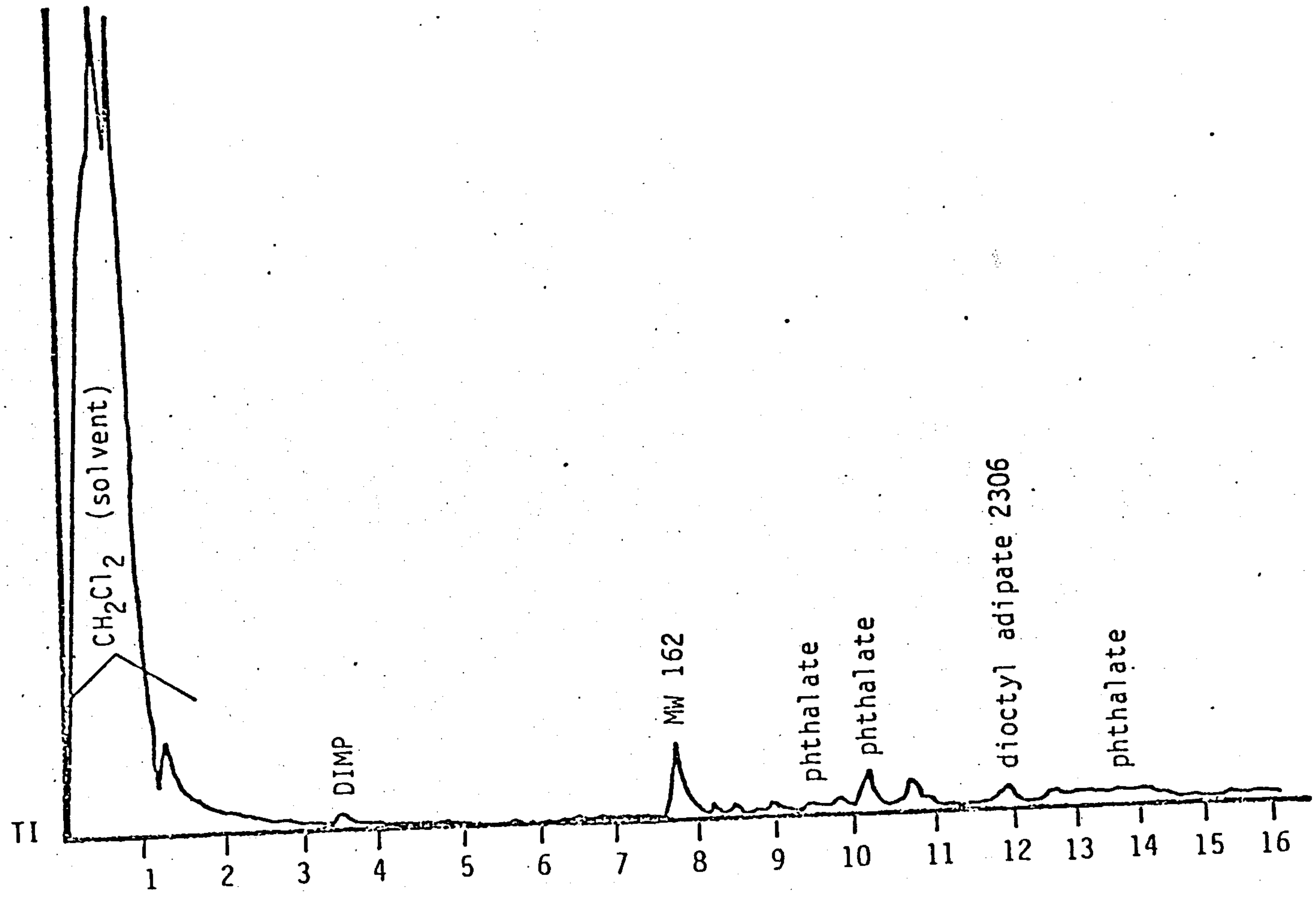


FIGURE 7. Typical GC/MS SCAN OF North Boundary Pilot TREATMENT SYSTEM EFFLUENT

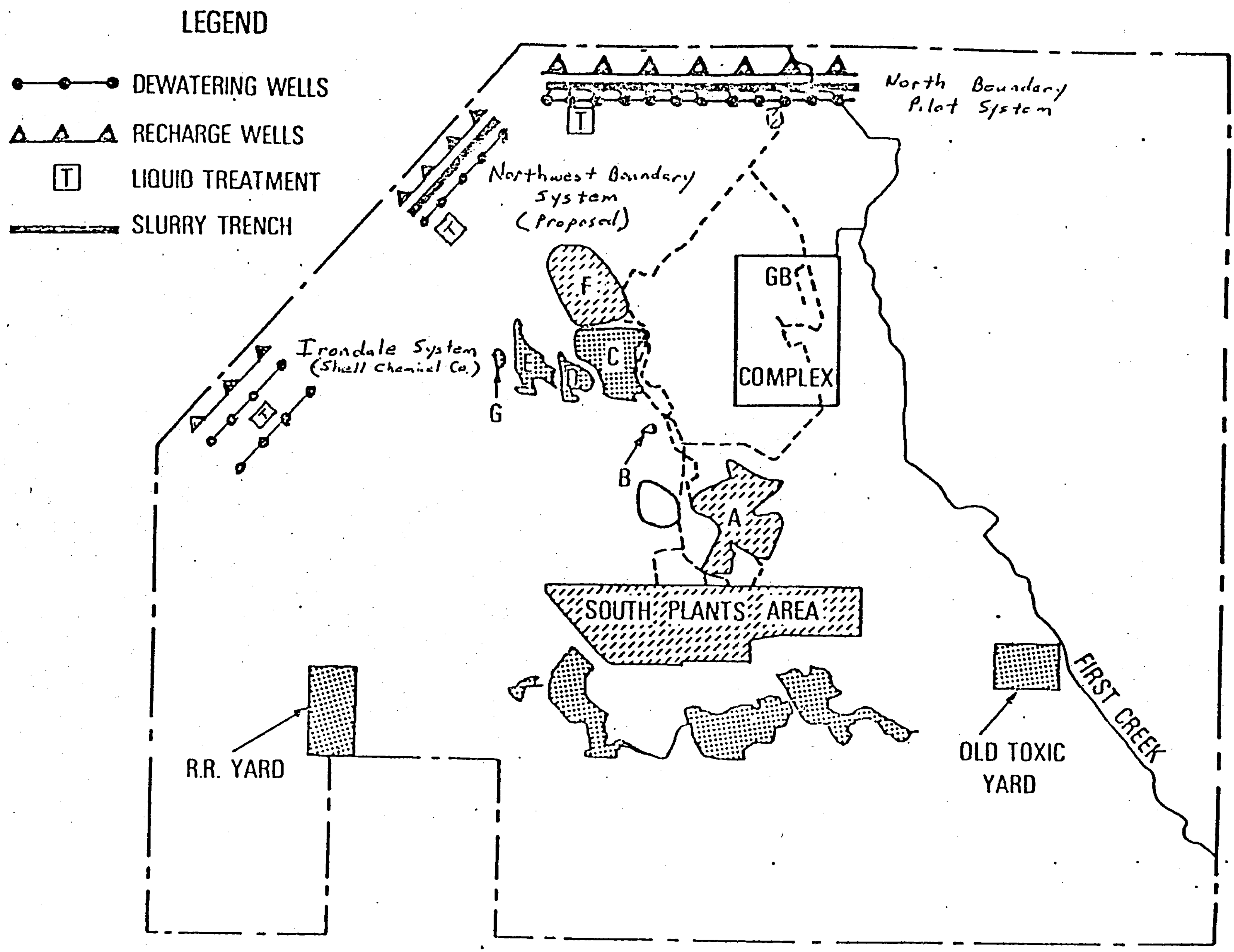


Figure 8. Location of Existing and Proposed Boundary Control Systems.